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RESEARCH ARTICLE

A Systematic Review of Relationships Between Mountain Wildfire and Ecosystem Services

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Abstract
Context Consideration of human–environment dimensions of wildfire make ecosystem services (ES) a useful framework for understanding wildfire challenges and devising viable management strategies. Scientific literature on wildfire and ES is growing rapidly, but connections are disparate and evolving.
Objectives We review relationships between mountain wildfire and a comprehensive list of 50 relevant ES informed by the Millennium Ecosystem Assessment. Our conceptual framework is used to evaluate underlying mechanisms and the direction and scale of wildfire impacts on ES.
Methods We focus the review on the Colorado Front Range of the Rocky Mountains, one of the best-studied landscapes in the world for understanding fire-ES relationships and evaluating how regional differences contribute to broader understanding of ES globally. We begin our review by considering key relationships, followed by a structured literature search of wildfire impacts with tabulated trends and findings.
Results Key findings from the review: (1) current fire regimes mostly have negative impacts on ES, with some positive effects on cultural services, (2) changes to vegetation composition and structure are the most common mechanism, (3) mechanisms acting at local and landscape scales impact ES at broader scales, (4) intermediate services warrant attention and management resources, and (5) regional differences may provide opportunities for stronger global synthesis.
Conclusions Familiarity with landscape legacies, current land use practices, and stakeholder values uniquely positions landscape ecologists to contribute to future studies of wildfire-ES connections. A framework that considers the complete suite of ES can guide researchers to seek collaborations that more completely characterize their regions.

Keywords Human dimensions · Environmental/ ecological mechanisms · Scales of mechanisms · Scales of impact · Intermediate services · Cultural services · Landscape legacy · ES gradient of transformation · Millennium Ecosystem Assessment (MA) · Colorado Front Range

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Introduction

Removal of wildfire from fire-adapted landscapes has changed ecological disturbance regimes and compromised resilience (Johnstone et al. 2016). Fire suppression and resultant fuel loading has led to extreme wildfire risk in many regions, including western North America, Europe, and Australia (Chapin et al. 2008; Bowman et al. 2011; Stephens et al. 2014). When fires do occur, they are larger and hotter than the historic regimes in which ecosystems evolved (Van Wagtendonk and Lutz 2007) and these fires can impact the environment through changes in water quality and quality (Smith et al. 2011), land-cover (Moreira et al. 2011), hazard regulation (Cannon et al. 2001), and atmospheric emissions (Loehman et al. 2014), among others. In many regions, wildfire has become a complex environmental issue (Fischer et al. 2016); stakeholders have different views on the value of wildfire and the desirability or detriment of environmental changes can only be interpreted in the context of human needs and wants. For example, some effects of fire exclusion may be perceived as beneficial, such as the carbon storage (Goodale et al. 2002) or maintaining scenic views (Stetler et al. 2010), other effects, such as increased fuel loading (Stephens et al. 2014) and decreased streamflow (Smith et al. 2011), may be undesirable.

Consideration of both the human and environmental dimensions of wildfire make the concept of ecosystem services (ES) a useful framework for understanding wildfire holistically and devising viable land management strategies (Balvanera et al. 2001; Rodríguez et al. 2006). ES are the services and benefits provided by natural systems that contribute to making human life both possible and worth living (UK NEA 2011). The value and significance of ES for supporting wellbeing are well-established (Costanza et al. 1997; Bennett et al. 2009; Fisher et al. 2009) and interest from scientists in the benefits provided by ecosystems has grown significantly since the publication of the Millennium Ecosystem Assessment (MA 2003). Ecosystem services link the societal and ecological components of social–ecological systems (SES), making an ES framework well suited to decision-making and policy development. Resource management, economic markets, demographic changes, and regulatory structures (i.e. "societal components"), coupled with both long-term and acute disturbances, directly impact ecosystem structure and function and thereby the production of ES. ES are only services if they are perceived as such and ES are thus connected to society through a valuation function. Different actors value different services and valued services change with place and time. This valuation function creates a feedback loop that influences governance, resource management, and markets, and in turn affects ecological systems (Collins et al. 2007; Dick et al. 2011). Ultimately, ES provide the crucial link between social and natural systems.

In fire-prone landscapes, understanding the nuanced roles that fire plays in ES is critical to characterizing the trade-offs between people's needs and desires and the sustainability of complex social-ecological systems. Detailing relationships between mountain wildfires and ES is an excellent place to start because mountain environments provide a wide spectrum of ES, ranging from recreation and tourism to natural hazard regulation, erosion control, and food and water security (Fig. 1). In regions such as the Rocky Mountains of the western USA, fire is a key disturbance that reduces fuel loading, maintains biological and biogeochemical processes, recycles nutrients, regulates succession and plant regeneration, maintains diversity and regulates interactions between flora and fauna, and controls insect and disease populations (Keane et al. 2002). Removal of fire from these systems can cause cascading changes that affect both mountain and lower-elevation ecosystems (Benda et al. 2003; Backer et al. 2004; Smith et al. 2011).

Some ES such as water quantity, soil retention, pest management and natural hazard regulation have been extensively studied in relationship to fire. But other services, such as pollination and the human dimensions of knowledge systems, sense of place and aesthetic values have received less attention. Broad comprehensive assessment efforts, like the Millennium Ecosystem Assessment (2003, 2005), provide a global perspective, but are short on details when considering specific disturbance regimes and provide little guidance on how to integrate ecosystem service concepts into management and decision-making. Because the scientific literature connecting fire to ES is evolving and disparate, relevant research often has not explicitly identified the roles that fire plays in "ecosystem services". Only when the whole spectrum of services is considered will land managers and

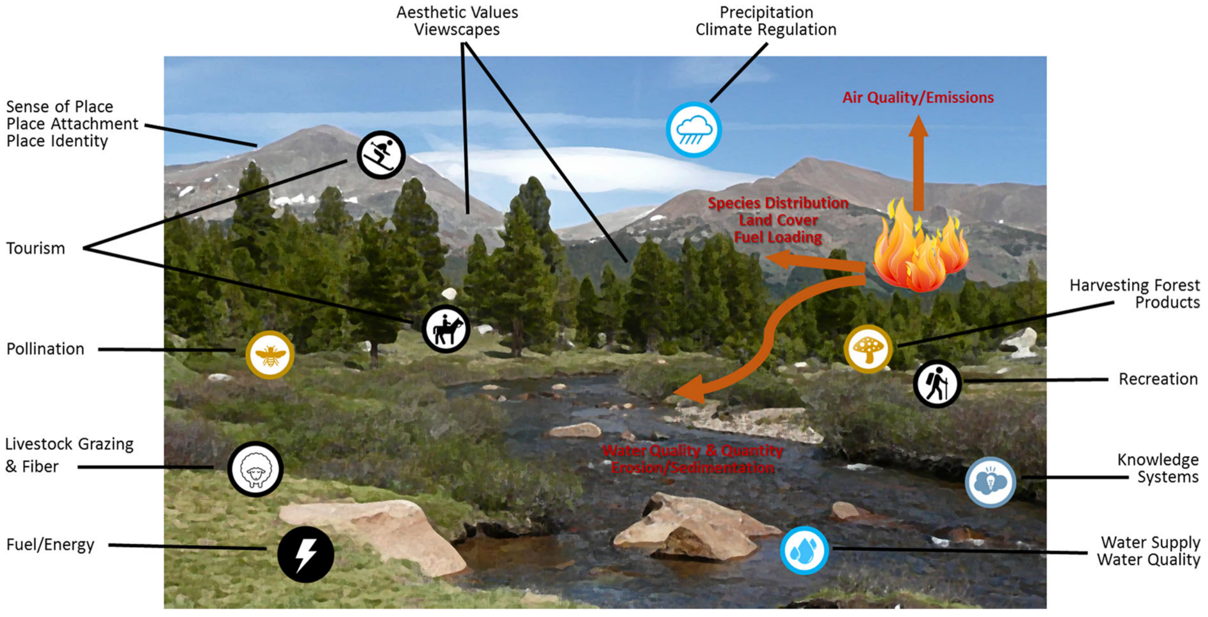

Fig. 1 Mountain systems provide a multitude of ecosystem services (icons and labels). The supply of these services can be impacted by fire through a variety of mechanisms, including land cover change, impacts on air quality, and changes in water quality and quantity (orange arrows)

stakeholders be able to assess the impacts and trade-offs of management actions.

In this article, we review relationships between mountain wildfire and a comprehensive list of 50 relevant ecosystem services informed by the Millennium Ecosystem Assessment (2005). We focus the review on the Colorado Front Range of the Rocky Mountains, one of the best-studied mountain systems in the world for understanding connections between fire and ecosystem services and evaluating how regional differences contribute to broader understanding of ecosystem services globally. The Front Range supports almost five million people (ACS 2016) with most of its population living in low-density exurban developments surrounded by fire-prone lands with active suppression policies and high-risk fire hazards. We evaluate connections between wildfire and ecosystem services using a conceptual framework that synthesizes underlying mechanisms and the direction and scale of the effects.

The framework allows a number of new questions to be addressed, such as (i) does wildfire positively (increased supply), or negatively (decreased supply) impact the provisioning of ES?; (ii) through which ecological or environmental mechanisms does fire affect ES?; (iii) at what spatial scale(s) are ES changes experienced; and (iv) how are wildfire-ES connections positioned in the supply chain (the amount of human capital required to create a service)? Are they intermediate services that humans utilize indirectly, final services that humans utilize directly, or benefits that are directly consumed? We begin our review by explaining how the categories emerged from the MA and broader ES literature, followed by a structured literature search of wildfire impacts with tabulated trends and findings. To our knowledge, this is the first study to consider relationships between wildfire and a complete suite of affected ecosystem services.

Background: types, mechanisms, and scales of impacts

Drawing from the MA, we catalogue a comprehensive, yet selective, set of ES criteria to establish a framework for understanding how the human and environmental dimensions of wildfire can be evaluated (Table 1).

Table 1 Conceptual framework for systematic review

Literature review categories	Description
Impact of fire on ES (positive, negative, unknown)	The impact of fire on the provisioning of ES can be positive (increased supply), negative (decreased supply) or unknown. The impacts of fire on an ES can depend on fire intensity and/or fire size. If multiple fire intensities can affect a service differently, each was counted:
	High intensity fire consumes half to all of the forest canopy and everything on the forest floor. The resulting ash offers little protection from rainfall and erosion. A water-repellent soil layer may form that decreases water infiltration and increases runoff and soil erosion, especially in the first rains following the fire
	Medium intensity fire burns into the forest canopy and consumes the needles and leaves from many trees, but not all. Fire consumes a portion of the ground cover. The biggest and most vigorous trees are typically left alive, so some forest cover remains
	*Low intensit*y fires clear out the underbrush, thin out young trees, and reduce the amount of fuel accumulating on the forest floor
Ecological/environmental mechanism of change	The ecological or environmental mechanism by which fire affects the service. Examples include changes in land-cover, water quality/quantity, nutrient status, and abundance of culturally- and spiritually-important species and landscapes
Scale of the mechanism (site, landscape, region, global)	Mechanism of change can act at different—and multiple—scales, from Site (1–10 km), Landscape (10–100 km), Region (100–10,000 km), to Global (10,000 + km). For those services for which there was more than one mechanism, the scales of each were considered
Scale of the impact (site, landscape, region, global)	The impacts of those changes can be felt at different—and multiple—scales, from Site (1–10 km), Landscape (10–100 km), Region (100–10,000 km), to Global (10,000 + km). The impacts of change may not act on the same scale(s) as the mechanisms. For those services for which there was more than one mechanism, the scales of impact for each were considered
Direction of change in the Front Range (increasing, decreasing, unknown)	In the Colorado Front Range is the overall provisioning of the service increasing or decreasing? The direction of change reflects current the fire regime and fire management history through landscape legacy
Position in the ES chain (intermediate service, final service, benefit)	The position in the supply chain, or the gradient of transformation, refers to the amount of human capital required to create a service
	• *Intermediate service* service that humans utilize indirectly (e.g. nutrient cycling)
	• *Final service* service that humans utilize directly (e.g. clean water provision)
	• *Benefit* direct consumption by humans (e.g. clean water consumed for drinking)

Types of ES impacts

ES may be either positively (increased supply) or negatively (decreased supply) impacted by fire. The MA is foundational and far-reaching in ES research and management. A key result of the MA (2005) was that 15 of the 24 ecosystem services evaluated are being degraded or used unsustainably globally. Increasing human demand for 20 of these 24 services suggests the possibility of positive feedbacks between demand and degradation and greater unsustainability. Literature on ES is uneven across the MA's four broad categories of supporting, provisioning, regulating and cultural resources. Biophysical data and available statistical datasets are the most commonly used data sources when it comes to mapping ES and therefore regulations services are the most commonly mapped, followed by provisioning, cultural, and supporting (Martínez-Harms and Balvanera 2012). In trade-off assessments, decisions show a preference for provisioning, regulating, and cultural service (in that order), while supporting services are more likely to be taken for granted (Rodríguez et al. 2006). Cultural services go almost entirely unquantified in scenario modeling, which means that model results do not fully capture trade-offs with cultural services (Rodríguez et al. 2006).

Of the three categories of cultural services evaluated in the MA Synthesis (2005), two (spiritual and religious values and aesthetic values) are decreasing or degraded, while recreation and ecotourism was mixed, with an overall 70% decline in cultural services reported. The MA notes the loss of language and traditional knowledge systems and the decline in protected areas and sacred groves, as well as a decline in the quantity and quality of aesthetically pleasing natural landscapes. The report suggests that while the use of cultural services has continued to grow, the capability of ecosystems to provide cultural benefits has been significantly diminished in the past century (MA 2005). These findings of overall decline may have framed future work around loss. Importantly, seven groups of cultural ES, including cultural diversity, knowledge systems, educational values, inspiration, social relations, sense of place, and cultural heritage values were not assessed within the MA (2005).

Mechanisms of impact

In considering the suite of ES, a mechanistic understanding of changes to both individual and multiple, connected ES can be predictive. A mechanistic understanding can help shed light on trade-offs between different management actions that affect vegetation structure and function, water quality or fuel loading and the impacts of those actions on the supply of ES. In some cases, more than one ecological or environmental mechanism can impact an ES. For example, recreation is a cultural service encompassing skiing, fishing, rafting, and wildlife viewing, among many other activities (Fig. 1). As such, the mechanisms through which fire affects recreation include changes to land-cover, water quality, water quantity, landscape configuration, and ecological communities.

Scales

Scale is an important issue in ES research because ecological processes are fundamentally scale dependent (Levin 1992; de Groot et al. 2010). Ecological or environmental mechanisms can act on site, landscape, regional, or even global scales. The consideration of both scales of mechanism and scales of impact is relevant because of the need to account for the spatial relationship between generation and consumption of ES (Fisher et al. 2009). Study of the scales of mechanisms is imperative for improved mechanistic understanding of the production function. Research to-date has largely involved spatially correlative studies across very large scales (Duncan et al. 2015). While these studies are management-relevant and have been helpful in generating knowledge about valuation and linkages, work at very large scales results in less information regarding the mechanisms underpinning relationships, as key ecological units may operate at much finer scales. Ecological functions underlying final ecosystem services may also depend on the spatial scale at which management is applied (e.g. Leibold et al. 2004), which generates context dependent responses of management interventions.

The dearth of empirical knowledge on the geographic context of ES values (Kozak et al. 2011) can mean that the shortcomings of different preference valuation studies are dwarfed by inaccuracies in geographically demarcating the populations served by ES (Loomis 1996). Examination of the scales of mechanisms and impacts enables understanding of the population(s) being served by an ES and can clarify the strengths and weaknesses of different valuation approaches (Kozak et al. 2011). The large number of divergent approaches to studying spatial scale in ecological research (Blackburn and Gaston 2002) further presents a challenge to the integration of different research fields (Lima and Zollner 1996), which is crucial in an interdisciplinary context, such as ES research (Cumming et al. 2013). These challenges and the scale-dependent nature of ecosystem function point to a critical need in ES science, where all avenues of research can be better informed by improved understanding of the scales of mechanisms and impacts.

Regional differences: the Colorado Front Range

Regional differences provide opportunities to study spatial production functions and contribute to our understanding of global processes and trends. One challenge for researchers and managers is to scientifically address cause-and-effect when the production of ES in one place affects the production of ES in another and that cause-and-effect relationship is spatial. ES depend on highly complex and non-uniform systems and a causal relationship in one location may not hold in other locations. These causal relationships in complex social-ecological systems should be tested at each location, through rigorous, data-intensive empirical and scientific methods.

The supply of a service can be difficult to quantify and the change in that supply, even more so. Energy and matter move and this movement is often linked—the movement of one thing, such as water flowing downstream, can trigger the movement of other things, like topsoil. The intermediate and final services upon which the benefits consumed by humans ultimately depend might occur at a different location and/or at different scales than the benefits. For example, downstream water quality depends on upstream land-use and land-cover. Single-point combustion can affect regional air quality far from the combustion site. The benefits that human consume often depend on physical conditions at a great distance from the ES itself. It can therefore be informative to assess current knowledge of the relationships between wildfire and ES both for a specific region and across mountain systems.

The ES chain: intermediate services

Human capital (energy, technological, and labor) can be required to create a service. The position in the supply chain, or the gradient of transformation, refers to the amount of human capital required to create a service (Fisher et al. 2009). Complex ecosystem processes and functions give rise to ecosystem services (final and intermediate services), which when interface with direct human usage and provide benefits. For example, nutrient cycling is a process of which one outcome is clean water. Nutrient cycling is a service that humans utilize, but indirectly (intermediate service). Clean water provision is also a service that humans utilize, but directly (final service). Clean water, when consumed for drinking, is a benefit of ecosystem services (Table 1).

The Millennium Ecosystem Assessment (2005) explicitly considers supporting services as ecosystem functions underlying other ecosystem services. These intermediate services (Fisher et al. 2009) are the ecosystem functions underpinning the goods and services directly used and valued by humans. Some have argued that to avoid double counting, use of the term “ecosystem service” should be restricted to the final benefits obtained by humans, noting the risk for ES valuation (Boyd and Banzhaf 2007). However, the intermediate services, which often remain invisible, are at risk of being underprovided if research does not consider their contributions to visible final services and benefits (Birkhofer et al. 2015). Anthropogenic changes to mechanisms of impact often affect intermediate and then ultimately final ES (Raffaelli and White 2013). For example, change in vegetation composition and structure can affect water flows, which in turn contributed to natural hazard (flood) control (Mace et al. 2012). Given their importance, tabulation of intermediate services seems worthwhile when considering the complete suite of ES.

Methods

To provide a comprehensive framework for the study of wildfire, we took two approaches. First, we derived macro categories from the extant literature, as detailed in the preceding paragraphs. The resultant framework (Table 1) provides both context and macro-level categories against which wildfire trends could be evaluated. Second, we studied the original MA descriptions of 26 ES and then expanded and tailored the list to 50 ecosystem services found in mountain ecosystems generally and applicable to the Colorado Front Range (Fig. 2). Where possible (and applicable) we refined the broad MA services into more specific services. For example, we classified “food provisioning” (1 ES) as “farming”, “livestock grazing”, and “forest harvest products” (3 ES). Some categories of services, such as the provisioning of fuel or avalanche regulation, are common across mountain systems. Other services, such as presence of natural gas reserves or tourism, will vary between mountain systems. The 50 services we identified contribute to making human life both possible and worth living in

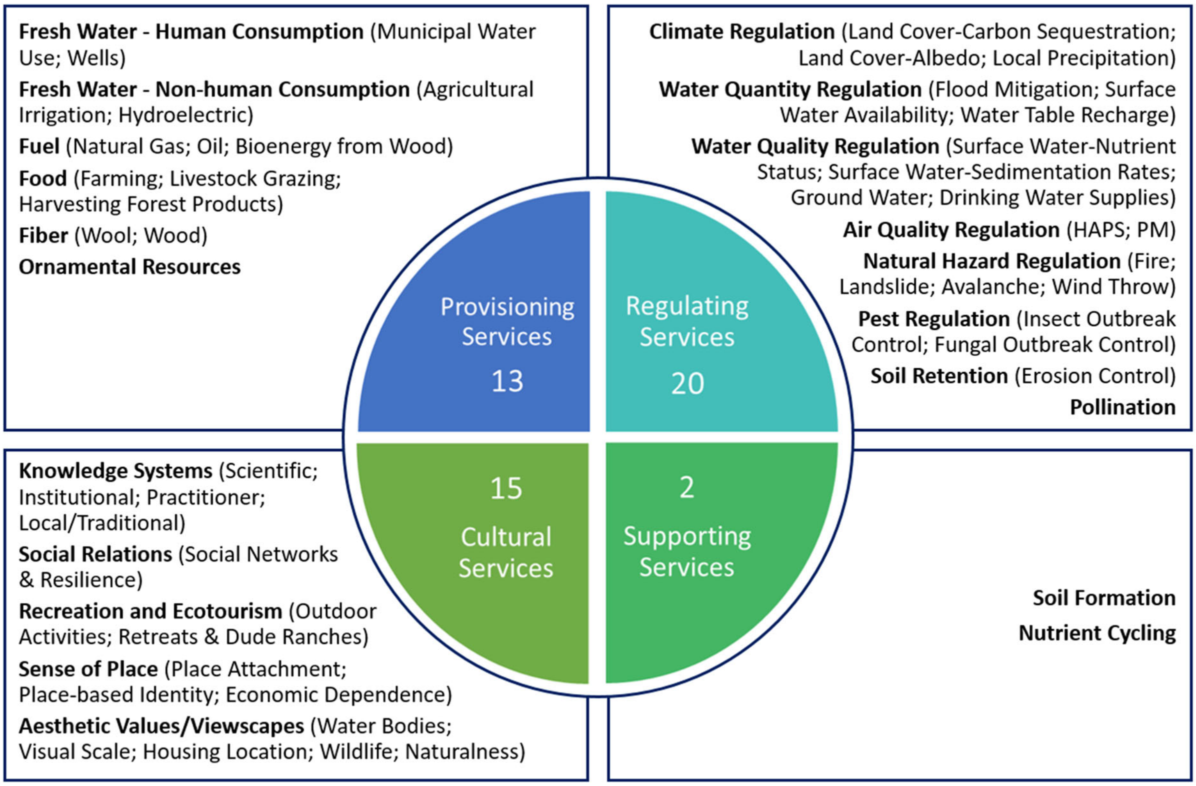

Fig. 2 Ecosystem services in mountain regions evaluated through the conceptual framework. Where broader categories of ES (bold) were refined into more specific services, these are listed in brackets. Tallies indicate the number of ES identified for each Millennium Ecosystem Assessment (MA) category

the Front Range. This two-pronged approach allowed us to recognize the complete suite of ecosystem services and then ground them in a comprehensive framework.

Using our conceptual framework (Table 1), we conducted a structured literature review to understand the relationship between fire and the 50 identified ES (Fig. 2). Our objective was to find a minimum of three relevant peer-reviewed papers for each ES, using a hierarchical, structured literature search (Google Scholar; 04/2016–02/2017) that included three components: (1) ecosystem service search term, (2) a geographic search term, and (3) fire search terms. Our aim was to identify studies conducted in the Colorado Front Range; for ES where relevant literature did not exist for the Front Range, we expanded the geographic search term in the following order: (1) the Colorado Front Range, (2) the Rocky Mountains, (3) western North America, and (4) mountain systems (worldwide). Similarly, the ES search terms started specific and became broader if necessary. For example, for the provisioning of water for agricultural irrigation, we used search terms in the following order: "agricultural irrigation", "crop irrigation", "agriculture water", and "crop water". In conjunction with the geographic search term(s) and the ES search(es), we included the fire search terms "wildfire" and "fire". In total, 265 papers were analyzed. Our goal was to gain an overall picture of the impact of fire on ES in mountain regions rather than to quantify relationships or provide a meta-analysis of specific impacts.

Findings

Types of ES impacts: current fire regimes have a negative impact overall on ES, with some increases to cultural services

Overall, the complete literature surveyed characterized fire as having a negative impact on the supply and availability of provisioning and regulating ES (Fig. 3),

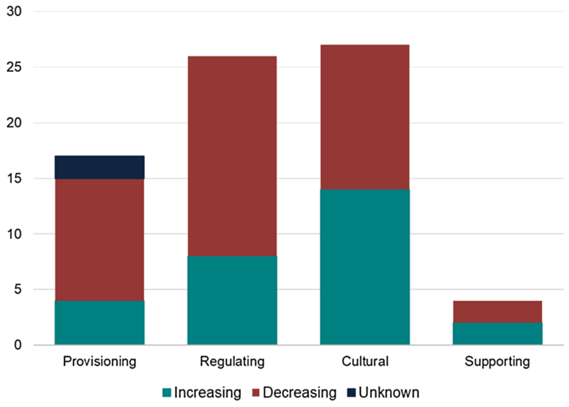

Fig. 3 Number of ecosystem services exhibiting a positive, negative or unknown effect from fire across the four MA ES categories. Where fire could create both a service and a disservice, depending on fire intensity and/or size, it was counted in both categories

which is consistent with overall trends in the MA. The notable exception was cultural services, where the impacts were equally positive and negative; this runs counter to the mostly negative trends documented in the MA. Many of the positive changes in cultural services related to wildfire stem from increases in knowledge systems. In particular, scientific, institutional, and practitioner knowledge systems have increased due to a both a proliferation of scholarship/experience and greater information sharing. The MA did not assess a number of important cultural ES, including knowledge systems, inspiration, or sense of place. The inclusion of these additional groups of cultural ES contributed to our finding of equally positive and negative impacts. The impact of fire on the provisioning of oil and natural gas in unclear and these services were categorized as "unknown".

Mechanisms of impact: change in vegetation composition and structure most commonly affect ES

The mechanisms by which fire affects ES, as addressed in the literature surveyed, include changes in vegetation composition and structure (land-cover change), water quantity and quality, nutrient status, and sedimentation rate (Fig. 4). The most common mechanism of impact was change in vegetation composition and structure, which impacted 20 services in all four categories of ES and whose impacts ranged from changes in the availability of food and fiber, to air and water regulation and aesthetic values. This finding broadly mirrors the MA (2005), which reported land cover change and the application of new technologies and management practices as the most important direct drivers of change in ES for terrestrial ecosystems over the past 50 years. Other important mechanisms include change in water quality (11 services), biomass/fuel removal or fuel loading (seven services), change in nutrient status or nutrient cycling (five services), emissions from combustion and change in air quality (five services), and change in ecological communities (seven services). The impacts to water quality are especially noteworthy in mountain systems, as these systems are vital to downstream water provisioning. Water quality also highlights the interrelatedness between services and the linkages between mechanisms. While changes in erosion rates and nutrient cycling are the primary ecological mechanism that impact the regulation of water quality, water quality, in turn, is the primary mechanism impacting the provisioning of freshwater for human consumption.

Scales: mechanisms acting at local and landscape scales impact ES at landscape and regional scales

Overall, the ecological or environmental mechanisms by which fire impacts ES tend to act on smaller spatial scales, with 34 and 48 ES impacted at the site and landscape scale respectively (Fig. 5a). Examples of mechanisms acting at larger spatial scales (regional and global) include changes in water quality and nutrient status, land cover change, emission from combustion and release of CO_2, and changes to the historic fire regime leading to new knowledge systems. For the majority of services, the identified mechanism(s) can acts on two, and in some cases even three, spatial scales.

The impacts of fire on ES are also felt at different and multiple scales. Our review found that the majority of impacts are felt at landscape (49 ES) and regional scales (42) (Fig. 5b). The impacts felt at the largest (global) scales include changes to the provisioning of fuel (oil and natural gas[1]), climate regulation, and advancement of scientific and institutional knowledge systems. Similar to the mechanisms by

[1] Wildfires impacts to fuel extraction can affect global energy markets.

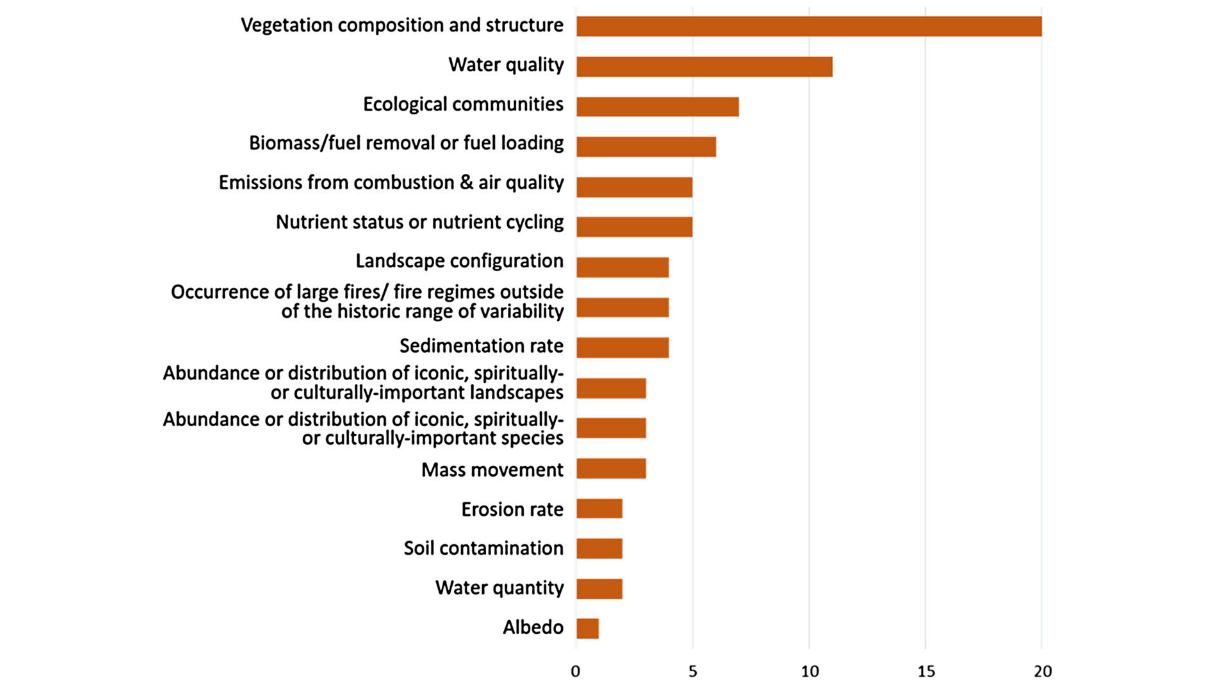

Fig. 4 The mechanisms by which fire affects mountain ecosystem services. Tallies indicate the number of services impacted by each environmental mechanism. Where multiple mechanisms affect an ES, each was included in the tally. Changes in ecological communities include changes in the density of host trees, number of vulnerable hosts, and pollinator populations

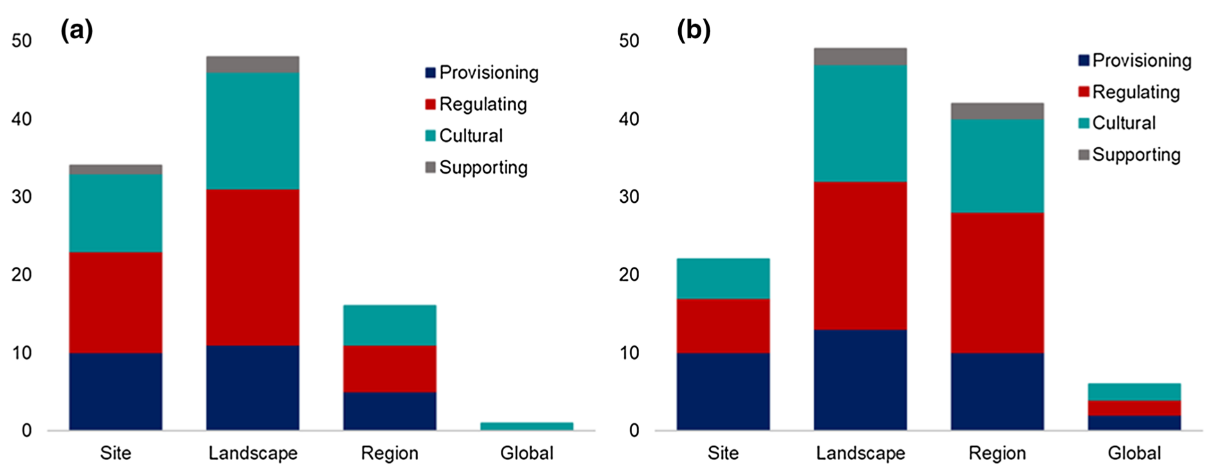

Fig. 5 **a** Scales at which environmental mechanisms act upon ecosystem services; **b** scales of the impact of fire on ecosystem services

which fire acts upon ES, the impacts can be felt at multiple scales. When it comes to impacts, there is a shift to larger scales from the scales of mechanism. In other words, the site- and landscape-scale mechanisms are having an impact at landscape- and regional-scales.

Regional differences are opportunities for future work

The literature surveyed in this study suggests that the supply of ES in the Colorado Front Range broadly mirror the impacts of fire on ES in general (Fig. 6). The supply of provisioning and regulating services in

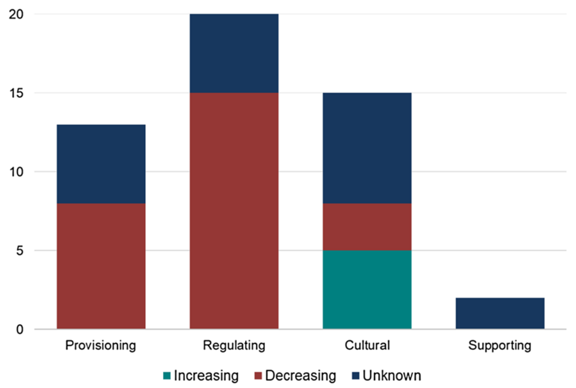

Fig. 6 Direction of change in the supply of ecosystem services in the Colorado Front Range

the Front Range is declining, while there is a slight increase overall in the supply of cultural services. By focusing on recent studies in the literature search, we have selected information that necessarily reflects over a century's worth of fire suppression (Keeley et al. 1999; Lloret and Marí 2001) and with it, an increase in fuel loading and large, hot fires (Piñol et al. 2005). The decline in ES in the surveyed literature reflects this land management legacy. However, for a substantial number of services, the direction of change is unknown.

The supply of forest products, such as pine nuts, herbs and mushrooms, for harvest in the Front Range is an example of an ES for which the change in supply in unknown. Depending on fire severity, changes to understory flora can be either beneficial or deleterious. Low-severity burning can promote herbaceous growth (Whittle et al. 1998), increase the amount of nutrients available to plants (Hart and Chen 2006), and thin overcrowded forests (Wade 1993), all of which can foster healthy systems and increased forest product yield. A high-severity fire in the same location could result in the destruction of seed banks (Roberts 2004), erosion (Robichaud and Waldrop 1994), and even the formation of a hydrophobic layer in the soil (DeBano 2000), causing a reduction in those same services. Increased tree density and subsequent buildup of fuels can cause a shift from low-severity to high-severity fires under conditions of hot, dry weather and strong winds; when stands are burned under these conditions, pine nut-producing pinyon species tends to be eliminated from the site and recolonize very slowly (Gruell 1999). Thin bark and lack of self-pruning also makes pinyon very susceptible to intense fire (Keeley and Zedler 1998), reducing the availability of those forest products. These in situ effects will interact with the movements of energy and matter and their associated impacts on physical conditions to affect the supply of forest products for harvest. Whether that supply is increasing or decreasing in the Front Range is unknown.

The ES chain: intermediate services warrant attention and management resources

For the Front Range, we identified nine intermediate services, 18 final services, and 23 benefits (Fig. 7). A small number of intermediate services, which stem from interactions between ecosystem structure and processes, lead a large number of final services and benefits. Manifold classification schemes and ES framings (e.g. Wallace 2007; Balmford et al. 2008; Fisher et al. 2009) make analyses and comparisons of intermediate services, final services, and benefits difficult. What the MA (2005) calls "supporting services" (two of our intermediate services), others have described as ecosystem functions between ecosystem processes and services (de Groot et al. 2010). Although the distinctions between function, service, and benefit are still debated, in general, benefits that contribute to human wellbeing are likely to be valued in economic or monetary terms (de Groot et al. 2010). Since people do not consume intermediate services directly or indirectly, they can be remain "hidden" or overlooked. Nutrient cycling or soil formation, for example, are long-cycle intermediate

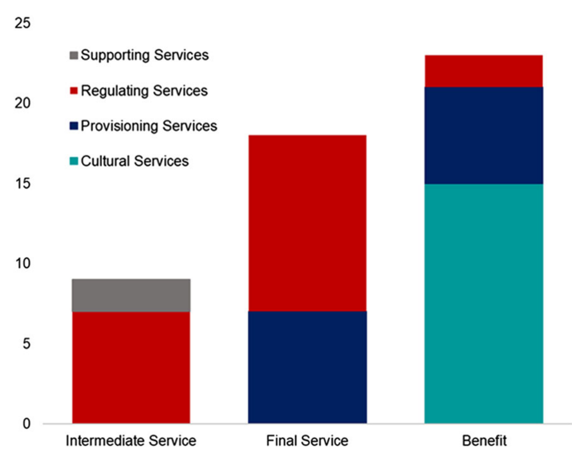

Fig. 7 Position in the supply chain (gradient of transformation) of identified ecosystem services

services that are difficult to see, especially compared to loss of timber resources and mudslides due to a decrease in natural hazard regulation (final services). Over the long term, however, natural hazard regulation depends on the ability to create soil and allow vegetation to establish. The finding that fewer intermediate services lead to many final services and benefits suggests that intermediate supporting and regulating services warrant greater consideration in management and allocation of resources.

Discussion

Study of the impacts and scales of mechanisms allows for improved understanding of both the production functions and the populations being served, as synthesized in Table 2. The framework we present helps to more systematically and comprehensively understand the relationships between fire and affected ecosystem services and the additional work needed.

Our analysis clarified that ecological processes are fundamentally scale dependent and our finding that site- and landscape-scale mechanisms are having an impact at landscape- and regional- (larger) scales has interesting implications for assessment, valuation and management. That mechanisms acting on "smaller" scales impact services at "larger" scales warrants consideration of nested systems where within each level ecological, social, and economic domains exhibit dynamic behavior (sensu Gunderson and Holling 2002). This finding might also suggest a different way to bundle groups of services. Whereas in the past we might have grouped "provisioning services"

Table 2 Wildfire impacts, mechanisms, scales, and direction of change in ES

Literature review categories	Description
Impact of fire on ES (positive, negative, unknown)	• Fire has a negative impact on the supply and availability of provisioning and regulating ES • Cultural services, due to increases in knowledge systems, are an exception with equally positive and negative impacts
Ecological/environmental mechanism of change	• Changes in vegetation composition and structure, water quantity and quality, nutrient status and sedimentation rate are the most common mechanisms by which fire affects ES • Of these, change in vegetation composition and structure (land-cover change) was the most prevalent mechanism of impact • Change in water quality is an especially important mechanism in mountain systems because it affects downstream water provisioning and provides linkages with other ES
Scale of the mechanism (site, landscape, region, global)	• The mechanisms of change act on multiple scales • The ecological or environmental mechanisms by which fire impacts ES tend to act on site or landscape spatial scales
Scale of the impact (site, landscape, region, global)	• The impacts of fire act on multiple scales • The impacts of fire are mostly felt at landscape and regional scales • Site- and landscape-scale mechanisms are having an impact at the landscape- and regional-scales.
Direction of change in the Front Range (increasing, decreasing, unknown)	• The supply of provisioning and regulating ES in the Colorado Front Range is declining. There is a slight increase in the overall supply of cultural services in the front range • For many ES, the direction of change in the Front Range is unknown
Position in the ES chain (intermediate service, final service, benefit)	• Of the 50 ES surveyed, 9 were identified as intermediate services, 18 as final services, and 23 as benefits • A relatively small number of intermediate services lead a large number of final services and benefits. Tabulation and/or economic valuation of intermediate services is worthwhile given their influence on the complete suite of ES

(Zhang et al. 2007) or all "water quality-related services" (Keeler et al. 2012) when considering management actions, perhaps it makes more sense to consider all "regional services" together regardless of their MA category. Such an approach could also provide a better way to match ES to decision-making scales.

Compared to spatial scale, the dimension of time has received little attention in ES research. Most of the existing ecological knowledge on ecosystem processes is based on investigations covering short periods of time (e.g. Cardinale et al. 2009). Ecological, social, and economic processes function of time scales from days (seedling establishment, soil moisture availability), years (species-driven CN cycling, zoning, interannual climate variability), decades (vegetation patch dynamics, national policies and land use planning, cultural values), and centuries (slope exposure, regional CN cycling). These processes interact with each other over specific spatial scales to create nested system hierarchies. Thus, studies of spatial scales are incomplete without concurrent considerations of time scales and represent a critical research need.

Scale may also play into our understanding of the environmental or ecological mechanism of change. Mechanisms that can be considered more "local", such as change in ecological communities, change in vegetation composition and structure, and soil contamination, can be characterized through field plots/studies or can be ground-truthed if assessed through remote sensing. These mechanisms are well described. We also have good understanding of dynamics that drive "regional" mechanisms, such as emissions from combustion and changes to air quality, changes to water quality and quantity, and mass movement. Downstream effects, which are crucial to understanding impacts in mountain systems, are an active area of study (e.g. Benda et al. 2003; Backer et al. 2004; Smith et al. 2011) and continued efforts will strengthen our ability to characterize impacts where there are spatial disconnects between where services are produced and where they are consumed. Environmental mechanisms of change interact with each other and as wildfires increase in size and severity, we are likely to see shift to new states that warrant further study of all mechanisms.

Fire regimes outside the historic range of variability was one environmental mechanism identified in our literature review. Climate change has the potential to alter conditions in many regions and with them the conditions underlying all mechanisms of impact. An encompassing mechanism of impact, climate change is the 800-lb gorilla that will drive fire regimes (Moritz et al. 2012; Stephens et al. 2013). Mountain regions are expected to be hit especially hard by climate change (Pepin et al. 2015) and hotter, drier conditions are expected to exacerbate wildfires (Jolly et al. 2015). Of great interest will be how human adaptations to climate change, such as response to water scarcity, will interact with wildfire response. Conceptually, one challenge will be whether we (a) treat climate change as a separate mechanism, (b) consider modifying our understanding of previously characterized mechanisms, such as new baselines for water quantity or emissions or (c) adopt hybrid approach(es), where mechanism characterizations are scale-dependent or vary with populations and adaptive capacity. We look forward to this area of scholarship with great interest.

The growing threats of intensified fire regimes (Moritz et al. 2012), coupled with changes in human settlement patterns (Williams 2013) and complex fire management legacies (Moreira et al. 2011) has spurred wildfire research. Similarly, growing interest in ES (Fisher et al. 2009) has attracted attention from a broader array of disciplines (Cooper et al. 2016) and contributed to increased shared knowledge. More journals have embraced open access options and new online platforms are helping scientists to share data and information. These changes have also extended the reach of scholarship from underrepresented regions, such as the Global South. For example, published research related to fire in sub-Saharan Africa (Angola, Democratic Republic of Congo, Sudan, and Central African Republic) and southeast Asia (Indonesia and the Philippines), has grown 881% and 1837% respectively since 2000 (Web of Science search; 5 June 2018). Scientific, institutional and practitioner knowledge systems have, in turn, increased in response to these new contributions. In reviewing the literature, we classified the trajectory of local/traditional knowledge systems as unknown—as Indigenous populations and languages are lost, there will be declines (e.g. Australian Human Rights Commission Social Justice Report 2009), but there are also new, innovative efforts to record and share Indigenous knowledge with broader audiences than ever before. For example, a recent discovery that kites and falcons will intentionally carry burning sticks to spread fire and increase feeding opportunities (Bonta et al. 2017) was grounded in traditional Indigenous ecological knowledge. This behavior has long been known to the Indigenous peoples of northern Australia (the birds are colloquially known as "firehawks") and is ingrained within some ceremonial practices, beliefs and creation accounts (Nicholas 2018). This finding generated worldwide interest, spread across popular media (Greshko 2018) and social network platforms, and opened the conversation about research opportunities at the intersection of Western and Indigenous knowledge.

Our finding that fire can positively impact ES, in particular with increases in knowledge systems, runs somewhat counter to the standard narrative of loss and raises the question of whether researchers are more likely to document decline rather than increase in ES research. Pragmatically and intuitively, we are more likely to evaluate characteristics that are readily measurable, which may explain why provisioning and regulating services, which tend to be more readily quantifiable, are more studied. Services such as sense of place or aesthetic values are more difficult to quantify and compare. Services that are hard to measure also tend to be difficult to value through standard economic mechanisms and are very susceptible to scales of study and arbitrary boundaries (Ascher and Steelman 2006; Kozak et al. 2011). We are also more likely to be moved to action, either in research or management, by negative change or loss—after all, most manuscript introductions are set up to explain or define "the problem". A consideration for future work may be the question of whether the explicit or implicit starting point of negative change contributes to selection bias in the ES chosen for study. This is an open area of scholarship with opportunities to contribute to a more balanced understanding of impacts.

Conclusions

The human–environment dimensions of wildfire make ecosystem services (ES) a useful framework for characterizing the trade-offs between human needs and the interactions among complex systems. This review of the relationships between mountain wildfire and a comprehensive list of 50 relevant ecosystem services helps to bridge the growing, but disparate, literature describing the connections between wildfire and ES.

Our results suggest that the supply of ES in the Colorado Front Range broadly mirror the impacts of fire on ES in general, however, for many services the direction of change in the Front Range is unknown. We found that current fire regimes mostly have a negative impact on ES, but that the impacts on cultural services are mixed. A bias toward negative characterization of ES may be inherent in the framing of questions and scholarship on the topic. The most common mechanism by which fire affects ES was through changes in vegetation composition and structure. Further, mechanisms acting at local and landscape scales impact ES at broader landscape and regional scales.

Regional perspectives from landscape ecologists may be one way to understand potential selection bias in the study of ES. Downscaling to lower levels may provide more nuanced understanding of complex relationships. Familiarity with local and regional landscape legacy, current land use and management actions, and stakeholder values and concerns make landscape ecologists with in-depth location-specific knowledge well positioned to contribute to future work. These perspectives will likely prove valuable in promoting consideration of intermediate services for natural resource management. A framework that considers the complete suite of ES, such as the one we develop here, provides stable and replicable guidelines for researchers to comprehensively, yet selectively characterize their regions. Our framework makes comparison across local and regional landscapes more feasible.

While cascading negative consequences on ES are more commonly documented, our framework holds the possibility of how positive impacts also might be catalogued, understood and promoted. The 50 ES are neutral in their outlook; they can be understood in a positive or negative light. The use of more beneficial fire, in the form of prescribed fire or large managed fires on the landscape, could be documented to illustrate the positive cascades that come with restoring this beneficial ecosystem function.

Trends related to wildfire all point to the same direction. We will have more wildfires that negatively affect ecosystem services in the western USA, as part of the growing consequences of climate change. The consideration of the entire spectrum of ES services affected by wildfire that we detail here, as well as the scales, mechanisms and directionality of change, can help land managers and stakeholders assess the impacts and trade-offs of various management actions. We also provide a framework to organize future research scholars who are interested in advancing understanding in this area.

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