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COASTAL WETLANDS

Fires in coastal wetlands: a review of research trends and management opportunities

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Abstract

Coastal wetlands face the growing problem of altered fire regimes that compromise ecosystem structures and functions, as well as the ecosystem services from which society benefits. In this review of the state of fire management research in coastal wetlands, we identified 81 publications on the topic over the last 35 years. Most studies analyzed the relationships between fire and ecosystems using geospatial tools and were conducted in swamps, marshes, savannas, mangroves, dunes and hammock forests. Productive activities in the coastal zone like agriculture, cattle ranching, and hunting as well as the increased demand of water for human consumption directly or indirectly favor a rise in both the frequency and intensity of fires in coastal wetlands. In addition to the local impacts of this altered regime, there are synergistic effects with alterations in the hydrological regime, land use changes and atmospheric changes that increase the susceptibility to unwanted fire in these ecosystems. We emphasize the need to move towards focuses that adopt a socio-ecological and interdisciplinary perspective to conserve and restore the fire regimes in coastal wetlands.

Keywords Integrated fire management · Socio-ecological systems · Wildfires · Interdisciplinary studies · Landscape sustainability

Resumen

Los humedales costeros se enfrentan al creciente problema de la alteración de los regímenes de incendios que comprometen las estructuras y funciones de los ecosistemas, así como los servicios ecosistémicos de los que se beneficia la sociedad. En esta revisión de la investigación sobre el manejo del fuego en los humedales costeros, identificamos 81 publicaciones de los últimos 35 años sobre esta temática. La mayoría de los estudios analizaron las relaciones entre el fuego y los ecosistemas utilizando herramientas geoespaciales y se realizaron en pantanos, marismas, sabanas, manglares, dunas y petenes. Las actividades productivas en la zona costera como la agricultura, la ganadería y la caza, así como el aumento de la demanda de agua para el consumo humano, favorecen directa o indirectamente el aumento de la frecuencia e intensidad de los incendios en los humedales costeros. Además de los impactos locales de la alteración al régimen, existen efectos sinérgicos con las alteraciones del régimen hidrológico, los cambios en el uso del suelo y los cambios atmosféricos que se combinan para aumentar la susceptibilidad al fuego no deseado en estos ecosistemas. Insistimos en la necesidad de avanzar hacia enfoques que adopten una perspectiva socio-ecológica e interdisciplinar para conservar y restaurar los regímenes de fuego en los humedales costeros.

Palabras clave Manejo integrado del fuego · sistemas socio-ecológicos · quema · estudios interdisciplinarios · sostenibilidad del paisaje

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Introduction

Coastal wetlands are ecosystems adapted to brackish or saltwater, and their high biodiversity supplies multiple ecosystem services, such as sediment and nutrient retention, storm buffering, and nursery habitats for many commercially important species (Rao et al. 2015). However, these ecosystems are subject to notable and accelerating rates of loss worldwide due to natural and anthropogenic drivers (Nicholls et al. 2011). Areas with elevations less than 10 m above mean sea level account only for 2% of the surface of the earth but are inhabited by approximately 10% of the human population (McGranahan et al. 2007; Neumann et al. 2015; Davidson 2014) estimated that natural coastal wetlands have declined by 62–63% over the course of the twentieth century. In addition, these ecosystems are particularly sensitive to sea-level rise and changes in the frequency and intensity of extreme natural phenomena (Spencer et al. 2016). Therefore, there are concerns as to how global environmental change will further modify these systems (Fagherazzi et al. 2012).

A synergy exists between humans, fires, and climate that is reshaping ecosystems worldwide (O'Connor et al. 2011; Kelly et al. 2020), particularly those in coastal zones characterized by rapid increases in human populations and development (Reguero et al. 2015). One might think that because coastal wetlands are associated with water to some degree, they do not burn, but this is not the case. The confluence of land-use change, urban expansion, alterations in hydrological regimes, and climate change influences fuel availability and alters the fire regimes in coastal wetlands (Kurki-Fox et al. 2019). Thus, coastal wetlands and the unique species that are inhabit them (Thompson and Rog 2019) are subject to changes in the frequency, magnitude, and severity of fires, depending on their degree of sensitivity to this shaping force (Flores et al. 2011).

There is no conclusive evidence regarding wildfire trends in coastal wetlands. Tendencies around the globe indicate a general decline in anthropogenic fire (Andela et al. 2017); however, local studies have reported increases in fire frequency in coastal wetlands associated with changes in vegetation cover, hydrology, and climate (e.g., Gopal 2013). In wetlands, an increased fire frequency puts various provisioning (e.g., food and raw materials), regulation (e.g., carbon sequestration and coastal protection from erosion), and cultural services (e.g., tourism, education, research, and religious activities) that benefit coastal communities at risk (Owuor et al. 2017; Sil et al. 2019; Reyes-Arroyo et al. 2021). The adverse effects of anthropogenic fires in coastal wetlands can have global impacts due to the ecosystem services that these environments provide, such as recharging aquifers, the conservation of biodiversity, and the ability of these systems to store carbon (Nellemann et al. 2009; Villalobos-Zapata and Vega 2010; McLeod et al. 2011; Pendleton et al. 2012; Mitsch et al. 2013; Howard et al. 2017; Aubrey et al. 2019).

Understanding and managing the effects of fires in coastal wetlands is challenging due to the complex relationships between these ecosystems and the fires themselves. These relationships are moderated by the dynamic nature of ecological processes and environmental factors as well as the complex interactions among economic and cultural activities along transition zones between terrestrial and marine areas (Kotze 2013). This review aims to analyze the published scientific literature regarding fire management in coastal wetlands. Identifying, understanding, and synthesizing this information will not only allow us to comprehend how this problem is being addressed worldwide and to identify trends in its management, but it will also elucidate the tools needed to conduct this task while furthering a scientific discussion. Enhancing our understanding of the factors that influence fires in coastal ecosystems and their subsequent effects will contribute to the design and implementation of comprehensive management strategies.

Materials and methods

This study was conducted through five iterative phases (Fig. 1). We identified relevant scientific studies on fire management in coastal wetlands published in the Web of Science (WoS) and Scopus search engines from 1987 up to January 2022. We used the following keywords: *Fire*, *Management*, *Coast*, and *Wetland* (Fire * + Management + Coast * Wetland *; the use of the asterisk returns results that include possible derivations of the keywords). We analyzed the abstracts to exclude unrelated studies that matched the search criteria (e.g., fire ants, Isla de Fuego). We expanded the search by adding studies recommended by experts that met the established criteria (e.g., scientific studies in Latin America). This resulted in the identification of 81 papers.

We categorized these studies and constructed a database following the criteria in Table 1. We analyzed location, timing, and spatial (i.e., global, regional, or local) and ecological (i.e., species, community, ecosystem, or biome/landscape) scales. We determined the focus of the research (i.e., fire-ecosystem or fire-socioecosystem) based on the objectives of the study. This process was iteratively conducted by three of the authors. One author submitted categorization proposals, which were discussed, reviewed, and validated by the other two authors.

We generated a map with the locations of the studies as well as the frequency of studies per country using ArcGIS Pro (Fig. 2). To graphically characterize the results of

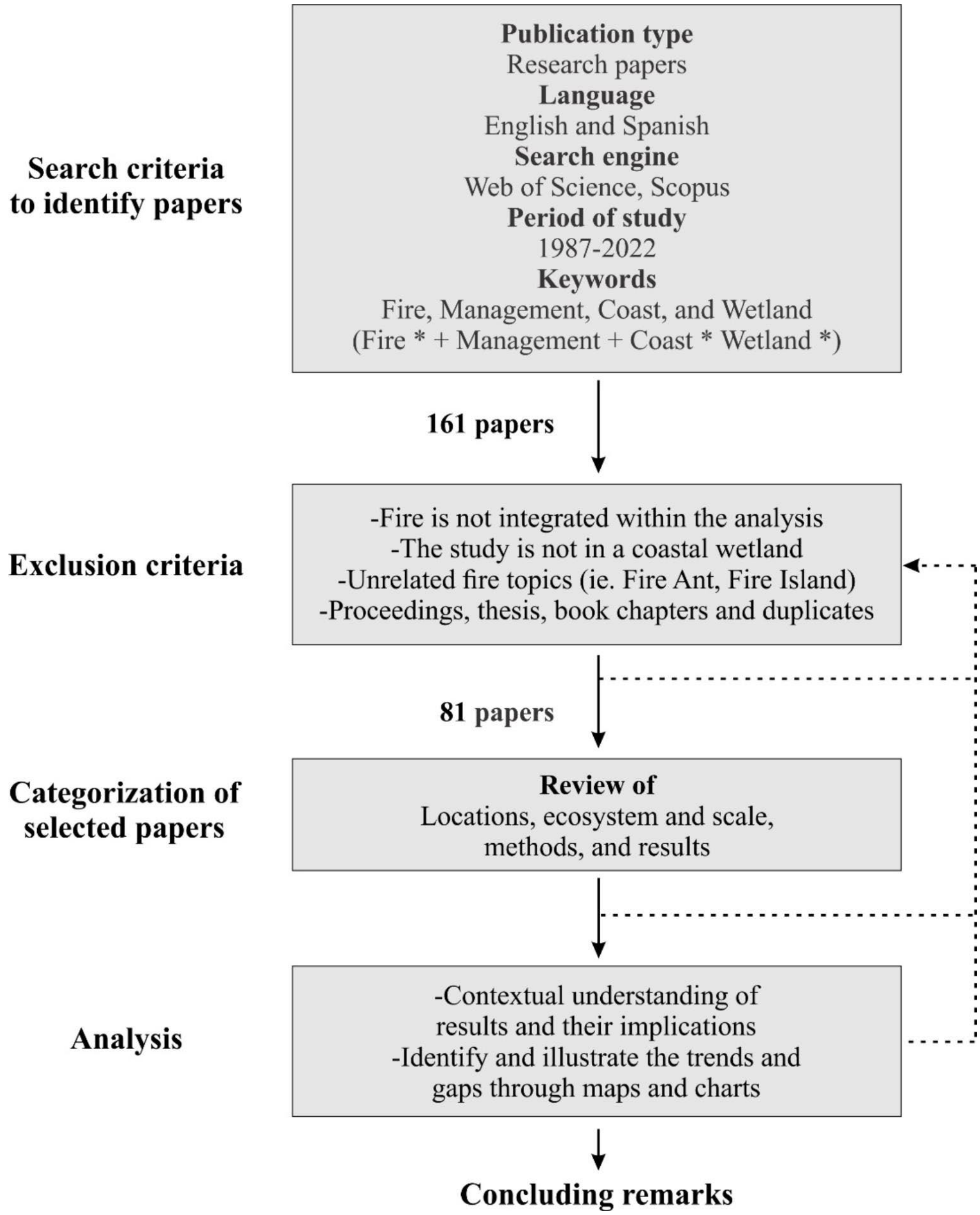

Fig. 1 Iterative analysis for the review of studies on fire management in coastal wetlands

Table 1, we generated a SankyMATIC (https://sankeymatic.com/build/), which illustrates the frequency and relationships between analytical criteria (Fig. 3). In addition, we registered the causes and effects of fires in coastal areas as well as fire management strategies (e.g., controlled burns), risk factors (e.g., meteorological variables), and management tools to deepen the understanding of what each study contributes to the knowledge of fire in coastal wetlands.

General overview of the study of fire in coastal wetlands

We identified 81 papers published from 1987 to 2022 that were conducted in 14 countries (Fig. 2; see supplementary material for the full list of studies). The majority of studies were from the United States (38) and Australia (17) The first study of fire in coastal wetlands that we identified in our research is the publication by Head (1987) on the history of resource exploitation in Australian coastal wetlands from pollen and charcoal analyses. A decade later, descriptive and explanatory studies on the relationships between fire and hydrological regimes in coastal wetlands began (Neldner et al. 1997; Johnson and Partridge 1998; Gabrey et al. 1999). Although there is no evident bias in the criteria for analysis between the U.S. and Australian studies, the management approach used to conduct the studies reveals a noteworthy pattern. Most of the research in the United States seeks to support restoration (22) and conservation (15) goals, while research in Australia follows conservation approaches (9).

Table 1 Analytical criteria applied in the systematic review

Criteria	Category	Description
Type of coastal wetland	Marshes	Continually or frequently flooded wetlands dominated by herbs and grasses (e.g., sedge marsh, grass marsh, and salt marsh).
	Swamps	Forested wetlands (e.g., Cypress swamps, cedar swamps, hardwood swamps, and peat swamps) with saturated soils and slowly flowing water.
	Savannas and grasslands	Seasonally flooded wetlands with a continuous and generally high herbaceous stratums and sparse tree canopies
	Hammocks	Wetlands associated with groundwater blooms that seasonally flow through the coastal plain and form islands of vegetation.
	Mangroves	Wetlands dominated by salt-tolerant tree species located in the transition zone between marine and terrestrial ecosystems; water flows periodically or permanently.
	Dunes	Wetlands dominated by sand and other biogenic components, with pioneer vegetation, shrubs, and trees. This category includes dune systems that form interdune lagoons.
Research focus	**fire-ecosystem**	Focus on the effects of fire on vegetation, fauna, and the atmosphere and the link between fire regime and ecosystem processes (e.g., hydrological processes). This focus can offer elements for fire management in ecosystems
	fire-socio-ecosystem	Focus on the link between the fire regime and the socio-ecosystem (e.g., hydrosphere, atmosphere, markets, and policies). These studies provide elements of the fire-society-nature interaction (e.g., impacts of fire on human health)
Ecological scale	**Biome -Landscape**	The analysis takes place in a geographic space where more than one ecosystem interacts, in addition to other environmental factors, such as relief, climate, hydrology, and infrastructure.
	Ecosystem	Research perspective is aimed at the systems in which plant and animal communities interact.
	Community	A set of plant or animal populations that share a geographic space is studied.
	Species	Research is focused on plant or animal organisms or populations.
Spatial scale	**Global**	Refers to research conducted worldwide.
	Regional	Includes national, sub-national, and multi-site studies spanning two or more states or provinces.
	Local	The research takes place in a geographic area delimited by a state division or smaller unit.

The most common ecological scale of these fire-wetland studies was that of biome/landscape (24), followed by ecosystem (32), community (16), and species (9). Most publications on wetland fire management were local case studies (60) conducted in six types of coastal wetlands, most notably marshes and swamps (29 and 28, respectively; Fig. 3). Regional studies (17) have been conducted mainly in swamps (10) and marshes (10), although studies have also been carried out in mangroves (6) and flooded savannas (5). Studies have also been conducted at the ecosystem and species levels addressing water quality responses to fire (Horwitz and Sommer 2005), the effects of fire on the structure and functioning of wetlands (Kotze 2013), the implications of the management and ecology on ecosystem invasion of Chinese tallow (*Triadica sebifera*) (Pile et al. 2017) and on the motivations for investing in ecological infrastructure to conserve natural ecosystems (Mbopha et al. 2021).

The main tools employed in coastal wetland research are related to spatial wetland management (32). Geographic information systems and remote sensing techniques allow for the positive and negative effects of fire to be identified and integrated into these spatial analyses (Neldner et al. 1997; Lowe et al. 2013) or statistical models (Smith et al. 2013; Chandler et al. 2015). Often, these spatial tools complement historical data analysis, field data collection (e.g., species inventories and soil profiles), experimental studies, and evaluations of the effects of prescribed burns (Blonder et al. 2018) or wildfires. However, the dynamism associated with coastal wetlands and, in some cases, the rapid recoveries of these environments (e.g., marshes), have constituted a challenge when it comes to understanding the fire history of these ecosystems. In this sense, remote sensing studies and those that employ techniques to analyze soil strata (e.g., carbon or pollen in sediments) highlight the need for information with high spatio-temporal resolution (Ross et al. 2019).

Fire as a critical ecological component shaping coastal wetlands

Fire is a critical component within ecological processes, functions, and structures in coastal wetlands. We identified 49 studies addressing fire interactions with soils, vegetation, and fauna. Fire is also influenced by hydrological conditions and atmospheric changes, which will be discussed in Sect. 4.2 and 5.2.

Both surface and ground fires influences soil properties (Smith et al. 2001). In general terms, fire impacts the microtopography of the soil due to the combustion of organic matter (Kotze 2013). Moreover, fire influences the nutrient cycle (e.g., the relationship between organic and inorganic phosphorus; Ogden et al. 2005), which can alter the physicochemical soil properties that regulate the distributions of

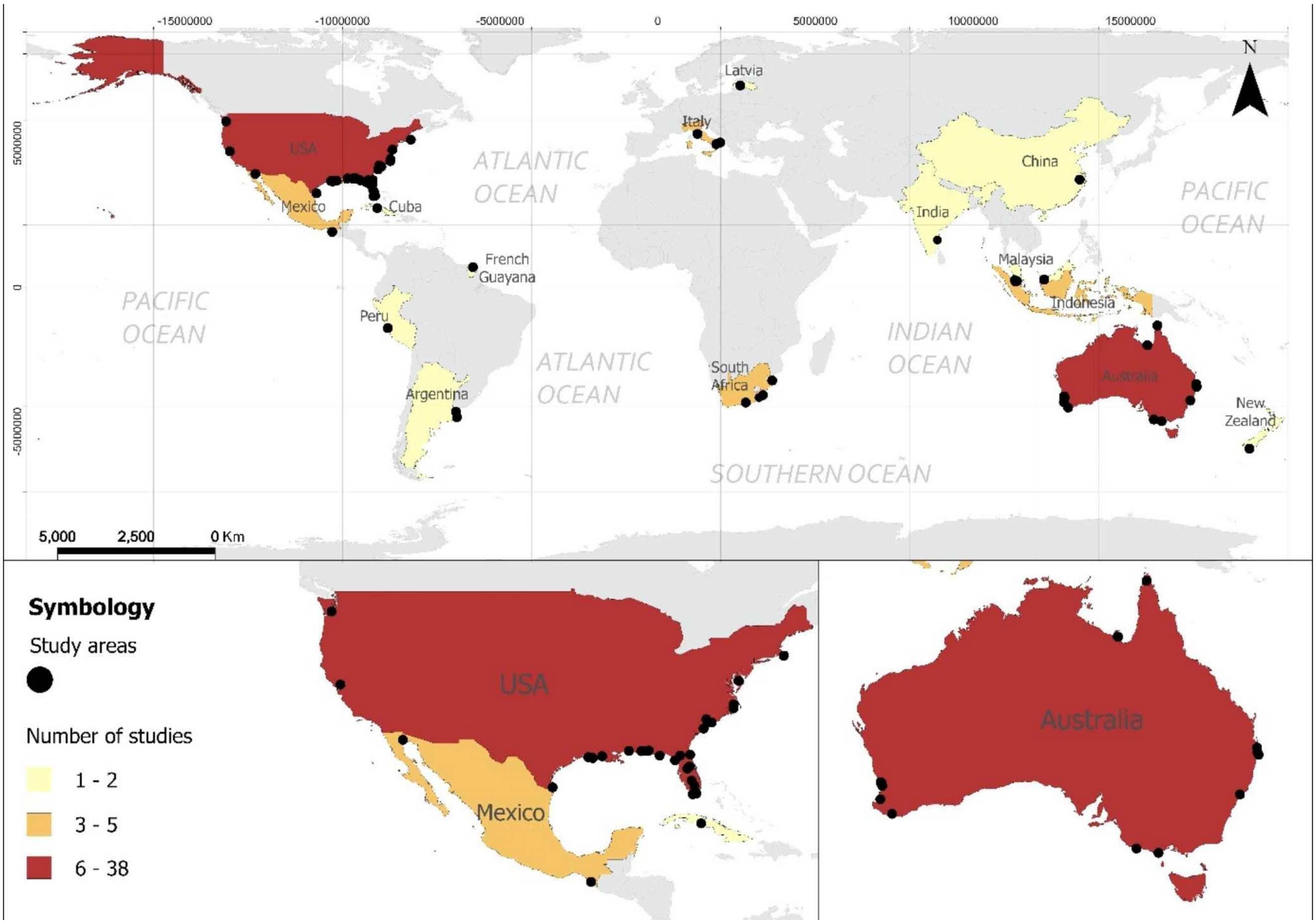

Fig. 2 Distribution and frequency of studies addressing fire management in coastal wetlands

plants. In addition, fires trigger soil erosion and ash transport due to the loss of vegetation in burned areas and sediment accumulation in low-lying areas (Kotze 2013).

Fire is one of the main drivers behind changes in the structure and composition of wetland vegetation (Steven and Toner 2004; Just et al. 2019). This can be seen in the Everglades, where changes in soil properties promote the settlement of opportunistic species (Smith et al. 2001). In fire-adapted coastal wetland ecosystems like savannas, fires result in opportunities for many organisms that depend on canopy clearance and high light penetration to propagate and develop (e.g., carnivorous plants; Luken 2005). Likewise, fire has been found to promote the growth of grasslands while improving their overall quality, which is crucial for the preservation of wetland habitats. This benefits various animal species like the Pampas deer (*Ozotoceros bezoarticus*; Vila et al. 2008) and a great variety of bird species in marshes (Gabrey et al. 1999). Although habitat requirements vary across species, fire results in new environments for feeding and guarantees nesting sites for multiple bird species in savannas (Morris et al. 2017), swamps (Loehle et al. 2009), and marshes (Ferrer-Sánchez et al. 2016). The above suggests the varied impacts that fire can have on plant-fauna interactions.

Fire and its interactions in coastal wetlands as a socio-ecological system

Studies have examined fire-society-nature interactions through a socio-ecosystem focus (32). These studies focused on the links between the fire regime and both ecological (e.g., hydrosphere and atmosphere) and social components (e.g., management, markets, and policies), acknowledging that there are no boundaries between "natural" and "human" fire. Chronologically the first study we identified under this focus is that of Foster et al. (2002), which reconstructs the socioecological history of the last 2000 years on the island of Martha's Vineyard in Massachusetts from long-term records of vegetation, fire, natural disturbances, and human activities. This line of research on the spatio-temporal changes of the landscape (and fire as a disturbance) from a socio-ecological focus has also been adopted in eight studies that have generally focused on marshes and swamps, although Moss et al. (2015) studied mangroves and dunes.

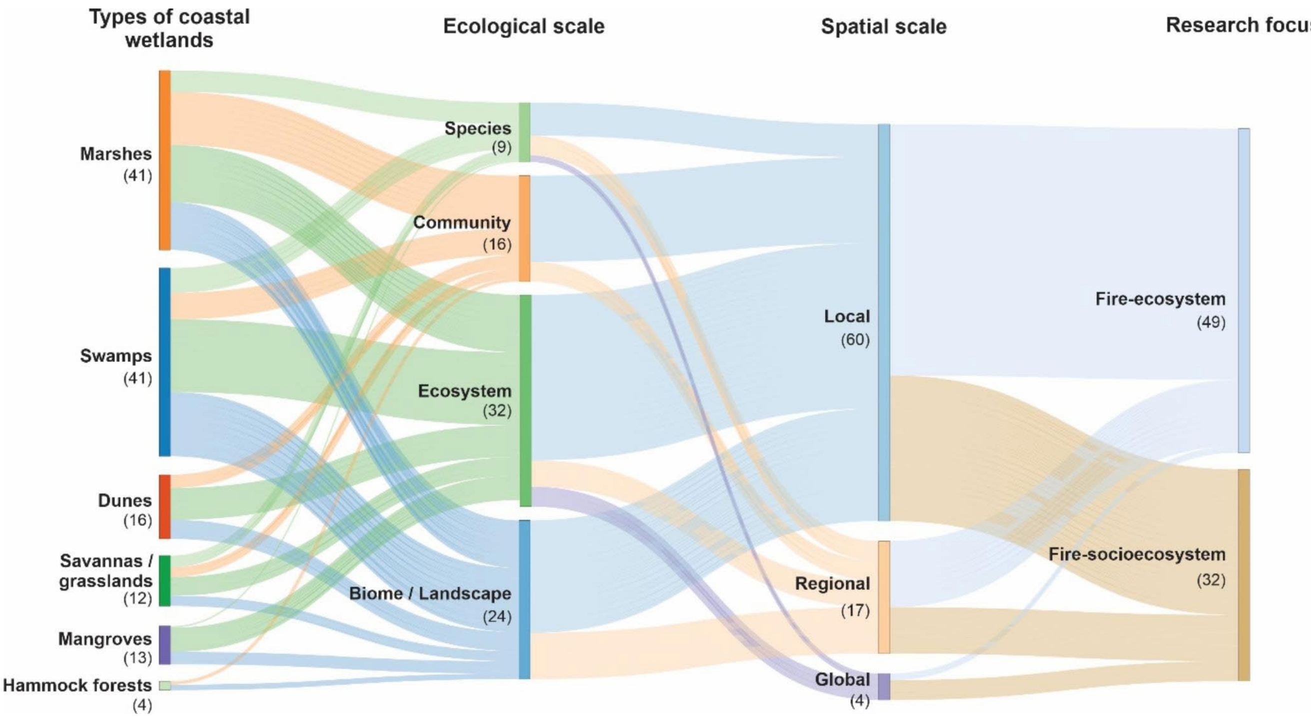

Fig. 3 Ecological and spatial scales of fire management across different coastal wetlands

Other applications of this focus include mapping areas based on fire vulnerability to identify priority conservation areas (Aretano et al. 2015), designing methodologies to use carbon credits as incentives for wetland restoration (Needelman et al. 2018), and developing land use planning models that integrate hydrological, land use, tenure information, and the knowledge and aspirations of local people (Syahza et al. 2020b). The study of Syahza et al. (2020b) is one of the few to integrate participatory tools (e.g., rapid rural appraisals) to incorporate local knowledge and practices.

Anthropogenic influence on fire in coastal wetlands

Many human decisions are framed by the need to meet food and housing needs, which generally result in landscape transformations associated with urbanization and land use change. These decisions can directly affect the presence of fire in the landscape, for example, when it is used as a land management tool or when it is excluded by regulatory mechanisms. Anthropogenic influence on the fire regime can also be indirect, such as when land use change alters hydrological regimes or contributes to climate change. In this section we describe the direct and indirect anthropogenic impacts that modify the frequency, intensity, severity, and initiation of fires in coastal wetlands, in addition to the effects of altered fire regimes in coastal wetlands.

Fire as a land management tool

Fire is used as a tool for burning vegetation prior to cultivation (i.e., slash-and-burn, stubble burn). This has been documented in different settings, for example in Indonesia for palm oil plantations (Syahza et al. 2020a), and in China for rice production (Zong et al. 2007). Agricultural burning has been reported as a practice that triggers fires in both forests and wetlands (Aretano et al. 2015). Other practices like livestock grazing affect the fire regime by reducing fuel loads, which lowers the fire frequency and favors the growth of woody plants and pasture-forest conversions (Neldner et al. 1997). Various exotic species that have been introduced by either agricultural practices or livestock tend to be better adapted to fire and burn more intensely, which in turn favors the spread of fire (Ogden et al. 2005).

Other uses of fire for food procurement include poaching activities. This has been studied in the coastal grasslands of Pondoland in South Africa where 69% of the fires are caused by poaching (Brooke et al. 2018). In other wetlands, such as Pantanos de Villa in Peru, wildfires have been associated with campfires associated with fishing or collecting culturally or economically important plant species, such as cattails (*Typha domingensis* Pers.) and sedges (*Schoenoplectus americanus*; Ramirez et al. 2018).

Urban expansion and changes in hydrological regimes

Water is crucial to proper wetland functioning, specifically the hydrological regime, with the hydroperiod driving fire regimes in coastal wetlands (Steven and Toner 2004). Population growth and the development of human settlements have increased the demand for water and compromised natural flows in many regions worldwide. Changes in surface and subsurface hydrological dynamics in coastal wetlands that are triggered by land use changes and water extraction increase their susceptibility to fire (Kurki-Fox et al. 2019). These reductions in water table levels have increased fire susceptibility in the coastal forests of North Carolina (Callahan et al. 2017) and peatlands of South Africa (Elshehawi et al. 2019). In addition to water extraction, changes in water flows are also associated with drainage. Such is the case of the Everglades, where the soil water balance has been compromised, increasing the wildfire frequency (Smith et al. 2001). These changes to the hydrological and fire regimes in coastal wetlands modify the capacity of these ecosystems to respond to other disturbances, such as drought, climate change, and saline intrusion (Ismail et al. 2021). Changes in coastal dynamics associated with low freshwater levels and saline intrusion have been observed in Florida and Indonesia (Ogden et al. 2005).

Adverse effects of altered fire regimes

Local and direct effects

Increases in fire frequency and intensity, triggered by human-environment interactions, have adverse consequences in coastal wetlands (Table 2). The major repercussions are associated with the effects of fire on the coverage, structure, and functions of these ecosystems, which leads to losses of habitat and biodiversity and by extension a loss of ecosystem services. This was reported in the mammal populations of the in the coastal swamps of Gnangara Groundwater System in Australia (Wilson et al. 2012) and the herpetofauna communities of southern Florida in the United States (Chandler et al. 2015). In addition, the loss of habitat and its relationship with ecosystem services was documented in La Encrucijada Biosphere Reserve in Mexico where the fire fragmented landscape enhanced exposure to meteorological events (e.g., storms), reducing provisioning services (e.g., building materials; Carranza-Ortiz et al. 2018).

Fire and its frequency, intensity, and timing determine the structure and composition of vegetation. Depending on the fire regime, a landscape will be dominated by either woody or herbaceous species. We identified some studies that reported the conversion of herbaceous to woody ecosystems (Holm and Sasser 2008; Watson et al. 2019). This transition is associated with a reduction in fire frequency and intensity. For example, in the mangrove-swamp ecotone of the Everglades National Park in the United States, Smith et al. (2013) documented a reduction in fire frequency associated with hydrological changes, which led to an increase in mangrove cover. We also identified studies that reported the opposite change from woody to herbaceous ecosystems. For example, on the Basilicata coast in Italy, an increase in the fire frequency along with interactions related to the processes of fragmentation, erosion, and saline intrusion resulted in woody plants being displaced by grasslands (Imbrenda et al. 2018). Finally, changes in plant communities have been found to modify landscape flammability, further contributing to the altered fire regime (Pile et al. 2017).

Synergistic and regional effects

One of the most critical aspects of the relationship between fire and wetlands refers to their capacity to act as carbon sinks and the feedback effects with hydrological processes. Fires modify the content of organic material and the soil

Table 2 Adverse effects of altered fire regimes on coastal wetlands

Effect	Source
Changes in wetland structure, coverage, and function	Wilson et al. 2012
Habitat loss	Chandler et al. 2015
Habitat fragmentation	Carranza-Ortiz et al. 2018
Conversion of vegetation types	Holm and Sasser 2008; Loehle et al. 2009; Smith et al. 2013; Imbrenda et al. 2018; Watson et al. 2019
Exotic species invasions	Ogden et al. 2005; Pile et al. 2017
Hydrological changes	Kotze 2013; Lowe et al. 2013
Greenhouse gas release	Blake et al. 2009; Laurance et al. 2011; Kotze 2013; Ramirez et al. 2018
Soil modifications	Smith et al. 2001; Ogden et al. 2005; Reardon et al. 2009; Iriarte et al. 2012; Kotze 2013; Kurki-Fox et al. 2019
Destabilization of dune ecosystems	Blonder et al. 2018; Carranza-Ortiz et al. 2018
Water quality	Blake et al. 2009; Glenn et al. 2013; Kotze 2013

structure (Smith et al. 2001). Changes in soil properties affect hydrological dynamics (Semeniuk and Semeniuk 2005) and promote oxidation while declining water tables can eventually expose soil to oxidation, resulting in the loss of blue carbon stored in wetlands (Kurki-Fox et al. 2019) and the release of greenhouse gases (Grundling et al. 2021). Therefore, fires in peatlands, which are characterized as large carbon reservoirs, are of great concern (Syahza et al. 2020a).

There is a relationship between atmospheric factors, fuel loads, and the fire regime (Brooke et al. 2018). Fire intensity and magnitude depend on the fuel load, which varies depending on the vegetation structure and density but also on fuel burnability which depends on hydrology, microtopography, and climate (i.e. prolonged dry spells) (Lowe et al. 2013; Barrios-Calderón et al. 2018, 2020). Thus, changes in vegetation coverage and the hydroperiod may increase fuel availability, which can lead to more frequent and intense wildfires in coastal wetlands. This has been documented in some regions of Australia, where drier conditions have been associated with an increased risk of fire (Wilson et al. 2012). In addition, in some coastal zones, wetland areas may be reduced or even isolated due to the effects of rising sea levels, the near-constant expansion of urban areas, and changes in fire frequencies and intensities (Kurki-Fox et al. 2019).

Warmer seasons are expected to increase the frequency of fires, along with the expectation that better adapted vegetation will displace vegetation that is more vulnerable to fire and other disturbances (Kotze 2013). For example, in a wet savanna in northwest Florida, Dixon et al. (2021) showed that 12 years of post-fire restoration efforts have been hampered by the presence of hurricanes and storm surges. A similar case was reported by Kominoski et al. (2020) for the Everglades in Florida, where nutrient concentrations in the water depended on multiple events such as fires, hurricanes, low temperatures, and shoreline proximity. Some studies have sought to determine the ecological thresholds associated with climate change. For example, some amphibians in Australian wetlands have been found to be highly resistant to fire, which may allow them to survive if fires become more frequent (Lowe et al. 2013). Ultimately, the impacts of these stressors on wetland ecosystems will be determined by the ability of species to adapt to changing conditions. Therefore, it is necessary to determine whether the flora and fauna that are characteristic of wetlands are resilient, while identifying management strategies that are needed in the short-, mid-, and long-term, such as prescribed burns or other adaptive management strategies.

Fire as a tool for ecosystem conservation and restoration

Ecosystem integrity depends on its functions and processes, such as fire regimes. Therefore, it is essential to determine and sustain the frequency and intensity of fire necessary for each ecosystem. This highly contextual knowledge is the basis of fire management, the goal of which is to reduce the risk of catastrophic fires, protect sensitive vegetation (Aretano et al. 2015), and conserve fire dependent species (Chandler et al. 2015).

The management of coastal wetlands with fire can result in unforeseen consequences and adverse complications for management objectives (Gabrey et al. 1999). Emergency suppression and fire containment are often the most widely used fire management strategies in coastal wetlands.

Table 3 Prescribed burning in coastal wetlands

Management objective	Impact of prescribed burns	Source
	- Reduces fuel loads (low–mid intensity fires)	Aretano et al. 2015
Wildfire prevention	- Protects fire-sensitive vegetation	Aretano et al. 2015
	- Reduces arson	Brooke et al. 2018
	Fire regime restauration	
	- Substitutes mechanical or chemical treatment of unwanted plant species (e.g., exotic species and woody plants).	Loehle et al. 2009
Restoration	- Contributes to the reestablishment of native species (adapted to the established fire regime)	Watson et al. 2019 Neldner et al. 1997; Ross et al. 2019; Watson et al. 2019.
	Restauration of ecosystems - Contributes to bioremediation (e.g., oil spills)	Lin et al. 2005b
	- Creates feeding grounds and nesting sites for wildlife	Ogden et al. 2005
	- Increases soil nutrient content	
Habitat improvement and maintenance	- Promotes seed germination, growth, and the regrowth of vegetation	Watson et al. 2019
	- Increases the abundance and diversity of species	
	- Improves aquatic environmental quality (e.g., increase in water nutrients) and light penetration by clearing the canopy.	Glenn et al. 2013

However, in regions like the coastal plain of the United States, fire exclusion has transformed herbaceous ecosystems into shrub-dominated landscapes (Smith et al. 2013). Other common strategies to prevent fires in wetlands, such as fire breaks, can have repercussions for the local hydrology (Lowe et al. 2013) and may generate access routes that facilitate the extraction of flora and fauna (Glenn et al. 2013). Likewise, management actions like prescribed burns that do not consider the diversity that is inherent in these coastal environments can result in conditions that are unfavorable to many organisms that use the wetlands to reproduce (Lowe et al. 2013).

Prescribed burns in coastal wetlands

Prescribed burning is one of the most widely used tools for fire management in coastal wetlands, as it can prevent wildfires, restore ecosystems and fire regimes, and improve habitats (Table 3). In places where the fire frequency has increased, prescribed burning has turned out to be favorable for reducing the amount of combustible materials and the subsequent wildfire frequency and associated ecological impacts (Aretano et al. 2015). In the long term, these burns eliminate the need for other treatments to prevent resprouting (i.e., mechanical removal of standing woody biomass or the use of herbicides; Watson et al. 2019). In addition, the soil is prepared for the successful germination of native grasses through the elimination of trunks, branches, and leaves (Loehle et al. 2009). Prescribed burning has been shown to have a positive impact on the Everglades due to its effect on natural succession and grass regrowth, which attracts species like deer and the carnivores that consume them (Ogden et al. 2005). This illustrates the effect of prescribed burning in conserving or restoring ecosystem functions and processes.

Implementation challenges and opportunities

Fire ecology has provided clarity concerning the role of fire and prescribed burns in coastal wetlands. Prescribed burns must seek to protect the soil, roots, rhizomes, and the life cycles of flora and fauna with a clear understanding of the species that benefit from or are vulnerable to fire. Therefore, prescribed burning in coastal wetlands must take into account several factors like the water depth and wetland type (Pahl et al. 2003; Lin et al. 2005a; Smith et al. 2013), soil and vegetation moisture, the frequency of the natural fire cycle (Bishop and Haas 2005; Erwin et al. 2016), fire intensity (Smith et al. 2013; Watson et al. 2019), and the fire season (Kotze 2013; Lowe et al. 2013).

One of the most charged discussions surrounding the use of fire as a tool to restore fire regimes and ecosystems revolves around the need to establish the objectives of prescribed burns and evaluate the positive and negative outcomes. In our review we found that prescribed burning is mentioned as a desirable tool in integrated fire management of coastal wetlands (Aretano et al. 2015; Ferrer-Sánchez et al. 2016; Barrios-Calderón et al. 2018). However, few studies formally evaluate the effects of prescribed burning as a bioremediation tool (Lin et al. 2005a, b) and to restore grasslands (Watson et al. 2019).

There is a general understanding of the ecological aspects that should be evaluated in prescribed burn outcomes, like the fire effects throughout bioclimatic regions (Price et al. 2015) as well as the ecological thresholds according to fire regime (Lowe et al. 2013). These can be measured through fuel loads, life cycles and animal behaviors (Gabrey et al. 1999). Monitoring fire effects in the permanence of native species or exotic species' proliferation of exotic species is key to inform analysis and evaluations (Neldner et al. 1997; Ross et al. 2019; Watson et al. 2019). In other words, assess the availability of resources and habitats as well as the differential species responses to the resulting prescribed burn conditions (Just et al. 2019). However, data limitations on the occurrence of fires in wetlands are highlighted, as well as the difficulty of distinguishing which of these records correspond to fires and which to prescribed burns (Bishop and Haas 2005; Loehle et al. 2009).

As fire scientists and managers, we should ask ourselves, should the restoration of fire regime (its frequency, timing, and intensity) through prescribed burns be defined based on our (limited) knowledge on natural fire regime? How do human values, interests, and preferences influence the objectives and evaluation outcomes? We argue that restoring the fire regimes requires understanding coastal wetlands as socio-ecosystems and fire as a phenomenon that causes local ecological, economic and social affects but also regional and synergistic effects which interact with climate and anthropogenic drivers (Sect. 5.2).

Contemporary approaches to fire management like prescribed burns usually take into account mitigation strategies to reduce potentially harmful impacts on human health and private property (Blake et al. 2009). Decisions to reduce the adverse effects of a prescribed burn (i.e., smoke management) are made on the basis of expert judgment (Blake et al. 2009). However, with few exceptions (Standley et al. 2009; Syahza et al. 2020b), we found no studies that integrate local participation for managing fires in coastal wetlands. The highly contextual understanding needed to restore fire regimes in coastal wetlands requires the integration of fire ecology as well as the interests, preferences, and knowledge of the people living in these ecosystems.

Final considerations

Fire shapes coastal wetlands and has been used as a land management tool since ancient times (Zong et al. 2007). Research on fire management in coastal wetlands is relatively recent, emerging as these ecosystems face complex challenges like those related to global environmental change. However, most of the research on fire in coastal wetlands has focused on its ecological scope, and studies with a socioecological perspective have only surfaced over the last decade. In this review, we found no studies addressing the social implications (e.g., governance or culture) of coastal wetland fires, which reveals a knowledge gap in the available literature. However, there are some examples of studies that focus on these topics in other ecosystems that highlight the risks associated with altered fire regimes for societies that depend on ecosystem integrity (Mistry 1998; Carmenta et al. 2017; Jefferson et al. 2020). Future studies on fires in coastal wetlands will increasingly have to face the challenge of integrating social and ecological components that allow for the effects of anthropogenic activities and climate change to be addressed. No single approach or tool will be sufficient for addressing the complex and difficult problems associated with changing fire regimes in coastal wetlands. We underscore the need for diverse and mixed methods that combine tools and data sources, including diverse forms of academic and non-academic knowledge.

The belief that fires in wetlands only pose a threat and that their management should be based only on suppression shows an incomplete understanding of their positive and negative effects (Armenteras et al. 2020). However, there is no consensus regarding whether or not management should only focus on fire control or if fires should even be used as a management tool (Aponte et al. 2015). For this reason, it is essential to understand both the species-specific responses of flora and fauna to fire in addition to the knowledge and fire management practices of local communities to incorporate these elements into the current management strategies for coastal ecosystems (Blonder et al. 2018). For successful management, it is necessary to determine the fire frequency, timing, and intensity required to sustain and restore ecological functions, such as those related to hydrology, erosion, nutrient availability, trophic networks, and habitat availability, which ultimately depend on the degree of landscape change (e.g., changes in hydrological variables, land cover, and pyrophyte species).

A paradigm shift in fire management is particularly important for the sustainability of coastal wetlands. It is becoming increasingly clear that fire management requires implementing strategies that mitigate the current challenges imposed by anthropogenic and climatic stressors in addition to understanding the multiple spatio-temporal scales involved (Watson et al. 2019). Although fire management efforts are commonly directed towards fire suppression or exclusion, previous studies have illustrated the importance of the ecological role of fire in ecosystems and the potential to use fire as a management tool. This transition from fire suppression to integrated fire management within socio-ecological systems requires understanding the ecological role of fire as well as the social context in which fire-use practices have developed. Understanding how the socio-environmental system benefits or is harmed by changes in the intensity, severity, and seasonality of fire will inform the design and implementation of sound strategies that guide coastal wetlands towards more sustainable trajectories.

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Declarations

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