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Economic drivers of global fire activity: A critical review using the DPSIR framework

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ABSTRACT

Overall decline of global burned area paradoxically hides a number of economic realities that have increased the likelihood and costs of wildfire-caused disasters. In this critical review, we address the pressing need to identify and incorporate economic elements shaping global wildfire activities. To synthesize our current understanding of economic drivers of wildfires, we leverage the DPSIR framework to structure the issues related to wildfires to establish coherent causal pathways between Drivers (D), Pressures (P), States (S), Impacts (I) and Responses (R). We identified global patterns of worsening wildfire risks with the double-exposure to globalization and climate change. Current developments call for a paradigm shift in how we understand and manage wildfires to promote an adaptation-mitigation-resilience strategy. We propose expanding the science-policy interface to global scale with new indicators for assessing and communicating the impacts of global economic drivers on wildfire activities, such as "Virtual wildfire trade" accounting to monitor delocalized fire activity—exported fires and land transformation from developed to developing regions with weak governance. We also identified the areas where research is lacking, highlighting future research areas in wildfire economics to advance effective, efficient, and equitable global governance of wildfires.

1. Introduction

Fire has been a traditional landscape management tool throughout human history and wildfires[1], ecosystems, and human societies have co-evolved over millennia (Bowman et al., 2011; Scott et al., 2013). In the Anthropocene, however, human influences are rapidly altering wildfire regimes established in evolutionary time. Colonization, rural exodus, aggressive wildfire suppression, urban sprawl, global trade, among other factors, have all contributed to recent wildfire disasters to varying, yet often interacting, degrees (Bond, 2016; Bowman et al., 2009, 2020; Hessburg et al., 2019). While global area burned overall declined during the past decades largely due to agricultural expansion and intensification, negative impacts of wildfires on society are worsening with ongoing environmental changes and economic globalization (Andela et al., 2019; Andela et al., 2017; Curtis et al., 2018; Doerr and Santín, 2016; Knorr et al., 2014). This situation was well exemplified by the 2015 fire season in Indonesia that released at least 0.35–0.60 Pg of carbon into the atmosphere (Nechita-Banda et al., 2018). Many small-scale human-caused fires (over 100,000) to prepare land mainly for oil palm agriculture grew out of control under the warm and drought condition of El Niño period and cost Indonesia at least $16 billion USD, or a 1.9 % loss in GDP (World Bank, 2016). The estimated cost does not include cumulative impacts on ecosystem or costs to other countries (World Bank, 2016). This double-exposure to globalization and climate change complicates our understanding of the climate-human-fire nexus, as environmental and economic ramifications tangle ((O'Brien and Barnett, 2013; O'Brien and Leichenko, 2000; Rockström et al., 2009).

After a number of recent catastrophic fire years, there are now growing calls for modern society to co-exist with wildfires, especially in fire-adapted ecosystems—as many traditional communities still do—rather than fight them (Doerr and Santín, 2016; Moritz et al., 2014; Mistry et al., 2016; Moore, 2019; Reinhardt et al., 2008; Yazzie et al., 2019). Effective wildfire governance requires comprehensive land use planning coordinated with risk and ecosystem management (Doerr and

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[1] We followed the definition of wildfires by IUFRO "as a general term encompassing a diversity of controlled and uncontrolled vegetation fires with landscape-scale impacts, including agricultural land, grassland, shrubland, peatland, and forest fires" (IUFRO, 2018, p14).

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Santín, 2016). However, characterization of wildfire risk is still heavily driven by ecological studies and human causes of fires are still poorly understood (Chuvieco et al., 2021), while costs and loss statistics dominate the global wildfire narrative (Gill et al., 2013; IUFRO, 2018; Moore, 2019; World Bank, 2020). In this critical review, we argue that devising a governance scheme addressing the worldwide wildfire "problem" should start with understanding macroeconomic forces underpinning wildfire hazard geography and its system-wide impacts. Notwithstanding the importance and variability of local factors influencing wildfire risk, we posit that common patterns exist worldwide. Our goal is twofold: 1) synthesizing our current understanding of wildfire economics and identifying where research is lacking, and 2) generating insights into economic dimensions of wildfires to inform sound policies and sustainable fire management. The focus is not on reviewing related economic theories and formalizations, which have received limited academic attention thus far (Rideout et al., 2008; Fitch and Kim, 2018). We employed the Drivers-Pressures-States-Impacts-Responses (DPSIR) framework to highlight economic drivers behind wildfire patterns and the economic consequences triggered by detrimental fires and advocate building inclusive cross-scaled science-policy interfaces to manage wildfires. We conclude with possible pathways forward for managing wildfires at a global scale.

2. Wildfire economics: an overview

From an economic perspective, wildfires can be viewed as stochastic events that disturb the flow of goods and services, although human actions affect and mediate their occurrences and impacts (Holmes et al., 2008). The economic goal of wildfire management is then to maximize the net land value, which means that investments in risk reduction are justified as long as their economic benefits outweigh the total costs of preparedness, suppression, losses, and restoration (Donovan and Rideout, 2003; Lueck and Yoder, 2016,). Earlier economic models developed in fire-adapted ecosystems in North America mainly focused on finding optimized levels of human responses (i.e., pre-suppression and suppression activities) to minimize the costs and losses related to wildfires, including timber, watershed, and property losses (Headley, 1916; Lovejoy, 1916; as cited in Pyne, 1997). However, investing in pre-suppression activities does not necessarily reduce suppression costs when the expected overall loss is increasing due to changing climate and growing socioeconomic assets to protect, such as expanding residential development (Donovan and Rideout, 2003; Fitch and Kim, 2018; Rideout et al., 2008; Rideout and Omi, 1990; Rideout and Ziesler, 2008). There has been empirical evidence, at least in the US, that while pre-suppression activities reduce wildfire-related loss, they do not necessarily reduce wildfire suppression costs (Sánchez et al., 2019). However, the tendency of oversimplifying wildfire policies as pre-suppression versus suppression still prevails in North America (Kline et al., 2017; Pyne, 2016) and in Europe (Badia et al., 2002; Moreira et al., 2020).

Advances in wildfire science increasingly point at the complexity of wildfires and full accounting of their economic costs, as well as benefits of risk mitigation, would be impossible (Venn and Calkin, 2011; Donovan and Rideout, 2003). This is true even in the US where an extensive body of literature exists for economic accounting of wildfire-related losses and changes in ecosystem services due to wildfire management (for the systematic reviews of wildfire related ecosystem services losses and costs in the US, see Sánchez et al., 2021; Thomas et al., 2017; Vukomanovic and Steelman, 2019). The economic complexity of natural disturbances, such as wildfires, goes beyond the narrow sectoral focus on pre-suppression and suppression activities (Hallegatte and Przyluski, 2010; Milne et al., 2014, Thomas et al., 2017, Headwaters Economics, 2018). Recent catastrophic wildfire events around the world further underlined that this simple dichotomy is insufficient for the purposes of wildfire governance. When wildfire events escalate as landscape-scale disasters, their economic consequences include emergency assistance relief, long-term healthcare burden (e.g. Rice et al., 2021; Forsyth, 2014), losses by insurance companies (Dixon et al., 2018), and perturbations to economic activities (e.g. loss of GDP) (World Bank, 2016), as well as risks to a range of ecosystem services. The DPSIR framework can help broaden our understanding of economic forces driving up wildfire risks and provide ways to incorporate some of the cross-scale climate-human-fire dynamics.

3. Drivers-Pressures-States-Impacts- Responses (DPSIR) framework

The Drivers-Pressures-States-Impacts-Responses (DPSIR) framework is a problem-structuring method that helps establish a coherent foundation and causal pathways between five categories of influential factors: Drivers (D), Pressures (P), States (S), Impacts (I) and Responses (R) (Smeets and Weterings, 1999). Within the context of this review, the framework allows integration of existing economic linkages connecting human, climate, and vegetation dynamics leading to detrimental wildfire effects across multiple scales (Balzan et al., 2019; Díaz et al., 2018; Pinto et al., 2013; Vidal-Abarca et al., 2014). DPSIR has been criticized for its apparent simplicity and inability to capture complex systems (Gregory et al., 2013; Svarstad et al., 2008). However, it is flexible and adaptable, and thus fitted for the general presentation of wildfire economics we want to convey in this review. The framework has benefited from many contextual adaptations and remains widely used for problem elicitation purposes, participatory environmental studies, and policy-making (Ruan et al., 2019; Kelble et al., 2013; Ness et al., 2010).

We modified the formalization by Balzan et al. (2019) as the adaptive wildfire DPSIR framework (Fig. 1), that addresses some of the main criticisms of the DPSIR framework for building linear relationships among compartmentalized components. The five categories are:

- Drivers (D), as underlying changes in the biophysical, social, economic and political systems, as well as their relationships, creating Pressures on social-ecological systems;
- Pressures (P), as consequences of underlying changes, which have the potential to cause both positive and negative Impacts. The analytical focus here is on the negative impacts;
- States (S) of wildfire systems, as represented by the fire triangle of fuel, heat and conducive conditions. Ecological conditions, such as structures and functions of forests, woodlands, grassland, and peat ecosystems, make the system vulnerable to wildfires and other disturbances, while social conditions can increase ignition sources and frequencies.
- Impacts (I), conceptualized in stages: changes in fire regimes affect ecosystem service supply and drive up costs and losses related to wildfires, which in turn drive changes in human perception, attitudes and values about wildfires leading to biased economic incentives aggravating wildfire disaster risks.
- Responses (R), as policy and management actions initiated by institutions or groups (e.g., politicians, managers, stakeholder groups) to prevent, eliminate, compensate, reduce or adapt to Impacts. Assessments of Drivers, Pressures and States and Impacts and their interactions are essential to inform and enable adequate Responses.

4. Drivers (D) and Pressures (P) on wildfires

4.1. Climate change

Climate patterns govern types and distributions of vegetation (i.e., biomes) as well as their flammability (i.e., species, fuel moisture, and fuel structure) and burning potential (i.e., ignition and spread) in general. Climate and weather are well-known and widespread drivers of natural disturbances and included in most natural disturbances and risk assessment endeavors. Although uncertainties around challenges posed by ongoing and future effects of climate remain, a relatively large body of literature exists on the topic. There is a global consensus among a

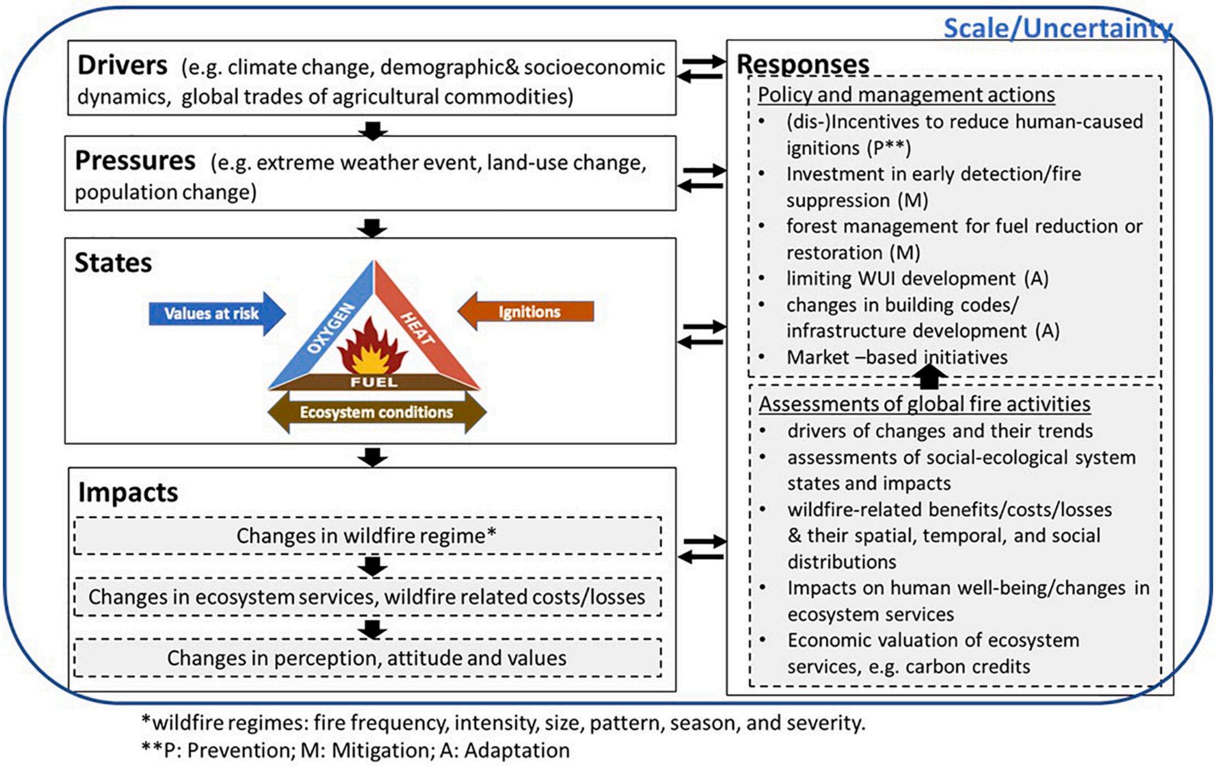

Fig. 1. DPSIR framework for economic drivers of global fire activities. Arrows indicate causal relationships between drivers, pressures, states, impacts and responses (adapted and modified from Balzan et al., 2019; Butry, 2009).

wide array of studies on climate-fire relationships that we are experiencing more hazardous fire-weather conditions over the recent decades, which is expected to get worse in the future under changing climate (e.g. Bedia et al., 2015; Dupuy et al., 2020; Hessburg et al., 2019; Liu et al., 2010; O'Connor et al., 2011). Although the overall decline in burned area in the past decades affirms effectiveness of fire suppression thus far (Doerr and Santín, 2016), the estimate based on coarse spatial-resolution sensors may be under-reporting total burned areas and fire carbon emission, as small fires that burn only a fraction of a pixel were not detected in widely used Moderate Resolution Imaging Spectroradiometer (MODIS) images (500 m) (Ramo et al., 2021). Human capability to control wildfires is likely overwhelmed by the interplay between human-caused ignitions and climate change increasing frequencies of extreme weather events combined with overall hotter and drier conditions in the future (Dupuy et al., 2020). However, research is still lacking in many active fire regions of the world, especially in tropical regions where altered fire regimes has become a global concern for greenhouse gas emission and biodiversity losses (Bowman et al., 2020).

4.2. *The worldwide growth of urban sprawl*

Urbanization is historically linked to economic growth, as investment and employment opportunities attracted entrepreneurs and manpower. As the Great Acceleration took place after the Second World War, many cities started to display an intense development of their suburbs. The phenomenon is now worldwide and occurs even at lower community levels (i.e., villages), and it is estimated that more than half the world population now lives in urban or near urban settings (UN, 2019). Urban sprawl and nearby resource exploitation often are characterized by extensive land use and transformation, with disseminated housing patterns and large-footprint infrastructures mixing with natural and agricultural areas, referred to as interfaces (Meyfroidt et al., 2013; Erb et al., 2009; Sanderson et al., 2002; Stewart et al., 2007). Growth of the world population by 2050—by nearly 2 billion people—is predicted to be highly concentrated in urban areas (UN, 2019). Global urban sprawl could multiply six times by the end of the century (Gao and O'Neill, 2020).

The growth of these interfaces rapidly became associated with the occurrence of wildfire-caused disasters. As a result, scientific studies on wildfire-related issues with expanding residential development near and within fire-prone wildlands, i.e. wildland-urban interface (WUI), has rapidly increased in the United States (Haight et al., 2004; Hammer et al., 2009; Keeley et al., 1999; Radeloff et al., 2005; Radeloff et al., 2018), Canada (Goemans and Ballamingie, 2013; Johnston and Flannigan, 2018; McFarlane et al., 2011; Whitman et al., 2013), Australia (Mell et al., 2010), southern Europe (Caballero et al., 2007; Darques, 2015; Lampin et al., 2010; Tonini et al., 2018) and expanded into other countries, such as Argentina (Argañaraz et al., 2017), and South Africa (van Wilgen et al., 2012). Diverse types of dispersed rural, intermix and interface communities have emerged and colonized fire-prone environments, setting up the conditions towards increased ignition risks, increased complexity and higher costs of management and suppression, and increased damages and losses (Fischer et al., 2016; Thomas et al., 2017). Increased exposure of human beings and assets lead to escalating firefighting expenditures and investments in crew pre-positioning and resource optimization (Plucinski, 2019; Wei et al., 2018). The large body of studies in North America on factors influencing the costs of wildfire suppression showed that one of the primary factors driving up wildfire suppression costs is the proximity of wildfires to WUI (e.g. Calkin and Gebert, 2006; Gebert et al., 2007, Hope et al., 2016; Liang et al., 2008, Plucinski, 2019; Prestemon et al., 2008, Yoder and Gebert 2012). Controlling spatial patterns of WUI development can effectively reduce fire suppression expenditures and can be an alternative to completely restricting WUI development (Clark et al., 2016). Improving and enforcing building codes and fire-wise urban planning are also a means to reduce wildfire-related losses (Syphard et al., 2017).

The WUI issue is also growing in emerging and developing countries, thus underlining the worldwide problem it has become (Chuvieco et al., 2014; Godoy et al., 2019; Pliscoff et al. 2020). Although there is no standardized methodology for defining and categorizing different types of wildland-urban intermixed landscapes, the WUI literature around the world point to some common root problems (Bento-Gonçalves and Vieira, 2020). Housing demands in WUI are often driven by amenity-seeking in-migration to the area for privacy, aesthetics and recreational uses of nearby forestlands (Gosnell and Abrams, 2011; Hjerpe et al., 2016; Radeloff et al., 2018). Lack of specific land management and planning encourage unplanned residential development in fire-prone areas with little or no building restrictions or codes (e.g. restriction on construction materials, housing arrangement, and fire-wise practices) (Rasker, 2015). The efforts to curb WUI development have been hindered by skewed benefit and cost sharing structure for risk management across different governing scales. For example, in the US, the majority of wildfire suppression costs is internalized in the national budget, while new residential developments are approved by local governments expecting increased property tax revenues from the development (Rasker, 2015). The need for asset protection increases suppression costs, with priority given to WUIs with highest values, while economically disadvantaged communities suffer more from the effects of wildfires (Akter and Grafton, 2021; Davies et al., 2018; Milne et al., 2014; Reid, 2013).

4.3. Global trades and land use changes

The relationship between land use/land cover change and landscape fires has been described across a range of spatial and temporal scales (Lavorel et al., 2007; Curtis et al., 2018; Moreira et al., 2011). However, most studies done at a large spatial extent used global databases of demographic drivers to understand the role of human populations in the observed levels of fire activity (Ganteaume et al., 2013; Knorr et al., 2014, 2016; Krawchuk et al., 2009). A few studies looked at the influence of GDP in explaining global fire patterns with various success (Aldersley et al., 2011; Bistinas et al., 2014; Chuvieco et al., 2021 Rodrigues et al., 2014). However, GDP may be a poor indicator of economic welfare and underlying wildfire-economics feedbacks (Bleys, 2012; Kubiszewski et al., 2013). Other works conducted in Europe and the USA revealed regional economic factors conditioning wildfire activity, such as unemployment, poverty, and economic downturns (Ganteaume et al., 2013; Wigtil et al., 2016; Viedma et al., 2015). Wildfire economic studies over large extents remain rare, while studies on local economic drivers of wildfires have received more attention, especially in the USA, and in Europe to a lesser extent.

In many areas around the world, research has shown that local to regional-scale land-use changes have been driven by macroscale (i.e., national to international) economic forces (Bruckner et al., 2015; Eakin et al., 2014; Lambin and Meyfroidt, 2011; Liu et al., 2015; Meyfroidt et al., 2013; Seto et al., 2012). Distant effect of global trade driven by the most affluent countries has had detrimental effects on wildfire activity, effects observed in South America, Africa, and southeast Asia (Nathaniel et al., 2021; Leal and Marques, 2021; Curtis et al., 2018; Ordway et al., 2017; Murdiyarso et al., 2004). Although wildfire is often mentioned in the studies related to global commodity trade-driven deforestation, research on specific effects of global trade on wildfire activities is generally lacking.

Globalization has brought "telecoupled" human–natural systems in which increased economic linkages have exported environmental degradation ((Butsic et al., 2015; Erb et al., 2009; Kanemoto et al., 2016, Meyfroidt et al., 2013; Pendrill et al., 2019). With increasing worldwide economic linkages, macroeconomic forces affect economic profitability of forest and agricultural commodities and influence demographic changes in landscapes as well as management decisions. For example, extensive and destructive fire activities in North America are linked to more than a century of forest management history focusing on timber protection and grazing (Covington, 2000; Pyne, 1997). Large-scale fire exclusion created a "fire-debt" in the ecosystem that is now being paid the hard way (Chen et al., 2020; Reinhardt et al., 2008; Schultz et al., 2019). However, the efforts to reduce forest fuel loads through thinning treatments have been hindered by high costs of the treatments with little or no economic value of small diameter timbers due to widely available and cheaper imported timbers (Nicholls et al., 2018). In Europe, modern wildfire activities are also linked to changes in the economic structure of society during the 20th century (Moreira et al., 2011). Declining economic profitability of agriculture led to aging and out-migration of rural population termed "rural exodus syndrome" (Hill et al., 2008). Resulting agricultural abandonment and concentration of population in the coastal areas and major urban centers drove increase in shrubland and forests in other areas and overall increases in fire hazards, which are well documented throughout southern Europe (Falcucci et al., 2007; Moreira and Russo, 2007; Moreira et al., 2011; Perpiña et al., 2020; Terres et al., 2015; Van Doorn and Bakker, 2007; Vidal-Macua et al., 2018).

Negative impacts of macroeconomic forces on land use changes may be most pronounced in non-fire-adapted ecosystems in the wet tropics, where extensive human-caused fires result in dramatic ecological degradation associated with losses of hydrological function, biodiversity, and organic soils such as peat, as well as increases in greenhouse gas emissions (Anderson and Bowen, 2000; Lavorel et al., 2007; Martin, 2019). Capacities of these systems to regulate the negative impacts are often overwhelmed by the pervasive influence of economic globalization, such as the unprecedented demands for agricultural lands to grow international commodity crops (Curtis et al., 2018; Herawati and Santoso, 2011; Knorr et al., 2014; Purnomo et al., 2017), and political influences from global capital (Varkkey, 2015) under weak governance and contested land tenure (Carmenta et al., 2017, 2019). Several local-to-regional pieces of evidence have pointed at the nexus among the economic level of local populations, fire activity, and the global 'appetite' for international commodities (e.g., the exploitation of oil palm in Indonesia) (Gross, 2015). Although there has been some progress in understanding economic drivers of fire activities at regional scale, especially in the Mediterranean (Moreno, 2014; Leone et al., 2003; Ganteaume et al., 2013), comprehensive assessment of the macroeconomic drivers of global fire activity is still lacking.

5. States (S) and impacts (I)

5.1. Human-caused ignitions

Humans mediate fire activities, acting as both initiators and suppressors as well as controlling fuel distribution and landscape structure (Liu et al., 2012). Out of the over 450 million hectares burned on average every year in the world, most come from human-caused fires ignited for a variety of reasons such as forest clearing, soil preparation for crops or fodder, outdoor activities, socio-economic conflicts, arson, and accidents (Andela et al., 2019; Ganteaume et al., 2013). The role of environmental and climate drivers of wildfires has been extensively addressed in the scientific literature, but the role played by humans is far less understood (Chuvieco et al., 2021; Costafreda-Aumedes et al., 2018). Human-related drivers of wildfire occurrence are known to be non-stationary, depicting contrasting effects at multiple scales (Oliveira et al., 2014). A variety of factors underlying fire ignition have been addressed using multiple approaches and proxies, though the link between humans and wildfires remains elusive (Costafreda-Aumedes et al., 2018). Despite its heterogeneous nature, the human component of wildfires is major in most fire-prone regions worldwide.

5.2. Changes in wildfire regimes worldwide

The interplay of humankind and climate has caused many changes to regional fire regimes worldwide (Rogers et al., 2020). Changes in fire regimes in North America have been well-documented through a number of empirical and modeling studies, in terms of increased frequencies and extents of large fires with high severity, lengthening durations of wildfires and fire-season, and their worsening trends with warmer and drier climate affecting regional water-balance (e.g. Abatzoglou and Williams, 2016; Dennison et al., 2014; Littell et al., 2016; Mueller et al., 2020; Singleton et al., 2019; Westerling et al., 2006; Whitehair et al., 2018). The trend of changing fire regime is similar in southern Europe (Curt and Frejaville, 2017; DaCamara et al., 2014; Fréjaville and Curt, 2017; Jiménez-Ruano et al., 2020; Rodrigues et al., 2020).

Wildfires became one of the most important agents of land-use/land-cover change in the tropics (Lavorel et al., 2007). However, the scientific capacity for detailed study of wildfires is lacking in many tropical developing and emerging countries (Barber et al., 2014). A handful of Western countries with specific risk profiles produces the majority of all wildfire science publications[2], even though studies have grown in numbers in some emerging powers (e.g. China), including in tropical countries dealing with commodity-driven fire activity (e.g. Indonesia and Brazil). Wildfire science shaped by the social perceptions, economic priorities, and investment capacities of the Western world is likely neither valid nor desirable everywhere (Paton et al., 2015; Smith et al., 2016; Moore, 2019). Fig. 2 highlights that burned areas are increasing in many regions with high global economic pressures and weak governance.

Total burned areas globally decreased mainly due to aggressive fire suppression and development of capital-intensive agriculture in the regions with low and intermediate levels of tree cover, including tropical savannas and ancient grasslands where high level of biodiversity has been maintained by seasonal and frequent fires (Andela et al., 2017; Bond, 2016). Despite efforts from scientists and practitioners to emphasize the positive role of natural and cultural fire regimes and active forest management using prescribed burns (Alcasena et al., 2018), the Western bias that frame wildfires as a 'public enemy' to be fought at all costs still dominates how policy-makers perceive and respond to wildfires globally (Matlock et al., 2017). Aggressive fire suppression and guilt-based mass education, the latter famously symbolized by Smokey Bear in the US (Donovan and Brown, 2007; Doerr and Santín, 2016; Stephens and Ruth, 2005; Moore, 2019), with the high level of media exposure, shape public perception of wildfires as negative and destructive forces of nature (Reinhardt et al., 2008). In many cases, the sustainable human use of fire for landscape management produces a range of ecosystem services and benefits that have great social, environmental, and economic values (Pausas and Keeley, 2019). For instance, traditional uses of fires by indigenous communities allow access to more varied sources of non-timber products as well as promoting and maintaining other ecosystem services, such as biodiversity and water quality (Burton et al., 2008; Frelich, 2017). More research is needed to understand changing wildfire regimes and their regional variations to elaborate more effective, efficient and equitable wildfire risk management at a global scale.

5.3. Changes in ecosystem services and wildfire-related costs and losses

Changes in wildfire regimes, both through decreases and increases in wildfires, affect the capacity of ecosystems to deliver goods and services for human well-being, such as carbon storage (Harris et al., 2019; Hurteau et al., 2008, 2014; Nechita-Banda et al., 2018), watershed services (Baldon et al., 2008; Boisramé et al., 2018; Hallema et al., 2018; Robinne et al., 2016, 2018, 2020;), and biodiversity (Chuvieco et al., 2014; Durán-Medraño et al., 2017; Miller et al., 2018; Schmerbeck and Fiener, 2015). Leveraging the economic importance of these key ecosystem services can be effective for promoting fuel management and forest restoration more generally. For example, national forests in the US are "essential" in the functioning of 325 hydroelectric dams across the country, comprising approximately 15% of total facilities, that over 60 million people from at least 3,400 cities and towns depend on as their primary sources of water supply (Furniss, 2010). Expected rising costs of providing municipal water services with climate change, economic values of enhanced hydrological services can be useful for promoting pro-active forest management (Loiselle et al., 2020; Becker et al., 2018). In the past decade, the number of studies adopting an economic rationale for active fire management for the purpose of water supply protection has increased rapidly in North America (e.g. Gannon et al., 2019; Warziniack et al., 2019; Warziniack and Thompson, 2013). Fire activities reduce annual evapotranspiration and increase runoffs affecting global water resource availability (Li et al., 2013; Li and Lawrence, 2017). However, economic studies looking at necessary investments in watershed protection remain rare and were published in a limited number of Western countries (Robinne et al., 2018; Robinne et al., 2021).

Direct costs of fire prevention and suppression are minor components in the full spectrum of economic costs and losses related to altered wildfire regimes (Fig. 3). Several studies have demonstrated significant willingness to pay among those potentially affected by wildfires to avoid fire danger in Australia, Spain and France (Ambrey et al., 2017; Couture and Reynaud, 2011; Varela et al., 2014), biodiversity loss in Spain and the US (Durán-Medraño et al., 2017; Loomis and González-Cabán, 2010), and cross-boundary haze from Indonesia in Singapore (Tan-Soo and Pattanayak, 2019; Tan-Soo, 2018). Economic effects of wildfires can be also measured by observing market transactions of properties with high wildfire risk (Hjerpe et al., 2016; Stetler et al., 2010) as well as changes in their values before and after wildfires (Mueller and Loomis, 2008; Mueller et al., 2009). However, economic studies on other negative impacts of wildfires are particularly lacking. For example, wildfire smoke exposure has been consistently linked to negative effects on general respiratory health, especially on elderly populations, in the US and Canada with mixed effects on cardiovascular outcomes (Gan et al., 2017; Le et al., 2014; Reid et al., 2016). Economic studies on adverse health impacts from wildfire smoke and wildfire-specific epidemiology are still limited (Fann et al., 2018; Kochi et al., 2010).

A comprehensive literature survey of the costs and losses of wildfires in the US estimated the annualized costs as $7.6 billion to $62.8 billion and annualized losses as $63.5 billion to $285.0 billion (Thomas et al., 2017). Despite the astronomical costs and losses related to wildfires, the efforts to manage wildfires through fuel management strategies rather than military-type large-scale suppression has been slow progress (North et al., 2015). One of the reasons is that occurrences and spread of wildfires are ultimately stochastic events. Even with extensive fuel treatments reducing fire severity, intense wildfires can occur and spread quickly depending on the weather conditions and cause costly damages to adjacent values at risk. Lack of incentives for fire managers to contain suppression costs, risk-aversion tendency of land managers toward fuel treatments, performance measures based on burned area size, and outsourcing of wildfire related activities are among the reasons that drive sub-optimal management of fuel management programs in North America (Mercer et al., 2007; Lankoande et al., 2006; Lueck and Yoder, 2015).

The majority of wildfire related losses are intangible or indirect and also distributed spatially, temporally and socially, which make them difficult to measure (Thomas et al., 2017; Venn and Calkin, 2011; Wu et al., 2011). Economic globalization expands the scope of cross-scale interactions externalizing ecological, social and health costs associated with wildfires in global scale, especially to tropical developing countries. For example, while a relatively small group of local elites and global investors benefits from the oil palm industry in Indonesia (Purnomo et al., 2017), the costs of fire and haze, including immediate and cumulative impacts of air pollution and loss of ecosystem services, are

[2] The Web of Science database showed 10,091 records of published studies with wildfire in their title as of August 2020 (since 1910; 9,456 records from 1980-2019). Top five countries, the US (35%), Canada (10%), Australia (9%), Spain (8%), China (6%), produced the majority of all scholarly papers (68%) in the database.

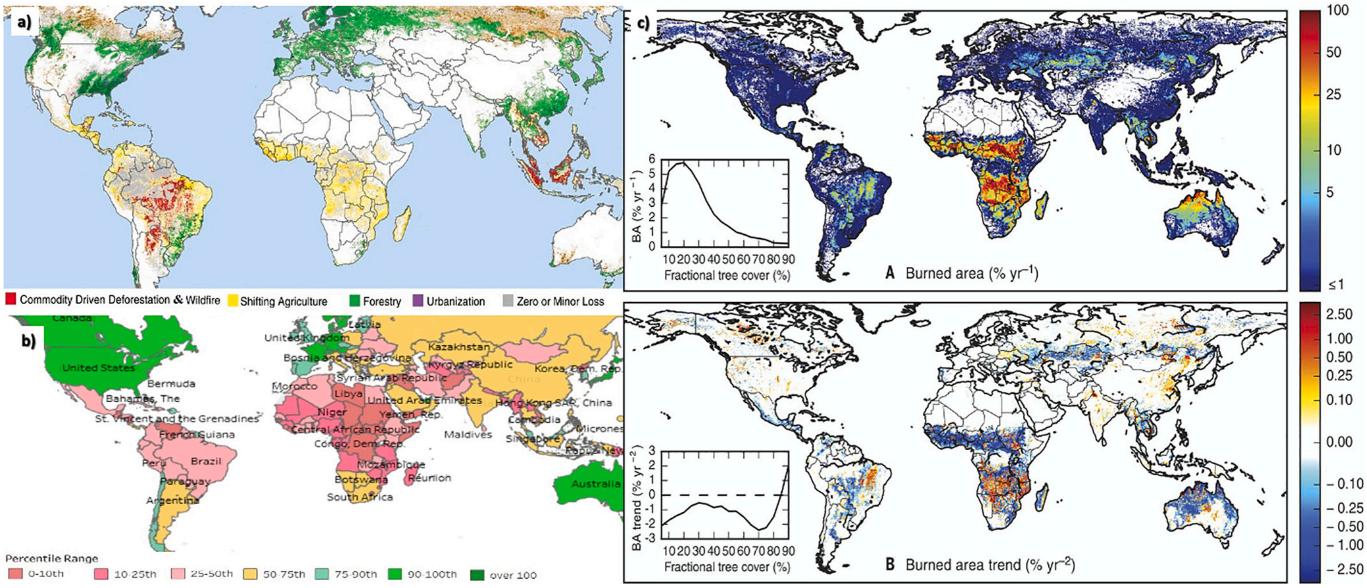

Fig. 2. Global map of: a) Primary drivers of forest cover loss 2001–2015; Commodity Driven Agriculture/Wildfires in red (Curtis et al., 2018); b) WorldWide Governance Indicators.(Kaufman and Kraay, 2019); Governance effectiveness indicator less than 50 percentile in light red to red (Kaufman and Kraay, 2019); c) A. Burned area %/yr); B. Burned area trend (%/yr) (Andela et al., 2017). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

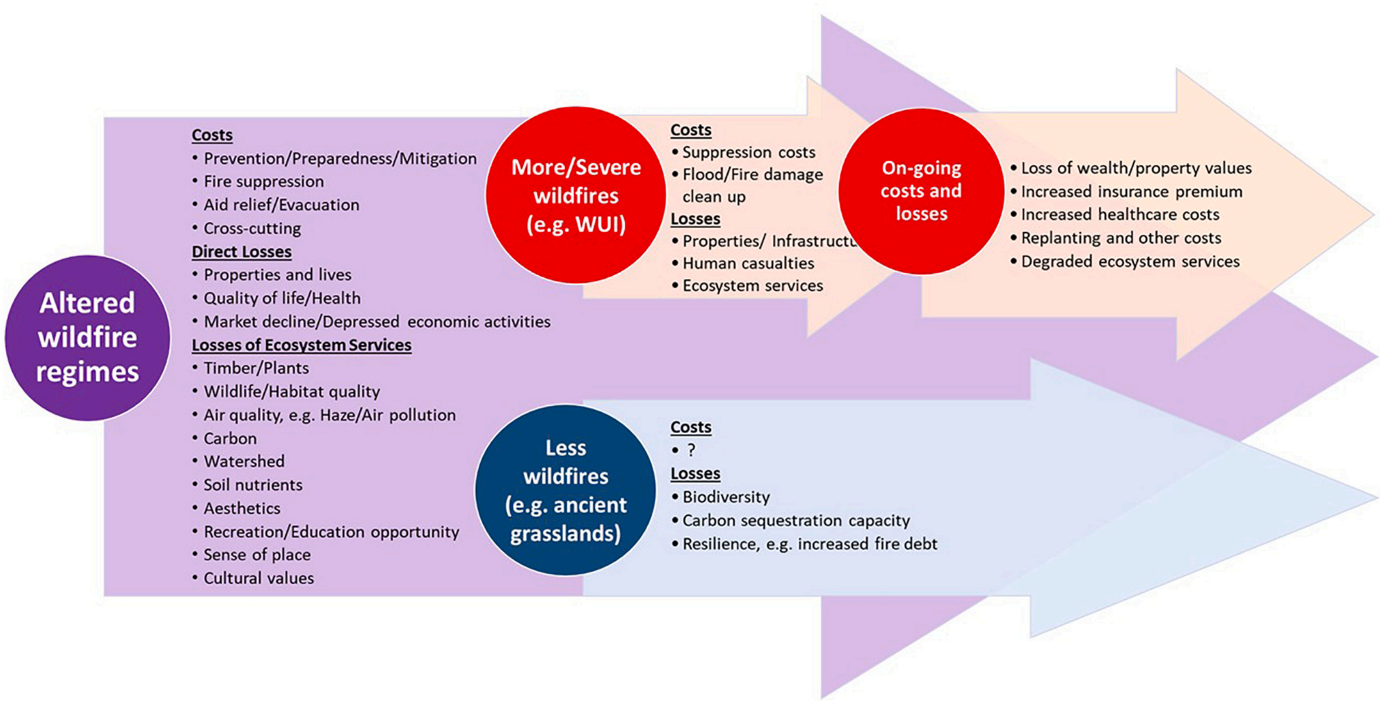

Fig. 3. Understanding costs and loss of altered wildfire regimes.

borne by broader local, regional and global populations now and in the future (Forsyth, 2014). Accounting for economic costs and losses across international borders is particularly challenging, as transferring estimated economic values in one location to other cases in different ecological and social settings is problematic (Thomas et al., 2017).

6. Responses (R): pathway forward for managing wildfires in global scale

Many scholars over the years called for a paradigm shift in how we understand and manage wildfires (e.g. Reinhardt et al., 2008; Moore, 2019; Moreira et al., 2020; Moritz et al., 2014). The main focus is on shifting the emphasis on fire prevention and suppression to mitigation and adaptation for learning to co-exist with fires in fire-adapted ecosystems, while addressing underlying drivers of human-cause ignitions in non-fire adapted ecosystems.

Devising appropriate responses to the worldwide wildfire “problem” should start with understanding of drivers of changes and their trends, assessments of social-ecological system states and impacts, wildfire-related benefits, costs, and losses and their spatial, temporal, and social distributions (Fig. 1). Improving economic valuation of ecosystem services as well as better accounting of overall costs (Hand et al., 2014) can attract necessary investment for better wildfire management (e.g. carbon credits) (Venn and Calkin, 2011). Limiting urban sprawl within fire-prone landscapes is another important part of the equation. Where possible, imposing a shared economic responsibility for fire management and disaster losses would certainly provide an incentive to rethink urban design. Limiting urban sprawl and land degradation or conversion though policy actions (e.g. higher property taxes, wildfire management cost-sharing, revised insurance policies, improved building codes) can have far reaching positive influence on curbing emissions as well. However, to manage wildfires under on-going global changes with increasing frequencies of extreme weather events and novel disturbances (e.g. the 2020 COVID-19 pandemic), more attention is needed to account for cross-scale interactions. For example, chronic fire crises in forests and peatlands in humid tropics have now been well linked to the global demand for agricultural commodities such as palm oil and soybeans, which call for the adoption of more sustainable lifestyles in the Western countries that could curb human-driven detrimental fire activities (Ripple et al., 2017; Venter et al., 2016; Gross, 2015).

Wildfire science has become a mature discipline to provide reliable and valuable information for science-based decisions, incorporating tremendous technological advances in our ability to observe the drivers and the extent of land use changes in multiple scales (e.g. Butchart et al., 2010; Curtis et al., 2018; Hansen et al., 2013; Kim et al., 2015), elements of anthropogenic fire regimes and pyrogeography (Knorr et al., 2016), as well as links between fine-scale vegetation structure, landscape pattern, and fire regimes, coupled with state-of-the-art remotely sensed data (Baccini et al., 2012). Biophysical science and ecosystem modelling efforts can provide bases for evaluating economic trade-offs, which will help policy-makers and managers to balance multiple objectives under budget constraints, especially when linked to management expenditure models (Thompson et al., 2018). However, there still are considerable gaps between the scientific community, wildfire managers, stakeholders and the general public as well as those between the Western countries that produce most of fire science and the rest of fire active regions. Developing integrated global fire management with expert criteria and science-based decision-making tools is currently hindered by lack of reliable data in many parts of the world (Leidig et al., 2016).

Wildfire science is often produced in particular ecological, social and political contexts, which make it difficult to transfer knowledge to other countries. Global ecosystem assessments often rely on satellite observations that tend to focus on tree cover density and prioritize ecosystem services of global concerns, such as biodiversity and carbon sequestrations (Kim et al., 2018). Focusing on increasing and maintaining tree cover may have detrimental effects on the ecosystems in the long run with altered fire regimes, either increasing fire debt or decreasing ecologically beneficial fires (Bond, 2016), as well as to local ecosystem services, such as watershed services (Kim et al., 2018). Under weak governance, global science can be used, ignored, or interpreted by those with ready access in a way to influence others to serve their interests (Lund 2015; Mistry et al., 2019; Ribot and Peluso 2003; Scott, 1998). Designing strategies that involve a broad range of stakeholders and their financial capabilities and responsibilities will generate incentive for everybody to do their part, as they bear the consequences of inaction. To develop sound science-policy interfaces for wildfire governance in global scale, we need better accounting of social-ecological system dynamics (e.g. Fischer et al., 2016), and remote connections and cross-scale interactions among distant and adjacent systems (e.g. Kapsar et al., 2019; Liu et al., 2015), as well as understanding what and how science is used, and omitted, in decision-making across governing scales. This is where the development of cohesive, integrated fire management strategies can make a difference, although they suppose political willingness.

With recent advances in the ways we understand the complexity of ecosystem service flows across geographic boundaries (Liu et al., 2015; Schröter et al., 2018), we can conceptualize interregional flows of drivers and impacts of wildfires. Development of an indicator measuring wildfire-linked land degradation for a variety of products and activities worldwide can help communicating on the distant yet pervasive role of modern consumption patterns on global fire activity. Similar to the “virtual water trade” (Oki and Kanae, 2004) and “virtual carbon trade” (Atkinson et al., 2011), “virtual wildfire trade” accounting could help estimate the “amount” of fire embedded in a given product shipped or consumed around the world; this would further allow more accurate calculation of carbon and environmental footprints (Pendrill et al., 2019). This indicator would primarily focus on those areas where increased human-caused fires are linked to regional an international land degradation and could combine different fire metrics such as area burned and the number of toxic compounds emitted by smoke. A “virtual wildfire trade” indicator can communicate a sense of responsibilities for distant land degradation by fire (i.e., teleconnections) and promote coordinated policies and management actions across governing scales by better accounting for emissions and distant degradation by fire (Hurteau et al., 2008, 2014; Norris et al., 2010; Keith et al., 2014).

7. Conclusions

In this critical review, we address the pressing need to incorporate economic drivers of wildfires to achieve a broader comprehension of wildfires within social-ecological systems that enables sound and solid science-based policymaking. To do so, we leverage the DPSIR framework to structure the issues related to wildfires to establish coherent causal pathways between Drivers (D), Pressures (P), States (S), Impacts (I) and Responses (R). Current developments call for a “paradigm shift” in how we understand and manage wildfires. We propose expanding science-policy interfaces to global scale with new indicators for assessing and communicating the impacts of global economic drivers on wildfire activities, such as “Virtual wildfire trade” accounting that fosters delocalized fire activity, exporting fires and land transformation from developed to developing regions with weak governance.

This critical review has focused on overviewing global scale economic drivers and their impacts, and we acknowledge that the economic forces reviewed here are interdependent, as well as controlled by other aspects of fire and land management overall, politics and ecology in particular. Wildfires and their negative consequences are part of an economic continuum embodied by the Pyrocene concept suggested by Pyne (Pyne 2021) showing the historical shift in the meaning of fire and combustion and the role of the capital economy and industrialization—maybe the most potent drivers of the current environmental state of the world—in explaining current global fire patterns.

Our review, however, did not cover the rich literatures in the US on economic optimization of fuel management strategies with fire modeling (e.g. Ager et al., 2018; Spies et al., 2017; Young et al., 2019), advances in behavioral sciences for understanding knowledge, attitudes and practices of individuals in fire-prone landscape (e.g. Dickinson et al., 2015; Paveglio et al., 2021) and institutional arrangements promoting adaptive fire governance (e.g. Abrams, 2019; Nelson and Chomitz, 2011; Schultz et al., 2019; Schultz and Moseley, 2019). Future research is needed to incorporate these aspects into wildfire economics as well as expand the research outside the US.

Declaration of Competing Interest

The authors declare no conflict of interest.

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