Dookie et al. *New Zealand Journal of Forestry Science* (2025) 55:4
https://doi.org/10.33494/nzjfs552025x405x
E-ISSN: 1179-5395
published on-line: 7/03/2025

REVIEW Open Access

New Zealand Journal of Forestry Science

Forest-fire interactions, impacts, and implications: a focus on mangroves

Sabrina Dookie*, Abdullah Adil Ansari and Sirpaul Jaikishun

Department of Biology, Faculty of Natural Sciences, University of Guyana, Georgetown, Guyana

*Corresponding author: sabrina.dookie@uog.edu.gy

(Received for publication 6 July 2024; accepted in revised form 14 February 2025)
Editor: Eckehard Brockerhoff

Abstract

Background: Fire plays a key role in the world's wetland ecosystems, affecting the fundamental aspects of their ecological functioning. The increased frequency of wildfires continues to exert a significant influence on the succession of mangrove ecosystems and the spatial distribution of species. Numerous studies have attempted to highlight the effect of fires on forest ecosystem function and integrity; however, the results are inconclusive. In particular, it remains uncertain whether forest fires have direct impacts and implications on mangrove ecosystems, a forest type known for its distinct characteristics and low ignition rates due to high moisture levels.

Methods: We have conducted a comprehensive review of over 120 relevant scholarly articles found through formal searches of literature and citation databases and by surveying relevant publications to identify and examine the interactions, prevalence, and implications of forest fires in mangrove ecosystems globally. We have also synthesised the impacts of recurrent fires on the numerous ecological goods and services offered by mangroves and highlighted the existing literature gaps and directions for future research.

Results: Mangrove forest fires are prevalent in many countries across the world with varying distributions of forested areas. While there are numerous causes of wildfires in mangroves, most occurrences are due to a combination of natural dry periods (El Niño events) and anthropogenic activities, which may deliberately or accidentally increase fire regimes. There are many negative effects of mangrove forest fires which can affect the goods and services provided to the environment and society, including habitat loss, pollution, and wildlife destruction. However, our findings have highlighted some cases where wildfires have positive effects on mangrove ecosystems by encouraging nutrient enrichment and habitat expansion. Our review reports numerous literature gaps with high priorities for future research on understanding sustainable forest management with the coexistence of fires through preservation, conservation, and public awareness.

Conclusions: Forest fires are prevalent in mangrove ecosystems due to a combination of natural phenomena and human-induced factors. With predominantly negative effects, forest fires result in a loss of ecological integrity, leading to severe economic losses and habitat degradation. Emphasis should therefore be placed on sustainable forestry and public awareness for the mitigation of the dynamic effects of forest fires on mangrove ecosystems.

Keywords: climate change; droughts; ecosystems; El Niño fires; forest fires; mangrove swamps; mangrove vegetation; mangroves; wetland fires; wildfires

Introduction

Fire acts as a potent biological filter, exerting a significant influence on the succession of terrestrial ecosystems and the spatial distribution of species. Human activities cause environmental change and disturb the natural patterns of fire occurrence worldwide, leading to a rise in the frequency and severity of fires (Harrison et al. 2024). Droughts are prevalent across all geographic regions and climates, resulting in substantial economic, agricultural, and environmental impacts. The combined magnitude of this phenomenon with the continuing impacts of climate change suggests that there will likely be a rise in the frequency, extent, and severity of droughts in numerous regions of the world, many of which are particularly susceptible to such events (Vogt et al. 2016). The persistent occurrence of El Niño, combined with climate change extremes (particularly high temperatures), has led to droughts that have repeatedly affected many nations, endangering wildlife as well as the local economy and society in numerous locations throughout continents (Arias et al. 2023).

Droughts not only alter the water cycle, causing heightened abnormalities in precipitation and associated water-related risk factors but are also known for their propensity to trigger catastrophic wildfires (Burton et al. 2021). Although they have both detrimental and beneficial biological effects, wildfires are a worldwide occurrence that entails significant repercussions for ecology, environment, population, and industry (Kumar 2022). The recent surge in fire activity is particularly alarming due to its potential to negatively affect local ecosystems and the global climate by depleting significant carbon reserves in the face of projected socio-environmental transformations (Mega 2020; Lizundia-Loiola et al. 2020). Traditionally, wildfires have not been regarded as a significant danger in forests, especially in tropical regions, because of the abundance of moisture and scarcity of natural sources of combustion. Scientists are concerned about the increasing likelihood of wildfires spreading over larger territories in the future. This is due to ongoing global climate change, which is causing warming and drying conditions that are expected to persist for centuries (Kala 2023).

Mangrove forests have firmly established themselves inland, along rivers, and bordering coastlines as significant, essential forested ecosystems worldwide, and are widely recognised for the multitude of valuable goods and services they provide (Crameri & Ellison 2022). Mangroves cover around 152,000 km^2 of the Earth's surface, which accounts for roughly 0.12% of the total terrestrial area. Indonesia, Mexico, Brazil, Nigeria, Venezuela, Papua New Guinea, Malaysia, Colombia, Thailand, and Gabon have extensive distributions of mangroves (Sadeer et al. 2019) (Figure 1). Mangroves are renowned for their versatile and perpetually shifting adaptations since they offer inherent and distinctive benefits to people.

Mangroves have a crucial role in safeguarding against natural calamities like tsunamis while also serving as a source of sustenance and other coastal commodities (Bourgeois et al. 2019; Hilaluddin et al. 2020). Mangroves face numerous challenges, such as flooding, catastrophic events, urbanisation for fuel and agriculture, excessive fishing, infrastructure development, and pollution from hazardous materials and chemicals. Additionally, studies have demonstrated that mangrove forests are also susceptible to wildfires, either directly or indirectly. Although there are many reviews that examine the different perturbations taking place in mangrove ecosystems, there is currently no extensive review that specifically covers the occurrence of forest fires in these habitats. This ultimately diminishes our understanding of this subject from a variety of perspectives.

We believe that investigating and analysing the impacts and implications of forest fires on mangrove ecosystems is critical. Forest fires have significant effects on vegetation composition, forest succession, carbon budgets, the socioeconomic standing of nations, and socially vulnerable populations (Chas-Amil et al. 2022; Kala et al. 2023). We acknowledge the significance of mangrove forests as 'blue carbon' forests because of their substantial ability to sequester and store carbon while mitigating greenhouse gas emissions (Song et al. 2023; Morrissette et al. 2023). Mangrove ecosystems actively contribute to mitigating the disruptive impact on the carbon cycle and promoting ecological equilibrium, closely linking forest fires and climate change. Within this context, the objectives of our review were to:

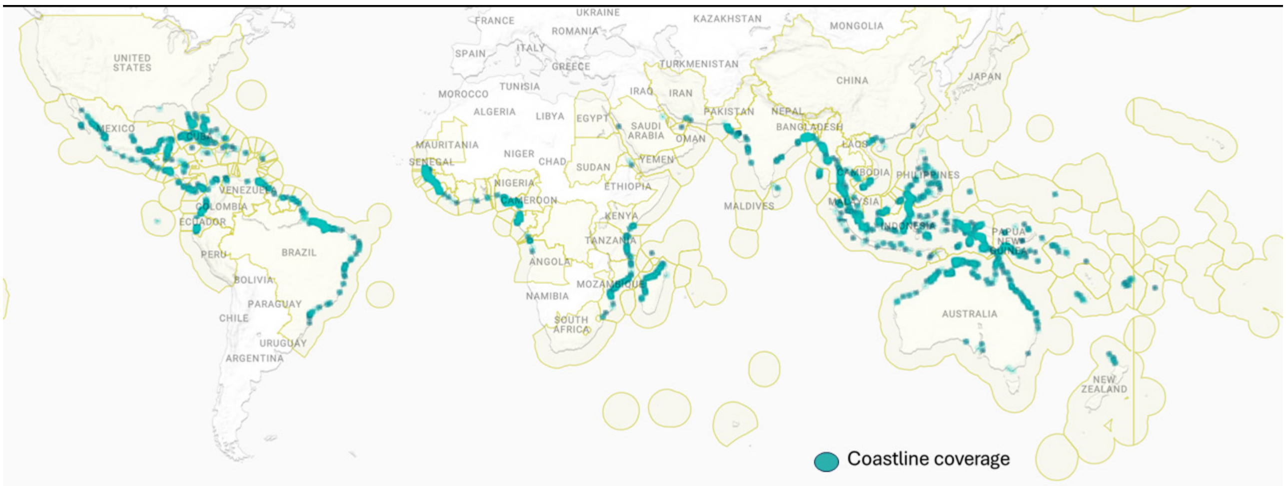

FIGURE 1: Global habitat extent of mangroves (including coastline coverage) from 1996 to 2020 (Adapted from: Bunting et al. 2022).

(i) provide a comprehensive overview of the prevalence and causes of mangrove forest fires locally and globally; and (ii) examine the effects and implications of fires on the health and ecological goods and services provided by mangrove forests.

Methods

Literature acquisition and selection

We gathered information on forest fires occurring in mangrove ecosystems by conducting a comprehensive search in reputable academic journals, databases, and books using the Scopus and Google Scholar platforms. The search was conducted during the period of 20 -25th June 2024 using the following key search terms: '*wildfires*', '*grass fires*', '*bush fires*', '*forest fires*', '*forest fire causes*', '*forest fire effects*', '*mangroves*', '*mangrove ecosystems*', '*mangrove wetlands*', *and* '*mangrove forests*'. The search was limited to publications in the English language, which were published in and after 2000 to 2024. This yielded approximately 192 relevant articles using the defined search criteria and these articles were manually screened. Articles not meeting any of the screening criteria were excluded from further analysis, i.e., (1) articles that were not available or accessible, (2) articles that were not relevant to the research objectives, i.e., did not articulate any specific interactions, impacts, or implications of fires in mangrove forests. After the manual screening, 120 articles fulfilled the criteria, which were considered for further analysis.

Prevalence and causes of mangrove forest fires

To assess the prevalence and causes of mangrove forest fires, we conducted a thorough examination of the selected literature pertaining to the interactions of forest fires in countries at both local and global scales. After viewing various research objectives/hypotheses and methodology sections of book chapters and articles, we then utilised various recommended online platforms such as 'Global Forest Watch', 'Mangrove Forest Watch', 'Global Mangrove Watch', and 'NASA FIRMS', as well as official government and non-governmental organisation websites to gather supporting information, including datasets, statistics, and visualisations, on the current extent of different mangrove forests worldwide and the number of recorded wildfires (prevalence). The results were further adjusted to concentrate on and convey relevant information on the distribution of mangrove forests and trends in forest fires occurring within them. This was accomplished by utilising applications like Microsoft Excel, QGIS, GIMP, and NASA FIRMS software to illustrate figures and graphs that depicted the patterns, causes of forest fires, and their prevalence in mangrove forests.

Impacts and implications of mangrove forest fires

To understand the effects and consequences (short and long-term) of fires on the health of mangrove forests, we conducted a comprehensive examination of countries with adequate distributions of mangroves that were or are currently affected by forest fires. We then identified the key variables contributing to forest fires and used this information to construct a table on their effects on mangrove vegetation and their adjacent biological systems. The existing information was then categorised into positive and negative impacts and was subsequently synthesised and displayed in corresponding figures and flowcharts. This enabled us to recognise the implications of forest fires on mangrove ecological goods and services as well as emphasise neglected study domains and future research directions. The findings derived from our examination of the literature followed an existing framework (Figure 2), were consolidated into a textual compilation, and organised according to the main topics of interest outlined below.

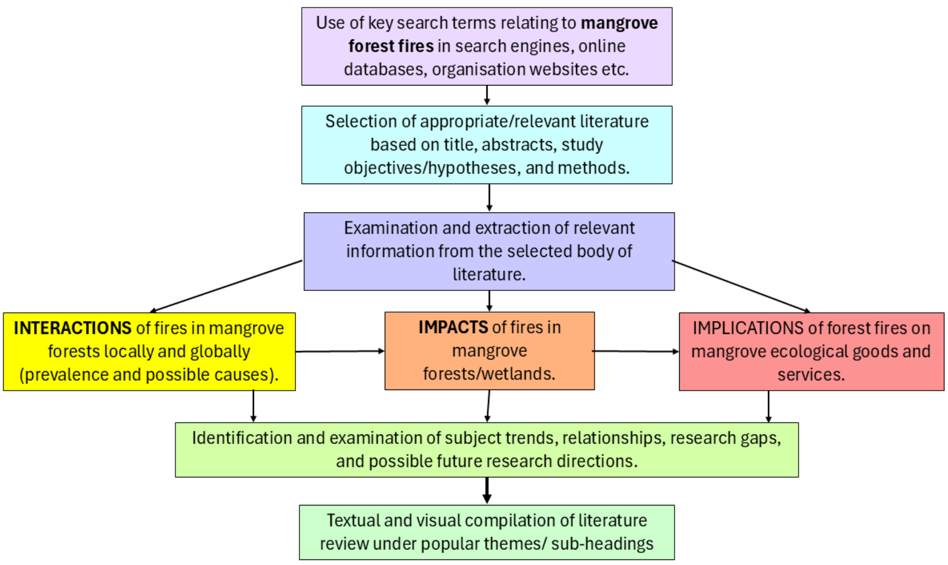

FIGURE 2: Framework showing the acquisition, selection, and presentation of articles compiled in our literature review.

Results and Discussion

The interactions and prevalence of mangrove forest fires

Fires are recognised as the most significant natural phenomenon that annually eliminates vast areas of plant and organic material while also impacting many ecosystems concurrently (Crowe 2020). Wetland ecosystems, with their considerable organic matter content, frequent and abundant rainfall, and limited natural drainage, have the ability to retain significant amounts of water in their soils. These factors contribute to an environment that is less susceptible to fires (Taufik et al. 2018). However, specialists often debate the fire vulnerability of mangroves, despite their classification as forested ecosystems, because of their naturally damp wetlands and habitats. Historically, the interactions of forest fires have been perceived to disrupt forest ecosystems, altering their physical features and impacting their native plants and animals (Enoh et al. 2021). There is currently substantial evidence indicating that as global warming persists, bushfires are becoming more prevalent and intense, especially in both local and global regions. Between 2001 and 2023, fires caused a cumulative loss of 138 Mha of tree cover worldwide, resulting in a 28% reduction in forest cover (Tyukavina et al. 2022). Fires significantly increased the loss of tree cover in 2023, resulting in a total loss of 11.9 Mha (42% of all tree cover loss) (Global Forest Watch 2024).

From 2019 to 2023, Global Forest Watch (GFW) datasets have predicted that the total forest cover (ha) was greatly reduced in countries with large forest distributions (including mangrove forests) such as the United States, Australia, Brazil, and Indonesia (Figure 3). Current wildfire datasets have also revealed that tree cover loss (inclusive of mangroves) in these countries was also positively linked to raging wildfires, which also increased during the five-year period (Figure 3) (Global Forest Watch 2024). In South Asia, 51% of forests were affected by fires in 15 years. Of the seven South Asian countries, Bangladesh has the highest emerging hotspot area (34.2%) in forests, followed by 32.2% in India and 29.5% in Nepal (Reddy et al. 2019). In the El Niño fires in Indonesia, the fires on dry organic matter spread quickly over a large area and caused megafires. Consequently, between 0.8 and 2.6 Gt of carbon were released into the atmosphere as a result of burning peat and mangrove vegetation (Page et al. 2002). This amount was equivalent to 13–40% of global carbon emissions (Darmawan et al. 2020). More than 24 fire events have occurred in the Sundarbans, the world's largest mangrove forest in Bangladesh, resulting in damage to 34.61 ha (0.005767% of the Sundarbans) of the forest (Mahmood et al. 2021).

The unprecedented Australian Black Summer bushfires led to the combustion of elevated peat swamps and coastal wetlands, impacting 183 ha of salt marshes and 23 ha of mangroves, covering 19 estuaries. The extent of fire-damaged salt marsh varied from 51%

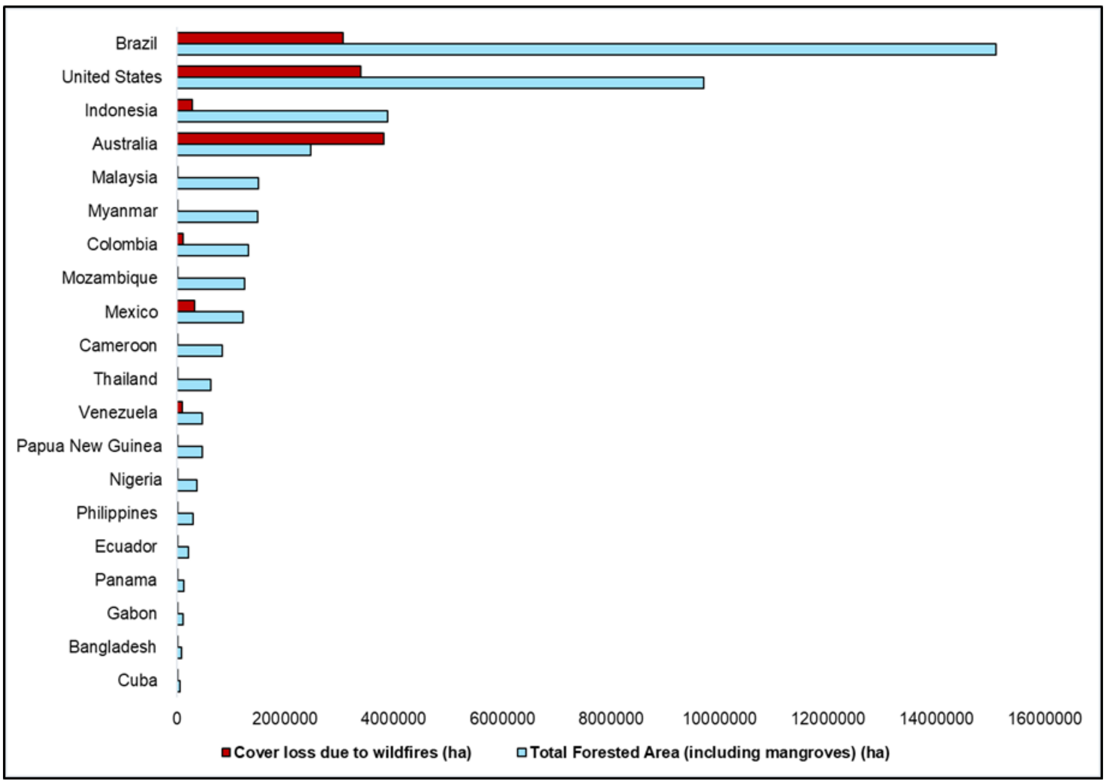

FIGURE 3: Total forest cover loss due to wildfires (ha) in countries with the largest forest distribution (including mangroves) during the period of 2019-2023(GFW 2024).

to 81% in the most severely affected estuaries (Ward et al. 2020). Approximately 50% of the mangroves in Wonboyn Lake were affected by fire, while in the other wetlands, approximately 5% of the mangroves were burned (Glasby et al. 2023). The global estimations for ongoing vegetation fires reveal that more than 70% of all such fire interactions take place in tropical regions. According to Matricardi et al. (2020), fire has been identified as a significant factor contributing to the destruction of forests in the Amazon. Between 2003 and 2020, Brazil accounted for an average of 73% of yearly active fire detections, with Bolivia and Peru following at 14.5% and 5.3%, respectively. Collectively, these three nations have consistently accounted for more than 87% of the total yearly active fire detections and interactions in the Amazon region. Between 2019 and 2020, Brazil experienced a 10% increase in burned area, while Venezuela reported a modest 2% increase. In contrast, Colombia, Guyana, Bolivia, and subsequently the entire Amazon region experienced significant increases of 63%, 51%, 36%, and 19%, respectively. The occurrence of wildfires in wetlands, excluding flooded woods, was shown to have the second-greatest mean percentage in Bolivia (34%) and Guyana (26.5%) (Silveira et al. 2022). In February and March 2024, Guyana experienced a forest fire that persisted for a week. This fire ravaged both natural and restored mangroves located along the Western Coast of Berbice, specifically in Bushlot, Bath and Woodley Park. The fire was caused by the prolonged dry season that overlapped with the El Niño period (Figure 4) (DPI Guyana, 2024; NAREI 2024).

Although the Caribbean region trails behind other locations in terms of fire forecast and monitoring, even a small increase in temperature and decrease in moisture could lead to more frequent fire interactions in sections of humid woods that have never been burned before. This was apparent in small island states like the Dominican Republic and Trinidad and Tobago (Al Tahir & Baban 2005; Robbins et al. 2008; LeBlanc et al. 2017). Furthermore, during dry periods common to West Africa, a 30% reduction in mangrove cover has been recorded over 25 years, primarily due to human activities, including bushfires (Padonou et al. 2021). The combustion of ground matter and dry litter (leaves, stems, buds, etc.) serves as fuel for the spontaneous ignition of flames originating from diverse sources. This phenomenon significantly contributes to the occurrence of flare-ups in many locations, ranging from Guinea to Nigeria (Lombard et al. 2023).

The causes of mangrove forest fires

Forest fires can result from various direct and indirect factors, which may be linked to both human activities and natural events occurring in or around mangrove forests. These fires can either happen sporadically in mangrove ecosystems or occur periodically (Figure 5).

Nevertheless, the significant impact of human activities on the mangrove environment might lead to the formation of new ecosystems that are more susceptible to fires due to changes in vegetation cover caused by timber harvesting, burning, and construction (Robbins et al. 2008). Ninety percent of all studies in this

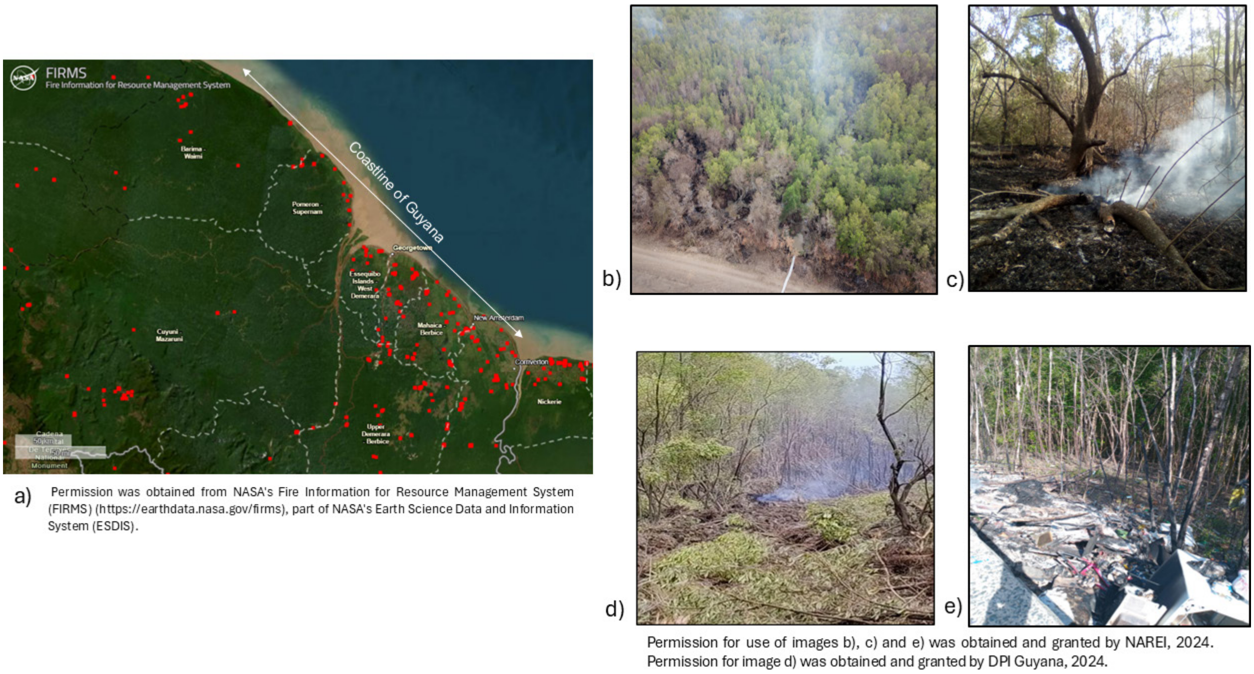

FIGURE 4: (Left) NASA FIRMS have detected increased active fire occurrences (red dots) along the coastal areas of Guyana which fosters the majority of mangrove forests within the entire country. (Right) Sections of the Bath mangrove forest (a and b) and Woodley Park mangrove forest (c) which was cleared due to raging wildfires which lasted one week along the coastline of Guyana, d) Section of the Better Hope mangrove forest which was deliberately lit by residents burning household garbage and shrimp waste dumped in the mangroves (Permission obtained for image use from DPI Guyana 2024 and NAREI 2024).

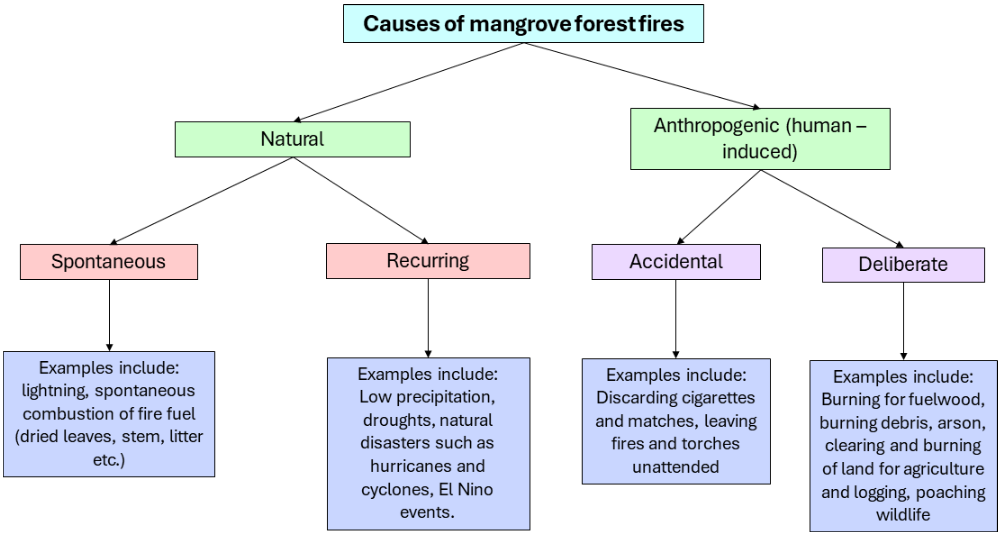

FIGURE 5: Possible causes of mangrove forest fires – synthesis of findings from our review.

review have emphasised the significant impact of human activities, whether through direct or indirect means, on the occurrence of forest fires. Wildfires become more severe and widespread during dry periods, which have shown a recurring pattern and positive relationship in many regions throughout the 21st century (Tian et al. 2021). Furthermore, in many parts of the globe, the overwhelming majority of ignition sources originate from the practice of using fire to regenerate deteriorated pasture vegetation and eliminate the surplus biomass following deforestation (Alencar et al. 2020). Furthermore, there is a growing likelihood of agricultural and deforestation fires spreading into nearby mangrove forests and resulting in uncontrollable wildfires (Silveira et al. 2022). Human activities, such as intentional 'slash and burn' farming on peatland and coastal areas, fishing, land conversion to infrastructure, and logging, are the primary causes of forest fires in extensive mangrove forests seen among heavily forested mangrove nations such as Indonesia (Darmawan et al. 2020).

Occasionally, mangrove forest fires in certain regions were the result of both unintentional and deliberate actions. In the Sundarbans, forest fires were caused by the negligent actions of woodcutters, indigenous fuelwood collectors, honey collectors, and fishermen. Cigarettes and torches used for honey harvesting were discarded on the desiccated woodland grounds. Intentional fires are deliberately set to clear areas for illegal cattle grazing, gather fuelwood, engage in fishing activities, and distract forest officials from illegal trade in wildlife and poaching activities (Mahmood et al. 2021). Studies have indicated that there is a connection between natural disasters, such as hurricanes and cyclones, and an increase in the occurrence of fires in hot tropical regions. Lightning-ignited fires are infrequent in dry tropical forests; however, the significance of lightning as a source of ignition in tropical forests has been emphasised in the literature (LeBlanc et al. 2017; Song et al. 2024). Additionally, factors such as slope factor, elevation, land cover, proximities to communities, and highways have had a significant impact on the occurrence of forest fires in mangroves (Jaiswal et al. 2002; Pandey & Ghosh 2018; Enoh et al. 2021). A summary of the primary factors contributing to mangrove forest fires in various countries is provided in Table 1.

The impacts of mangrove forest fires

The societal and scientific literature has widely recognised forest fires as a growing issue in recent decades, with an accepted notion that fires are becoming more frequent, and intense, causing greater damages (Figure 5). Fire can have both beneficial and detrimental impacts on the expansion of vegetation communities and species diversity in wetland systems, particularly mangroves (Osborne et al. 2013). Nevertheless, society commonly perceives fire as a natural hazard that primarily has adverse consequences (Doerr & Santín 2016). Research has indicated that forest fires have numerous implications for mangrove communities and their ecosystems. Furthermore, apart from the decline in biodiversity and destruction of natural habitats, these fires also have a significant influence on the quality of air, thereby impacting the well-being of local communities living near affected forests (Kala et al. 2023). Forest fires also result in substantial economic impacts, especially for the forestry, energy, and mining sectors. Additionally, there are expenses incurred by the devastation of infrastructure, such as roads and homes. In this review, we have evaluated both the negative and positive impacts of forest fires on mangroves, as synthesised in Figure 6.

Negative impacts

1. Changes to hydrology and soil biochemistry

Forest fires can impact several properties of soil and water, including mineralogical, physical, chemical, and biological characteristics. Forest fires (including those occurring in mangrove forests) have also been recognised as a possible source of organic pollutants in ecosystems (Wu et al. 2018). The impact of fire on soil and its characteristics is contingent upon various aspects, including the intensity of the fire and the variables that

TABLE 1: Factors contributing to forest fires in mangrove vegetative zones of various countries

Country	Causes of mangrove forest fires		Reference(s)
	Natural	***Anthropogenic***	
Indonesia	Increased hotspots due to decreased rainfall, El Niño driven haze over multiple areas.	Burned forest for plantation, land conversion, fishing, logging, utilised as weapons during regional land disputes between locals, migrant communities and companies, increased canalisation to drain excessive water into wetlands to make them suitable for agricultural practices.	Taufik et al. (2018) Thoha et al. (2018) Khan et al. (2020) Crowe (2020)
Bangladesh	Dry season, lack of rainfall, spontaneous combustion of litter and debris on forest floor.	Use of fire to remove honey from bee nests, unattended fires, illegal clearing for land and firewood.	Islam & Bhuiyan (2018) Mahmood et al. (2021)
Australia	Extremely dry periods due to high temperatures. Extreme fuel desiccation.	Exclusively due to extreme or high severity fires in adjacent terrestrial vegetation. Deliberate burning to manage species composition.	Collins et al. (2021) Glasby et al. (2023)
India	Low humidity, high temperatures, spontaneous combustion due to prevailing dry seasons.	Proximity and distance of forests from human activities and settlements. Careless disposal of matches and torches.	Jaiswal et al. (2002) Attri et al. (2020)
Brazil (Amazon)	El Niño events (weak to very strong).	Increased agriculture and shifting cultivation systems, deforestation, cattle ranching.	Cochrane & Laurance (2002) Juárez-Orozco et al. (2017)
Africa	Lightning strikes due to higher elevation in forested area, spontaneous combustion (due to dry weather) of leaves and dense vegetation.	Close proximity of humans, settlements, and roads to forests, oil spilling, bush burning due to the release of oil from oil spills, elimination of vegetation for easy use of herbicides, nomadic farming.	Otitoloju et al., (2006) Izah et al. (2017) Enoh et al. (2021)
United States	Lighting, spontaneous ignition of dry matter, spreading of fires from adjacent vegetation by the wind and dry matter accumulation.	Deliberate use of fire to reduce the cover of undesirable vegetation. Connectivity between roads and human settlements promoted larger incidences of human- induced fires.	Slocum et al. (2007) Smith et al. (2013) Nocentini et al., (2021)
Guyana	El Niño events, spontaneous combustion of dried leaves and litter.	Land clearing for agriculture (rice and shrimp), pest control (mosquitoes), burning household garbage and shrimp waste.	Hollowell (2005) DPI Guyana (2024)
Mexico	Lightning, spontaneous combustion of forest fire fuel under dry conditions as well as debris from hurricanes.	Adjacent burning from grasslands can spread into mangrove forests.	Trejo (2008)
Madagascar	Dry period events, El Niño.	Clearing land for agriculture, intentionally setting fire to forested land for cattle ranching rejuvenation, clearing of land and mangroves for charcoal and lime clay production.	Frappier-Brinton & Lehman (2022)

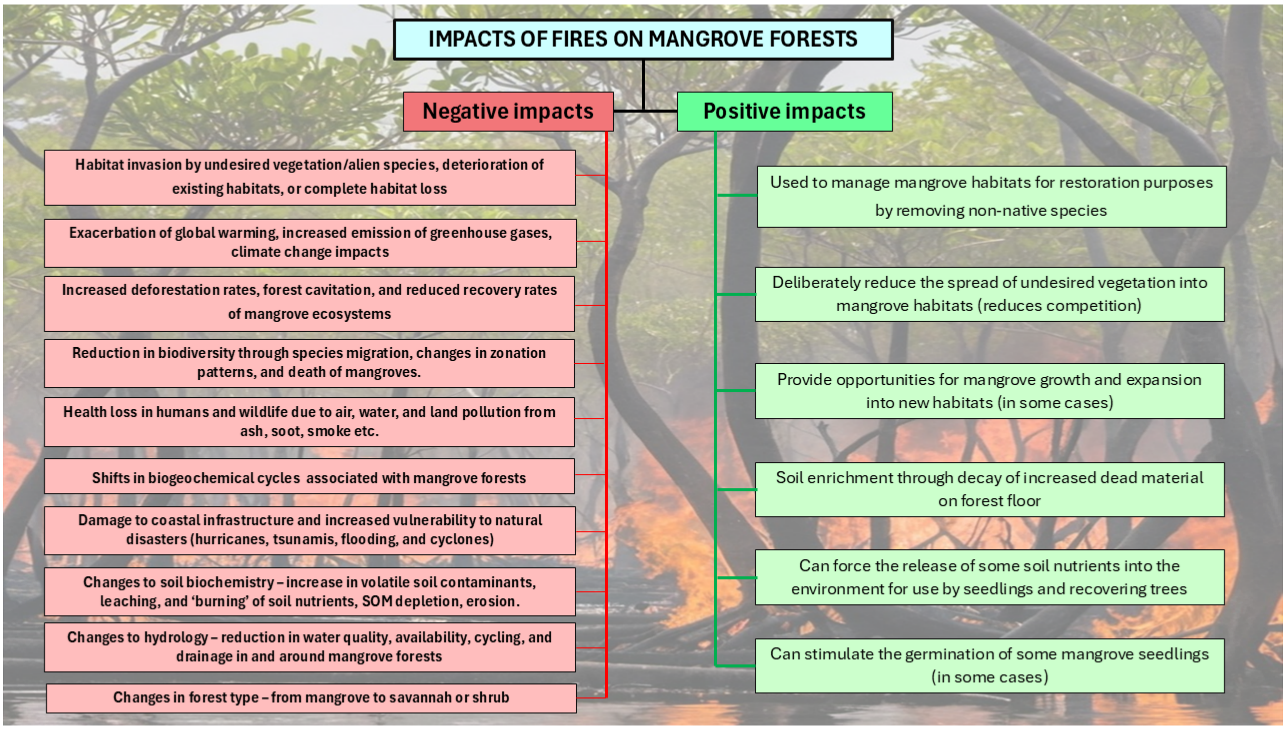

FIGURE 6: The negative and positive impacts of fires on mangrove forests – synthesis of findings from our review

affect the combustion process, such as the humidity, temperature, quantity and type of fuel, wind velocity, and the physical conditions of the region (Certini 2005). The first four secondary effects, which manifest in the short term immediately following a fire, largely influence the loss of sediments and nutrients in mangrove wetlands: soil erosion, depletion of soil organic matter (SOM), soil exposure to solar radiation, and increased availability of nutrients (Kotze 2013). Bushfires deplete vegetation, leading to enhanced soil erosion and increased mobilisation into streams, ultimately causing water to become cloudy. The increased silt load and reduced light in the water column has a significant impact on aquatic wildlife productivity. In a comparable way, elevated levels of metals can also have detrimental effects on marine organisms, leading to mortality due to toxicity or disrupting their ability to reproduce and grow at normal rates (Sydney Institute of Marine Science 2020). The emission of smoke and ash from fires elevates the concentrations of certain nutrients, such as nitrogen and phosphorus, in water bodies, thereby promoting the proliferation of phytoplankton and the formation of detrimental algal blooms (Wu et al. 2018). Intensified or recurrent hazard reduction burning could have adverse effects on coastal habitats, including heightened soil erosion and prolonged time frames for recovery (Symth 2020). In addition, the ash resulting from forest fires can either be washed away from the land, remain within the land, or act as a deposition site for ash produced in the wetland and ash that is carried into it from burned regions in the upstream catchment of the wetland (Ellery et al. 2009; Kotze 2013).

Studies have found that mangrove soils impacted by forest fires exhibit higher levels of chemical compounds such as total organic carbon (TOC) and polycyclic aromatic hydrocarbons (PAHs), which are known to be both carcinogenic and mutagenic to both people and animals, compared to unaffected areas (Sojinu et al. 2010). The presence of microcharcoal in the uppermost layers, a sign of nearby fires, suggests an association with hurricane-related forest disturbances (LeBlanc et al. 2017). Ground fires have a greater and more enduring effect on the accessibility of soil nutrients compared to surface fires. When the charred soil crumbles, a significant process by which this phenomenon takes place is the physical accumulation of non-volatile elements in mangrove soils, such as phosphorus and calcium (Smith et al. 2001). In addition to water pollution, forest fires also lead to elevated water temperatures in waterways. This is caused by the loss of canopy and riparian cover, which exposes rivers and streams to greater degrees of direct sunlight (Ice et al. 2004; Burton 2005). Rising temperatures can lead to a multitude of potential consequences. For example, when a species inhabits an area near the lower limit of its temperature tolerance, a rise in water temperature can enhance its productivity (Lamborn & Smith 2023). In addition, canalisation results in decreased groundwater levels during the dry season, which in turn leads to a heightened occurrence of high fire hazard levels. Draining natural wetland forests leads to an increase in the vulnerability to fire (Taufik et al. 2018). This provides evidence that alterations in the hydrology of mangrove ecosystems by processes such as canalisation can result in an extended duration of high fire risks as well as a significantly increased number of seasons with fires.

2. Habitat loss and degradation

Deforestation, the loss of mangrove habitats, and the degradation caused by forest fires have adverse effects on both soil and water quality, as well as contributing to climate change. Deforestation can lead to several issues such as soil erosion, depletion of nutrients, and decreased productivity in agriculture, due to the crucial role of trees in regulating water cycles and preventing erosion (Khan et al. 2021). Fire-affected mangrove forests have lower tree densities, are more exposed, experience more extreme temperatures, and contain more non-forest plants, leading to a decrease in biodiversity compared to unburned areas. Over time, monitoring ecological factors in unburned forests revealed that ecosystems were highly sensitive to repeated, intense fires in the surrounding areas (Harrison et al. 2024). Wildfires cause extensive habitat destruction, which has far-reaching consequences and intensifies global warming, as trees (especially mangroves) are essential for the removal of atmospheric carbon. Deforestation is a significant contributor to greenhouse gas emissions as it releases stored carbon into the atmosphere (Kundu et al. 2022). Research has indicated that the extent of forests (including mangroves) in the Sundarbans has had a notable decline of 3531.16 km^2 in 2004 to 3065.80 km^2 in 2022, with an annual reduction rate of 2.66% as a result of fires (Saoum & Sarkar 2024). In conditions similar to the Sundarbans, if there are high emissions, increased temperatures, decreased precipitation, and more fires in South American mangrove forests in the future, there could be a significant loss of canopy coverage, vegetation carbon, and productivity, leading to drier forests (Burton et al. 2017).

Research has also demonstrated that in certain mangrove environments, occurrences of natural fires are rare and the plant life is not well-adapted to withstand the effects of fire (Malhi et al. 2008). As a result, the forest has a diminished capacity to recover from disturbances and is susceptible to any changes in the pattern of fires. Possible consequences may involve the complete transformation of the mangrove forest into a seasonal forest or a savannah-like ecosystem (Lovejoy & Nobre 2018). Significant fires can sometimes hinder the regrowth of trees following natural disasters such as hurricanes (Urquhart 2009). Alternatively, in certain instances, fires have caused extensive harm to the forests, resulting in a substantial accumulation of dead, combustible wood. This, in turn, greatly heightens the likelihood of recurring fire disasters (Siegert et al. 2001). Fires can lead to habitat destruction, which in turn can provide favourable conditions for the proliferation of exotic plants, particularly grass species. These species can also cause significant harm to the structure and composition of forests where fires are naturally rare as well as forests that depend on fire but have had their fire regime changed to include more intense and/or frequent fires than the local vegetation is adapted to (in some cases restored mangrove forests) (Robbins et al. 2008).

3. Changes in species zonation, composition, density, and migration patterns

Fire can have a substantial impact on the dynamics of species in mangrove wetlands by altering or preserving vegetation communities and, consequently, their habitat. Fire can also cause abrupt changes in habitat, which can either benefit or harm organisms (Brennan et al. 2005; McWilliams et al. 2007). Mangroves depend on pneumatophores, often known as breathing roots, to obtain oxygen from the atmosphere and thrive in muddy coastlines. In addition to increased sedimentation, algal blooms, and seagrass wrack, which can all worsen following bushfires in the catchment, higher sea levels and coastal development pose the biggest threat to mangroves (OzCoast 2016). Even at the microbial level, fire significantly impacts wetlands' chemistry and biotic ecosystems. This element of fire ecology has not been extensively researched, yet it is extremely important since biogeochemical processes control the cycling of nutrients, productivity, and greenhouse gas emissions in these structures. The impact of fire on biogeochemical processes in wetlands is often unpredictable (Osborne et al. 2013). The destruction of forests poses a significant threat to numerous plant and animal species found within mangroves, potentially leading to their extinction. This not only adversely affects the survivability of those reliant on trees but also poses a threat to global food security and the quality of water (Saoum & Sarkar 2024).

Studies have demonstrated that the nutrients, sediments, debris, ash, and metals discharged by mangrove fires when carried into water bodies, can disrupt the feeding and reproductive habitats of aquatic animals, obstruct the gills of fish, and impair the respiration of filter-feeding organisms like mussels (Cheng 2021). During periods of inundation, the polluted sediment mass might gradually flow from within the forest towards the coast, causing harm to aquatic organisms in its path. Metals like mercury, lead, copper, and zinc, together with other pollutants discharged by wildfires, have the potential to alter the physiology and behaviours of marine organisms and gradually accumulate in the food chain (Symth 2020). The majority of wildfires exhibit a low to moderate intensity and hence have minimal repercussions on fish and fisheries. Nevertheless, there is an increasing occurrence of severe fires, which might have significant impacts on stream fish (Burton 2005; Lamborn & Smith 2023).

Generally, fire frequently triggers significant alterations in vegetation, typically through its interaction with other disturbances. Fire frequently interacts with the presence of extremely dry periods, creating conditions suitable for ground fires to occur (Loudermilk et al. 2022). Ground fires cause the destruction of vegetation and seed banks, leading to a physical and biological "opening" in the landscape. This, along with alterations in the hydrological and biogeochemical cycles, can cause significant changes in vegetation structure, even in moist mangrove forests (Kotze 2013). Nevertheless, many tropical forests exhibit signs of crucial biological thresholds and positive feedback mechanisms, in which drought, land-use changes, and fire may trigger a selfreinforcing shift towards vegetation with low biomass that is fire adapted (Brando et al. 2014).

4. Shifts in biogeochemical cycles in the face of climate change

The contribution of mangroves to both the adaptation and mitigation of climate change is widely considered to be one of the most significant among forests worldwide, especially in tropical regions. Additionally, they can offer safe and durable nutrient storage systems (nutrients, metals, carbon etc.) that are considerably resistant to fires. Therefore, it is crucial to prioritise their preservation (Crowe 2020). Climate change has partially contributed to the increased frequency and intensity of forest fires in recent years (Williams et al. 2019). According to Turco et al. (2018), forest fires can become more likely to change their patterns due to climate variability, droughts, heat waves, and local climate patterns. Mangrove wetlands are particularly vulnerable to hydrologic changes brought on by climate change, which is predicted to affect fuel conditions and therefore fire frequency through changes in rainfall, temperature, and salinity (Osborne et al. 2013). Deforestation disrupts local weather patterns, resulting in reduced evapotranspiration and elevated surface temperatures (Saoum & Sarkar 2024). Researchers have observed that climate change may result in heightened fire weather conditions and an elevation in the Forest Fire Danger Index, which is determined by factors such as relative humidity, wind speed, air temperature, and drought. Consequently, this could amplify the likelihood of "severe water quality events" even in mangrove forests (Symth 2020). Fire can impact the water cycle by changing the amount of water removed from the atmosphere through evapotranspiration and the amount of water that penetrates the soil through infiltration, due to shifts in hydraulic characteristics. Burning in dispersive soils can also contribute to the formation of soil crusts (Mills & Fey 2004). These consequences, in turn, lead to a decrease in the amount of water that can permeate into the ground, which is likely to cause more surface runoff during storms and a decrease in the sustained supply of groundwater into and out of wetlands.

Within certain forested zones, a confluence of natural occurrences and human-driven influences leads to alterations in the regular patterns of nature, resulting in the creation of circumstances that are conducive to heightened occurrences of fires in wetlands. For example, Indonesia has a humid environment with significant levels of precipitation, particularly during monsoonal seasons, which makes it inherently resistant to burning. Extensive and significant deforestation in Indonesia has resulted in the drying up or excavation of substantial portions of the country's wetlands, which has exposed flammable materials (Crowe 2020). El Niño causes a decrease in rainfall, resulting in reduced groundwater levels in wetland ecosystems. This leads to a drier climate, which promotes the occurrence of more frequent and widespread forest fires (Taufik et al. 2018). Similarly, it is expected that the South American region will experience an increase in burned areas and fire emissions in the future as a result of hotter and drier circumstances (Fonseca et al. 2019). This will lead to significant reductions in carbon storage, particularly when combined with the ongoing increase in land-use alteration. Combining climate and land use change scenarios, it is projected that fire danger in Amazonia might increase by 21% to 113% by the end of the century (Burton et al. 2021).

According to Jaafar and Loh (2014), the haze caused by bushfires has the potential to reduce sunlight and disrupt the process of photosynthesis in marine ecosystems, such as coral reefs, seagrasses, and mangroves. This consequently impacts the carbon cycle to a certain degree in these environments. Despite covering just 0.5% of the world's coastal area, mangroves play a significant role in carbon storage, accounting for 10-15% (24 Tg C y^{-1}) of coastal sediment carbon storage and exporting 10–11% of terrestrial carbon into the ocean (Alongi 2014). Carbon deposition in the atmosphere can have a notable impact in regions with frequent fires, particularly in mangrove forests located in Indonesia, Australia, and Bangladesh (Sundarbans). These areas see high concentrations of black carbon (BC) from smoke and dust during certain seasons (Jurado et al. 2008).

Smoke particles can exacerbate drought conditions. In a study conducted by Liu (2005), it was discovered that smoke particles emitted from bushfires had the ability to absorb solar radiation, resulting in a decrease in rainfall and an intensification of dry conditions. The combustion of mangrove vegetation releases various gases such as carbon monoxide (CO), carbon dioxide (CO_2), hydrogen gas (H_2), methane (CH_4), nitric oxide (NO), chloromethane (CH_3Cl), carbonyl sulphide (COS), hydrogen cyanide (HCN), and particulate carbon. These gases have an impact on the atmospheric cycles and the Earth's radiation balance. Additionally, fires are a major contributor to greenhouse gas emissions on a global scale (Archibald et al. 2009). When vegetation burns, it releases the carbon that has been retained within it. This is the primary cause of the atmospheric CO_2 emissions from massive forest fires, which greatly accelerate the rate of climate change (Singh 2022).

Moreover, ground fires, specifically, are distinguished by slow-burning combustion, resulting in significant releases of carbon monoxide, volatile organic compounds, and polyaromatic hydrocarbons, which can have severe implications for human well-being (Blake et al. 2009). Black carbon (BC) significantly impacts the carbon budget and plays an essential part in the global carbon sink (Guo et al. 2018). BC is expected to play a crucial role in the coastal carbon pool due to its external origin and resistance to decomposition (Taillardat et al. 2018). This can have a significant impact on carbon storage in mangrove sediments, influencing the distribution and sequestration of carbon stocks in mangroves. This consequently affects the overall global blue carbon budget (Zhang et al. 2022). BC exhibits substantial deposition in sediments with varying sizes of particles, particularly in the size fractions following coastal forest fires (including mangroves). This BC originates from a combination of biomass and mineral combustion (Wang et al. 2022).

5. Damage to defence structures and increased vulnerability to coastal disasters

Mangroves in numerous tropical and subtropical areas mitigate the impact of storm surges and wave actions, acting as a primary barrier against flooding, coastline erosion, waves, and tidal bores (Thampanya et al. 2006). These benefits are derived from factors such as bottom friction, the width of forests in relation to the shoreline, and the density and shape of trees (Barbier et al. 2011). Mangrove forests utilise aerial roots to hold sediments, thereby anchoring intertidal soil and mitigating erosion. The presence of canopies, trunks, and roots helps to disperse storm surges and waves (Spalding et al. 2013). However, the upsurge in forest fires in these ecosystems leads to the destruction of habitats, which in turn heightens the vulnerability of coastal areas, especially in developed regions with a high concentration of coastal inhabitants (Menéndez et al. 2020).

The primary benefit of mangrove ecosystems is their ability to safeguard coastal areas from calamities such as tsunamis and hurricanes. This helps to reduce the detrimental impact on both human life and property (Osti et al. 2009). The factors that determine the level of protection provided by mangroves against natural disasters include the width of the forest, the slope of the forest floor, the density and diameter of the trees, the proportion of root biomass, the height of the trees, the texture of the soil, the location of the forest (open coast, lagoon, or inland) (Unnikrishnan et al. 2012), the type of vegetation and cover in the surrounding lowland area, the presence of foreshore habitats such as seagrass meadows, dunes, and coral reefs, the magnitude and velocity of tsunamis or hurricanes, and the distance from tectonic events (Gholami 2016).

Mangrove wetlands, such as those found in South Africa, provide more effective mitigation against the threat of fires and droughts due to the consistent availability of moisture (Belle et al. 2018). Wildfires heighten the likelihood of both flash floods and flows of debris in the wetland. Furthermore, we must emphasise that the hydrological response to a fire does not consistently diminish smoothly and linearly over time. Several studies conducted after fires have observed that even low-intensity rainfall events can lead to a small first runoff response immediately after the wildfire (Li et al. 2020). Severely burned watersheds have a higher likelihood of experiencing postfire flooding and debris flows (Brogan et al. 2019). Considering that a fire could increase the chances of a severe flooding occurrence, operational culverts or other structures may become inaccessible during postfire flooding. The simultaneous occurrence of postfire water and debris can result in erosion, obstruction, impairment, and ultimately modification of a structure to such an extent that wildlife movement becomes exceedingly challenging or unattainable (Lamhorn & Smith 2023).

(b) **Positive impacts**

Although the detrimental impacts of forest fires are greater than their positive impacts on the environment, we have identified a few cases where forest fires have gradually brought about favourable changes in mangrove ecosystems. Forest fires have been employed for habitat management in both upland, inland, and wetland populations (Boughton et al. 2006). Fire often promotes regrowth by creating openings in the upper layer of vegetation, enhancing the availability of nutrients to plants, and clearing away debris. However, it normally has a minimal impact on the survival of seeds, although it may encourage their germination (Kotze 2013). Heating wetland soils directly can enhance the accessibility of some soil nutrients, particularly phosphorus (P) (Giardina et al. 2000). The rise in greenhouse gases can potentially mitigate the vulnerability of certain species (including mangroves) to future droughts and accelerate their recovery after disturbances by enhancing photosynthesis, carbon absorption, and water usage efficiency (Castanho et al. 2016). In addition, the act of removing litter through fire resulted in a substantial increase in both the diversity of plant species and the temperature of the soil, which improves nutrient availability and plant reabsorption rates (Heim et al. 2021).

Forest fires vs. non-native plants in mangrove forests

A noteworthy relationship has been established between fires and the distribution of invasive/alien plant species in mangrove forests. Fires can either facilitate the proliferation of non-native species occurring due to human influence or eliminate them through intentional rehabilitation measures for forest restoration. Uncontrolled wildfires can largely facilitate the advancement of alien and invasive grasses in and around mangrove forests (Robbins et al. 2008). These invasions can have long-term impacts on forests by modifying fuel qualities, which can affect fire behaviour and, eventually, alter fire regime frequency, severity, extent, type, and seasonality. If the regime shifts encourage the dominance of non-native plant species resulting in the establishment of an invasive plant-fire regime cycle (Brooks et al. 2004) (Figure 7).

Moreover, modified fire regimes may adversely impact native plant and animal species on a long-term basis. The cycle of invasive plants and fire regimes may increase the availability of fuels or speed up the recovery of fuels after a fire, which could lead to more or stronger fires (Underwood et al. 2019). On the other hand, it may decrease fuels in a way that prevents fires from spreading in places where it is beneficial. This type of disturbance regime can be considered a significant factor influencing species adaptation and evolution. The alteration of fire regime characteristics outside their adaptive range may shift plant communities towards new dominant species (Brooks 2008). This modification in vegetation may impact higher trophic levels in mangrove ecosystems.

Our review also highlights a few cases where fires were occasionally employed as a tactic in wetlands to deliberately diminish the presence of unwanted vegetation, particularly shrubs and trees. Despite long-term negative impacts in some cases, the consequences of forest fires in mangrove ecotones have presented

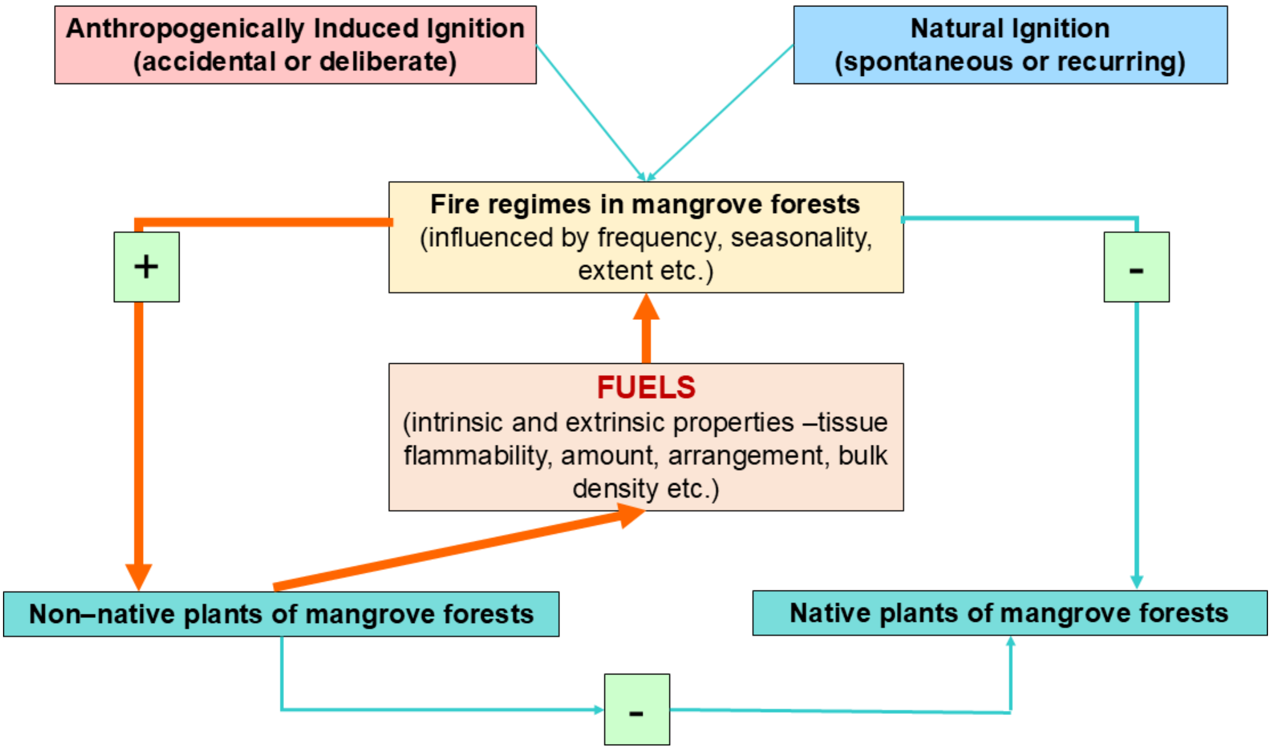

FIGURE 7: The invasive plant/fire regime cycle: positive (+) and negative (-) interactions in mangrove forests (Modified from Brooks 2008).

prospects for the re-establishment and expansion of native plant species in mangroves (Williams-Jara et al. 2022). Periodic fires in ecosystems provide benefits by eliminating accumulated dead organic matter, hence promoting the survival, reproduction, and expansion of certain plant and animal populations (Brown 2022). For example, this practice was employed over 50 years ago in Mexico, where the Ursulo Galván project used deliberate fire channels to restore mangrove forests and native vegetation that were destroyed by uncontrolled fires (Cedeño 2000). Smith et al. (2013) also emphasised that the Everglades of Florida experienced significant migration of the mangrove ecotone, particularly in areas with the highest frequency of fires. Additionally, Kautz et al. (2011) have shown that forest gaps resulting from lightning strikes supply dead matter that enhances soil fertility and facilitates the natural reemergence of native mangrove vegetation. As such, specific flora and fauna within such ecosystems have developed a reliance on regular wildfires to maintain ecological equilibrium (Shivanna 2022).

Implications of forest fires on mangrove ecological goods and services

Fire is widely acknowledged as a significant factor that has a large impact on the environment and affects numerous ecosystem services (Sil et al. 2019). Wildfires are frequently recognised as a significant disruption that has a detrimental effect on the resources and benefits offered by many land-based ecosystems, such as mangrove forests and other wetlands (Thom & Seidl 2016). When considering the overall value of nature to a country's economic welfare, society often underestimates and disregards the economic significance of mangroves (Queiroz et al. 2017). The primary value of mangrove ecosystems lies not in their ability to generate revenue but in the importance of their contribution to communities through their regulating environmental services. This value becomes apparent when society incurs the expenses associated with the absence of the goods and services previously provided by the mangroves, which were freely available to society at large (Moonsammy[1]). The livelihoods of many coastal residents rely heavily on the resources and productivity of mangrove forests. Mangrove forests play a crucial role in the local economy as they offer valuable timber, medicinal herbs, and various other natural assets (Atkinson et al. 2016).

Undoubtedly, the efficiency of these ecosystems is demonstrated by the valuable outputs they provide, including fisheries, lumber and its byproducts, fresh and oxygenated water, clean air, and coastline defence (Ribeiro et al. 2019). Mangroves play a significant role in reducing poverty, ensuring food security, empowering rural women, regulating climate, and adapting to climate change through ecosystem-based approaches (Sinsin et al. 2023). The forests support a diverse range of commercially valuable fish and shellfish species, which

[1] Moonsammy, S. (2020). *Rapid economic assessment of mangrove ecosystems in Guyana.* Unpublished Technical Report. Trowbridge, United Kingdom: Landell Mills International.

in turn support local fishing enterprises and ensure food security for millions of people worldwide (Rahman et al. 2013). Despite this, the effects on fisheries resulting from water pollution produced by forest fires may bear similarities to those generated by catchment clearing, draining, and coastal development. This provides a forecast of the possible damage to culturally and economically significant fisheries and ecosystem services caused by bushfires. These fires pose a threat to the future of recreational and commercial fishing, as well as related tourism and aquaculture industries (Symth 2020).

The cost of building the infrastructure to replace one kilometre of lost mangroves along the coast and associated coastal protection services is estimated to be US$ 10.9 million (Moonsammy[1]). The annual economic worth of the ecosystem services provided by one hectare of mangroves is estimated to be US$193,845. On the other hand, it has been estimated that changes in land use worldwide have cost between $4.3 and $20.2 trillion annually in lost ecosystem services (Costanza et al. 2011; 2014). The loss of services provided by mangroves in many countries reflects the economic impact of forest fires. For example, forest fires in Southeast Asia impacted almost 35 million people. Smog pollution incurred a financial burden of around USD 674–799 million and is linked to carbon emission losses equating to nearly USD 2.8 billion (Darmawan et al. 2020).

Moreover, East Gippsland and the southern coast of New South Wales in Australia are popular tourist locations among numerous Australians. However, the increasing frequency of wildfires (including those on wetlands) has led to mandatory evacuations and the cancellation of vacations, resulting in substantial financial losses to Australia's tourism sector. Estimates suggest that these losses might range from hundreds of millions of dollars to over $4 billion, taking into account the absence of foreign tourists (Butler & Wahlquist 2020). The recent forest fires in Guyana's coastal mangrove forests resulted in a financial loss of USD 28,700 due to damages to infrastructure and coastal defences (DPI Guyana 2024). Mangroves are now recognised as ecosystems with a high carbon content that should be conserved and restored (Siikamaki et al. 2012). They are ecologically and economically valuable, with the ability to regulate climate by capturing and preserving large amounts of carbon. This helps offset the human-generated releases of CO_2 (Alongi 2014). In addition to having negative effects on greenhouse gas emissions and global warming, fire damage to these habitats would also lessen their capacity to store blue carbon (Symth 2020).

Research gaps and future research directions

In many regions, fire poses severe disturbances, but we have yet to fully assess and evaluate its long-term consequences on mangrove ecosystem services. Fire management in mangrove forests necessitates an awareness of the ecological consequences of fires and the ecosystem's ability to recover. Mangrove forests must be maintained in the surrounding environment in order to continue providing products and services. One endeavour to safeguard mangrove ecosystems is through conducting studies focused on identifying changes in mangrove forest health in the aftermath of fire. This initiative can serve as the foundation for sustainable mangrove forest management. While fire avoidance is critical, long-term, context-specific forest restoration is required to address the negative effects of fire.

Monitoring and evaluating decreases in mangrove vegetation health is critical for implementing effective preservation, restoration, and management methods. Understanding these changes in plant and seedling health can help to improve land use strategy, ecosystem restoration, and efficient resource utilisation in many places around the world, reducing degradation and promoting vegetative sustenance and resilience. Furthermore, the future of land use is required to complement planning and regulations. Research can address this element by promoting land cover change modelling as a tool for analysing the long-term causes and implications of land cover change resulting from fire. Most studies we have examined focused on short-term impacts and were rarely structured to identify the positive benefits of fire on ecosystem services, despite the fact that fire is essential for the survival of wildfire-adapted ecosystems.

Research conducted over the previous three decades does not reveal any discernible patterns in terms of direct fatalities caused by fire and the associated economic losses linked to mangrove forests. We have not adequately quantified the indirect effects, such as health issues caused by smoke or disturbances to social functioning, for examination. Global forecasts of heightened fire activity due to climate change further underscore the urgency of coexisting with fire. Therefore, we propose that future research should focus on diminishing misconceptions and promoting a better comprehension of the actualities of global forest fires.

Preserving mangrove forests is critical not only for environmental reasons but also for benefits to society and the economy. It is critical to educate people about the value of these dynamic forests and integrate them into conservation efforts. By conducting comprehensive research, we can fully recognise their significance and implement proactive measures to conserve and restore them. We strongly advocate for further investigations into the crucial factors necessary for the effective recovery of mangrove forests after fire events, given the current situation and limited study findings. Immediate implementation of projects and research is necessary to facilitate the widespread dissemination of knowledge and improve agricultural and silvicultural management practices in forested ecosystems and communities. This will enable a transition away from irresponsible and destructive use of fire. Therefore, additional research must be undertaken and supported by rigorous land use rules and environmental legislation to enhance the effectiveness of efforts to combat illicit fire usage in agriculture, deforestation, and land mining.

Conclusions

Forest fires, while understudied, are prevalent in mangrove forests in many countries. While many factors contribute to increased forest fires in these ecosystems, our review highlights many natural and human-induced causes, particularly climate change as a result of El Niño, which was aggravated by accidental or deliberate human actions aimed at forest clearing for agriculture, silviculture, mining, and fisheries. These actions, combined with natural phenomena, have led to many negative effects on mangrove-forested areas, such as damage to coastal defence structures, habitat loss and degradation, loss and migration of species and vegetative cover, disruption of biogeochemical cycles, and reductions in water quality and soil biochemistry. Contrary to popular belief, forest fires also have positive impacts on mangrove ecosystems, such as soil enrichment and nutrient release, habitat management, and providing opportunities for mangal growth and expansion. Our review also indicates a notable relationship between fires and the distribution of invasive species in mangrove forests, either by facilitating the proliferation of these species when occurring due to human influence, or by eliminating them through intentional measures for forest restoration. Forest fires have detrimental implications for the goods and services provided by mangrove ecosystems, leading to a loss of revenue and severe economic impacts on both society and the environment. These impacts include tourism loss, pollution, soil and water degradation, and habitat and wildlife destruction. This ultimately reduces the ability of mangroves to function as blue-carbon ecosystems and maintain their ecological integrity in the fight against climate change. Based on our findings, we have identified several research gaps and recommend conducting future research in areas that focus on both short- and long-term effects of fires on mangrove health, the direct factors contributing to increased forest fire regimes, enhancing education and awareness on the use of illegal fire activities in mangrove communities, and implementing sustainable mangrove forestry management with focal points on the preservation and restoration of mangrove forests affected by fires.

Abbreviations

BC – Black Carbon
CH_3Cl – Chloromethane
CH_4 – Methane
CO – Carbon monoxide
CO_2 – Carbon dioxide
COS – Carbonyl sulphide
H_2 – Hydrogen (gas)
HCN – Hydrogen cyanide
NO – Nitric oxide
P – Phosphorus
PAH - Polycyclic Aromatic Hydrocarbons
SOM – Soil Organic Matter
TOC – Total Organic Carbon

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

All authors contributed to the study's conception, direction, and completion. All authors reviewed and approved the final version of the manuscript.

Acknowledgements

We thank the staff of the University of Guyana (Faculty of Natural Sciences -Department of Biology) for their guidance and provision of resources to complete this review article and the Department of Public Information (DPI) and the National Agricultural Research and Extension Institute (NAREI) mangrove department for the use of their photos on the recent mangrove forest fires in Guyana. We acknowledge the use of imagery from NASA's Fire Information for Resource Management System (FIRMS), part of NASA's Earth Science Data and Information System (ESDIS). We would like to express our gratitude to the editor and reviewers of the New Zealand Journal of Forestry Science for their valuable time and insightful comments, which significantly improved the quality of our review article for publication.

References

Al Tahir, R., & Baban, S.M.J. (2005). An evaluation of recent changes in mangrove forest habitats in Trinidad, West Indies. *Tropical Biodiversity*, *8*(3), 187-198.

Alongi, D.M. (2014). Carbon cycling and storage in mangrove forests. *Annual Review of Marine Science*, *6*(1), 195-219. https://doi.org/10.1146/annurev-marine-010213-135020

Archibald, S., Roy, D.P., Van Wilgen, B.W., & Scholes, R.J. (2009). What limits fire? An examination of drivers of burnt area in Southern Africa. *Global Change Biology*, *15*(3), 613-630. https://doi.org/10.1111/j.1365-2486.2008.01754.x

Arias, P.A., Rivera, J.A., Sörensson, A.A., Zachariah, M., Barnes, C., Philip, S., Kew, S., Vautard, R., Koren, G., Pinto, I., Vahlberg, M., Singh, R., Raju, E., Li, S., Yang, W., Vecchi, G.A., & Otto, F.E.L. (2023). Interplay between climate change and climate variability: the 2022 drought in Central South America. *Climatic Change*, *177*(1): 6. https://doi.org/10.1007/s10584-023-03664-4

Atkinson, S.C., Jupiter, S.D., Adams, V.M., Ingram, J.C., Narayan, S., Klein, C.J., & Possingham, H.P. (2016). Prioritising mangrove ecosystem services results in spatially variable management priorities. *PLOS ONE*, *11*(3): e0151992. https://doi.org/10.1371/journal.pone.0151992

Attri, V., Dhiman, R., & Sarvade, S. (2020). A review on status, implications and recent trends of forest fire management. *Archives of Agriculture and Environmental Science*, *5*(4), 592-602. https://doi.org/10.26832/24566632.2020.0504024

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., & Silliman, B.R. (2011). The value of estuarine and coastal ecosystem services. *Ecological Monographs*, *81*(2), 169-193. https://doi.org/10.1890/10-1510.1

Belle, J.A., Collins, N., & Jordaan, A. (2018). Managing wetlands for disaster risk reduction: A case study of the eastern Free State, South Africa. *Jàmbá: Journal of Disaster Risk Studies*, *10*(1). https://doi.org/10.4102/jamba.v10i1.400

Blake, D., Hinwood, A.L., & Horwitz, P. (2009). Peat fires and air quality: Volatile organic compounds and particulates. *Chemosphere*, *76*(3), 419-423. https://doi.org/10.1016/j.chemosphere.2009.03.047

Boughton, E.A., Quintana-Ascencio, A.F., Menges, E.S., & Boughton, R.K. (2006). Association of ecotones with relative elevation and fire in an upland Florida landscape. *Journal of Vegetation Science*, *17*(3), 361-368. https://doi.org/10.1111/j.1654-1103.2006.tb02456.x

Bourgeois, C., Alfaro, A.C., Leopold, A., Rémi Andréoli, Bisson, E., Desnues, A., Duprey, J.L., & Marchland, C. (2019). Sedimentary and elemental dynamics as a function of the elevation profile in a semi-arid mangrove toposequence. *Catena*, *173*, 289-301. https://doi.org/10.1016/j.catena.2018.10.025

Brando, P.M., Balch, J.K., Nepstad, D.C., Morton, D.C., Putz, F.E., Coe, M.T., Silvério, D., Macedo, M.N., Davidson, E.A., Nóbrega, C.C., Alencar, A., & Soares-Filho, B.S. (2014). Abrupt increases in Amazonian tree mortality due to drought-fire interactions. *Proceedings of the National Academy of Sciences*, *111*(17), 6347-6352. https://doi.org/10.1073/pnas.1305499111

Brennan, E.K., Smith, L.M., Haukos, D.A., & LaGrange, T.G. (2005). Short-term response of wetland birds to prescribed burning in Rainwater Basin wetlands. *Wetlands*, *25*(3), 667-674. https://doi.org/10.1672/0277-5212(2005)025[0667:SROWBT]2.0.CO;2

Brogan, D.S., MacDonald, L.H., Nelson, P.S., & Morgan, J.R. (2019). Geomorphic complexity and sensitivity in channels to fire and floods in mountain catchments. *Geomorphology*, *337*(337), 53-68. https://doi.org/10.1016/j.geomorph.2019.03.031

Brooks, M.L., D'Antonio, C.M., Richardson, D.M., Grace, J.B., Keeley, J.E., DiTomaso, J.M., Hobbs, R.J., Pellant, M., & Pyke, D. (2004). Effects of Invasive Alien Plants on Fire Regimes. *BioScience*, 54(7), 677. https://doi.org/10.1641/0006-3568(2004)054[0677:EOIAPO]2.0.CO;2

Brooks, M.L. (2008). Chapter 3: Plant invasions and fire regimes. In: Zouhar, K.; Smith, J.K.; Sutherland, S., Brooks, M.L. *Wildland fire in ecosystems: fire and nonnative invasive plants.* USDA Forest Service General Technical Report. RMRS-GTR-42-Vol. 6. Ogden, UT, USA: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. p. 33-46.

Brown, S. (2022, July 22). Brazil's new deforestation data board sparks fear of censorship of forest loss, fires. Mongabay Environmental News. https://news.mongabay.com/2022/07/bolsonaros-new-deforestation-data-board-sparks-fear-of-censorship-of-forest-loss-fires/

Bunting, P., Rosenqvist, A., Hilarides, L., Lucas, R.M., Thomas, N., Tadono, T., Worthington TA, Spalding M, Murray NJ, Rebelo L-M. (2022). Global mangrove extent change 1996-2020: Global Mangrove Watch Version 3.0. *Remote Sensing, 14*(15): 3657. https://doi.org/10.3390/rs14153657

Burton, C., Kelley, D.I., Jones, C.D., Betts, R.A., Cardoso, M., & Anderson, L. (2021). South American fires and their impacts on ecosystems increase with continued emissions. *Climate Resilience and Sustainability*, *1*(1): e8. https://doi.org/10.1002/cli2.8

Burton, T.A. (2005). Fish and stream habitat risks from uncharacteristic wildfire: Observations from 17 years of fire-related disturbances on the Boise National Forest, Idaho. *Forest Ecology and Management*, *211*(1-2), 140-149. https://doi.org/10.1016/j.foreco.2005.02.063

Butler, B., & Wahlquist, C. (2020, January 2). Australian bushfire crisis predicted to cost tourism industry hundreds of millions. *The Guardian*.

Castanho, A.D. de A., Galbraith, D., Zhang, K., Coe, M.T., Costa, M.H., & Moorcroft, P. (2016). Changing Amazon biomass and the role of atmospheric CO_2 concentration, climate, and land use. *Global Biogeochemical Cycles*, *30*(1), 18-39. https://doi.org/10.1002/2015GB005135

Cedeño, O. (2000). *Global Forest Fire Assessment 1990-2000 - FRA WP 55:6.1.4 Fire Management in Mexico* (SEMARNAP). Rome: FAO.

Certini, G. (2005). Effects of fire on properties of forest soils: a review. *Oecologia*, *143*(1), 1-10. https://doi.org/10.1007/s00442-004-1788-8

Chas-Amil, M.-L., Nogueira-Moure, E., Prestemon, J.P., & Touza, J. (2022). Spatial patterns of social vulnerability in relation to wildfire risk and wildland-urban interface presence. *Landscape and Urban Planning*, *228*, 104577-104577. https://doi.org/10.1016/j.landurbplan.2022.104577

Cheng, J. (2021, August 17). *A review of wildfire effects on soils, hydrologic processes and water* (WS 548 Major Project Paper). University of British Columbia.

Cochrane, M.A., & Laurance, W.F. (2002). Fire as a large-scale edge effect in Amazonian forests. *Journal of Tropical Ecology*, *18*(03), 311-325. https://doi.org/10.1017/S0266467402002237

Collins, L., Bradstock, R.A., Clarke, H., Clarke, M.F., Nolan, R.H., & Penman, T.D. (2021). The 2019/2020 mega-fires exposed Australian ecosystems to an unprecedented extent of high-severity fire. *Environmental Research Letters*, *16*(4), 044029-044029. https://doi.org/10.1088/1748-9326/abeb9e

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Ferber, S., & Turner, R.K. (2014). Changes in the global value of ecosystem services. *Global Environmental Change*, *26*, 152-158. https://doi.org/10.1016/j.gloenvcha.2014.04.002

Costanza, R., Kubiszewski, I., Ervin, D., Bluffstone, R., Boyd, J., Brown, D., Chang, H., Dujon, V., Granek, E., Polasky, S., Shandas. V. & Yeakley, A. (2011). Valuing ecological systems and services. *F1000 Biology Reports*, *3*: 14. https://doi.org/10.3410/B3-14

Crameri, N.J., & Ellison, J.C. (2022). Atoll inland and coastal mangrove climate change vulnerability assessment. *Wetlands Ecology and Management, 30,* 527-546. https://doi.org/10.1007/s11273-022-09878-0

Crowe, M. (2020). *Do Mangroves Burn? A remote sensed study of the impacts of forest fires on mangrove populations in South Sumatra, Indonesia* (Master's Thesis). King's College, London.

Darmawan, S., Sari, D.K., Wikantika, K., Tridawati, A., Hernawati, R., & Sedu, M.K. (2020). Identification before-after forest fire and prediction of mangrove forest based on Markov-cellular automata in part of Sembilang National Park, Banyuasin, South Sumatra, Indonesia. *Remote Sensing*, *12*(22), 3700-3700. https://doi.org/10.3390/rs12223700

Department of Public Information - Guyana. (2024, March 7). Government's quells week long Woodley Park, mangrove fires. *DPI Guyana*.

Doerr, S.H., & Santín, C. (2016). Global trends in wildfire and its impacts: perceptions versus realities in a changing world. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1696), 1-10. https://doi.org/10.1098/rstb.2015.0345

Ellery, W.N., Grenfell, M., Kotze, D.C., McCarthy, T.S., Tooth, S., Grundling, P.L., Beckedahl, H., le Maitre, E.D., Ramsay, L. (2009). *WET-Origins: controls on the distribution and dynamics of wetlands in South Africa.* WRC Report No. TT 334/09. Pretoria: Water Research Commission.

Enoh, M.A., Okeke, U.C., & Narinua, N.Y. (2021). Identification and modelling of forest fire severity and risk zones in the Cross-Niger transition forest with remotely sensed satellite data. *The Egyptian Journal of Remote Sensing and Space Sciences*, *24*(3), 879-887. https://doi.org/10.1016/j.ejrs.2021.09.002

Fonseca, M.G., Alves, L.M., Aguiar, A.P.D., Arai, E., Anderson, L.O., Rosan, T.M., Shimabukuro, Y.E., & de Aragão, L.E.O.e.C. (2019). Effects of climate and land-use change scenarios on fire probability during the 21st century in the Brazilian Amazon. *Global Change Biology*, *25*(9), 2931-2946. https://doi.org/10.1111/gcb.14709

Frappier-Brinton, T., & Lehman, S.M. (2022). The burning island: Spatiotemporal patterns of fire occurrence in Madagascar. *PloS One*, *17*(3), e0263313-e0263313. https://doi.org/10.1371/journal.pone.0263313

Gholami, D.M. (2016). *An overview on role of mangroves in mitigating coastal disasters (with special focus on tsunamis, floods and cyclones).* Presented at the International Conference on Architecture, Urbanism, Civil Engineering, Art, Environment, Tehran, Iran, Institute of Art and Architecture (SID): ICAUCAE 2016.

Giardina, C.P., Sanford, R.L., & Døckersmith, I.C. (2000). Changes in soil phosphorus and nitrogen during slash-and-burn clearing of a dry tropical forest. *Soil Science Society of America Journal*, *64*(1), 399-405. https://doi.org/10.2136/sssaj2000.641399x

Glasby, T.M., Gibson, P.T., Laird, R., Swadling, D.S., & West, G. (2023). Black summer bushfires caused extensive damage to estuarine wetlands in New South Wales, Australia. *Ecological Management & Restoration*, *24*(1), 27-35. https://doi.org/10.1111/emr.12572Global Forest Watch. (2024). Global Deforestation Rates & Statistics by Country | GFW. *www.globalforestwatch.org*. Data available at https://glad.umd.edu/dataset/Fire_GFL/

Guo, P., Sun, Y., Su, H., Wang, M., & Zhang, Y. (2018). Spatial and temporal trends in total organic carbon (TOC), black carbon (BC), and total nitrogen (TN) and their relationships under different planting patterns in a restored coastal mangrove wetland: case study in Fujian, China. *Chemical Speciation & Bioavailability*, *30*(1), 47-56. https://doi.org/10.1080/09542299.2018.1484673

Harrison, M.E., Deere, N.J., Imron, M.A., Nasir, D., Asti, H.A., Aragay Soler, J., Boyd, N.C., Cheyne, S.M., Collins, S.A., D'Arcy, L.J., Erb, W.M., Green, H., Healy, W., Holly, B., Houlihan, P.R., Husson, S.J., Jeffers, K.A., Kulu, I.P., Kusin, K., Marchant, N.C., Morrogh-Bernard, H.C., Page, S.E., Purwanto, A., Ripoll Capilla, B., de Rivera Ortega, O.R., Spencer, K.L., Sugardjito, J., Supriatna, J., Thornton, S.A., Frank van Veen, F.J., & Struebig, M.J. (2024). Impacts of fire and prospects for recovery in a tropical peat forest ecosystem. *Proceedings of the National Academy of Sciences of the United States of America*, *121*(17). https://doi.org/10.1073/pnas.2307216121

Heim, R.J., Heim, W., Darman, G.F., Heinken, T., Smirenski, S.M., & Hölzel, N. (2021). Litter removal through fire - A key process for wetland vegetation and ecosystem dynamics. *Science of the total environment*, *755*(2), 142659-142659. https://doi.org/10.1016/j.scitotenv.2020.142659

Hilaluddin, F., Yusoff, F.M., Natrah, F.M.I., & Lim, P.T. (2020). Disturbance of mangrove forests causes alterations in estuarine phytoplankton community structure in Malaysian Matang mangrove forests. *Marine Environmental Research*, *158*, 104935-104935. https://doi.org/10.1016/j.marenvres.2020.104935

Hollowell, T.H. (2005). *Plant community structure, fire disturbance, and recovery in mangrove swamps of the Waini Peninsula, Guyana.* [Unpublished Master's Thesis] Fairfax, VA, USA: George Mason University.

Ice, G.G., Neary, D.G., & Adams, P.W. (2004). Effects of wildfire on soils and watershed processes. *Journal of Forestry*, *102*(6), 16-20. https://doi.org/10.1093/jof/102.6.16

Islam, S.M.D.U., & Bhuiyan, M.A.H. (2018). Sundarbans mangrove forest of Bangladesh: causes of degradation and sustainable management options. *Environmental Sustainability*, *1*(2), 113-131. https://doi.org/10.1007/s42398-018-0018-y

Izah, S.C., Angaye, T.C.N., Aigberua, A.O., & Nduka, J.O. (2017). Uncontrolled bush burning in the Niger Delta region of Nigeria: potential causes and impacts on biodiversity. *International Journal of Molecular Ecology and Conservation*, *7*: 1. https://doi.org/10.5376/ijmec.2017.07.0001

Jaafar, Z., & Loh, T.-L. (2014). Linking land, air and sea: potential impacts of biomass burning and the resultant haze on marine ecosystems of Southeast Asia. *Global Change Biology*, *20*(9), 2701-2707. https://doi.org/10.1111/gcb.12539

Jaiswal, R.K., Mukherjee, S., Raju, K.D., & Saxena, R. (2002). Forest fire risk zone mapping from satellite imagery and GIS. *International Journal of Applied Earth Observation and Geoinformation*, *4*(1), 1-10. https://doi.org/10.1016/S0303-2434(02)00006-5

Juárez-Orozco, S.M., Siebe, C., & Fernández y Fernández, D. (2017). Causes and effects of forest fires in tropical rainforests: a bibliometric approach. *Tropical Conservation Science*, *10*, 194008291773720. https://doi.org/10.1177/1940082917737207

Jurado, E., Dachs, J., Duarte, C.M., & Simó, R. (2008). Atmospheric deposition of organic and black carbon to the global oceans. *Atmospheric Environment*, *42*(34), 7931-7939. https://doi.org/10.1016/j.atmosenv.2008.07.029

Kala, C.P. (2023). Environmental and socioeconomic impacts of forest fires: A call for multilateral cooperation and management interventions. *Natural Hazards Research*, *3*(2), 286-294. https://doi.org/10.1016/j.nhres.2023.04.003

Kautz, M., Berger, U., Stoyan, D., Vogt, J., Khan, N.I., Diele, K., Saint-Paul, U., Triet, T., & Nam, V.N. (2011). Desynchronizing effects of lightning strike disturbances on cyclic forest dynamics in mangrove plantations. *Aquatic Botany*, *95*(3), 173-181. https://doi.org/10.1016/j.aquabot.2011.05.005

Khan, A.R., Khan, A., Masud, S., & Rahman, R.M. (2021). Analyzing the land cover change and degradation in Sundarbans mangrove forest using machine learning and remote sensing technique. *Advances in Computational Intelligence*, 429-438. https://doi.org/10.1007/978-3-030-85099-9_35

Khan, M.F., Hamid, A.H., Rahim, H.A., Maulud, A., Latif, M.T., Nadzir, M.S.M., Sahani, M., Qin, K., Kumar, P., Varkkey, H., Faruque, M.R.I., Guan, N.C., Ahmadi, S.P., & Yusoff, S. (2020). El Niño driven haze over the Southern Malaysian Peninsula and Borneo. *Science of the Total Environment*, *730*, 139091-139091. https://doi.org/10.1016/j.scitotenv.2020.139091

Kotze, D.C. (2013). The effects of fire on wetland structure and functioning. *African Journal of Aquatic Science*, *38*(3), 237-247. https://doi.org/10.2989/16085914.2013.828008

Kumar, A. (2022). Ecosystem-based adaptation approach: concept and its ingredients. *Elsevier eBooks*, 105-141. https://doi.org/10.1016/B978-0-12-815025-2.00003-4

Kundu, K., Halder, P., & Mandal, J.K. (2022). estimation and analysis of change detection, forest canopy density, and forest fragmentation: a case study of the Indian Sundarbans. *Journal of Sustainable Forestry*, 1-16. https://doi.org/10.1080/10549811.2022.2059515

Lamborn, C.C., & Smith, J.W. (2023). Social and ecological impacts of fire to coastal fisheries: A Study of the Kenai River fishery (Alaska, USA). *Marine and Coastal Fisheries*, *15*(3): e10240. https://doi.org/10.1002/mcf2.10240

LeBlanc, A.R., Kennedy, L.M., Liu, K., & Lane, C.S. (2017). Linking hurricane landfalls, precipitation variability, fires, and vegetation response over the past millennium from analysis of coastal lagoon sediments, southwestern Dominican Republic. *Journal of Paleolimnology*, *58*(2), 135-150. https://doi.org/10.1007/s10933-017-9965-z

Li, X., Song, K., & Liu, G. (2020). Wetland fire scar monitoring and its response to changes of the Pantanal Wetland. *Sensors*, *20*(15), 4268. https://doi.org/10.3390/s20154268

Liu, Y. (2005). Enhancement of the 1988 northern U.S. drought due to wildfires. *Geophysical Research Letters*, *32*(10). https://doi.org/10.1029/2005GL022411

Lizundia-Loiola, J., Pettinari, M.L., & Chuvieco, E. (2020). Temporal anomalies in burned area trends: satellite estimations of the amazonian 2019 fire crisis. *Remote Sensing*, *12*(1), 151. https://doi.org/10.3390/rs12010151

Lombard, F., Soumaré, S., Andrieu, J., & Josselin, D. (2023). Mangrove zonation mapping in West Africa, at 10-m resolution, optimized for inter-annual monitoring. *Ecological Informatics*, *75*, 102027-102027. https://doi.org/10.1016/j.ecoinf.2023.102027

Loudermilk, E.L., O'Brien, J.J., Goodrick, S.L., Linn, R.R., Skowronski, N.S., & Hiers, J.K. (2022). Vegetation's influence on fire behavior goes beyond just being fuel. *Fire Ecology*, *18*(1). https://doi.org/10.1186/s42408-022-00132-9

Lovejoy, T.E., & Nobre, C. (2018). Amazon tipping point. *Science Advances*, *4*(2), eaat2340. https://doi.org/10.1126/sciadv.aat2340

Mahmood, H., Ahmed, M., Islam, T., Uddin, M.Z., Ahmed, Z.U., & Saha, C. (2021). Paradigm shift in the management of the Sundarbans mangrove forest of Bangladesh: Issues and challenges. *Trees, Forests and People*, *5*, 100094. https://doi.org/10.1016/j.tfp.2021.100094

Malhi, Y., Roberts, J.T., Betts, R.A., Killeen, T.J., Li, W., & Nobre, C.A. (2008). Climate change, deforestation, and the fate of the Amazon. *Science*, *319*(5860), 169-172. https://doi.org/10.1126/science.1146961

McWilliams, S.R., Sloat, T., Toft, C.A., & Hatch, D. (2007). Effects of prescribed fall burning on a wetland plant community, with implications for management of plants and herbivores. *Western North American Naturalist*, *67*(2), 299-317. https://doi.org/10.3398/1527-0904(2007)67[299:EOPFBO]2.0.CO;2

Mega, E.R. (2020). "Apocalyptic" fires are ravaging the world's largest tropical wetland. *Nature*, *586*(7827), 20-21. https://doi.org/10.1038/d41586-020-02716-4

Menéndez, P., Losada, I.J., Torres-Ortega, S., Narayan, S., & Beck, M.W. (2020). The global flood protection benefits of mangroves. *Scientific Reports*, *10*: 4404. https://doi.org/10.1038/s41598-020-61136-6

Mills, A.J., & Fey, M.V. (2004). Frequent fires intensify soil crusting: physicochemical feedback in the pedoderm of long-term burn experiments in South Africa. *Geoderma*, *121*(1-2), 45-64. https://doi.org/10.1016/j.geoderma.2003.10.004

Moonsammy, S. (2021). Ecosystem services and rehabilitation of mangroves - an economic perspective. *Journal of Academic Research and Essays eBooks*, 10-12. https://doi.org/10.52377/YIXP5191

Morrissette, H.K., Baez, S.K., Beers, L., Bood, N., Martinez, N.D., Novelo, K., Andrews, G., Balan, L., Beers, C.S., Betancourt, S.A., Blanco, R., Bowden, E., Burns-Perez, V., Carcamo, M., Chevez, L., Crooks, S., Feller, I.C., Galvez, G., Garbutt, K., Gongora, R., Grijalva, E., Lefcheck, J., Mahung, A., Mattis, C., McKoy, T., McLaughlin, D., Meza, J., Pott, E., Ramirez, G., Ramnarace, V., Rash, A., Rosado, S., Santos, H., Santoya, L., Sosa, W., Ugarte, G., Viamil, J., Young, A., Young, J., & Canty, S.W.J. (2023). Belize Blue Carbon: Establishing a national carbon stock estimate for mangrove ecosystems. *Science of The Total Environment*, 870, 161829. https://doi.org/10.1016/j.scitotenv.2023.161829

Nocentini, A., Kominoski, J.S., & Sah, J. (2021). Interactive effects of hydrology and fire drive differential biogeochemical legacies in subtropical wetlands. *Ecosphere*, *12*(3): e03408. https://doi.org/10.1002/ecs2.3408

Osborne, T.Z., Kobziar, L.N., & Inglett, P.W. (2013). Fire and water: new perspectives on fire's role in shaping wetland ecosystems. *Fire Ecology*, *9*(1), 1-5. https://doi.org/10.4996/fireecology.0901001

Osti, R., Tanaka, S., & Tokioka, T. (2009). The importance of mangrove forest in tsunami disaster mitigation. *Disasters*, *33*(2), 203-213. https://doi.org/10.1111/j.1467-7717.2008.01070.x

Otitoloju, A.A., Are, T., & Junaid, K.A. (2006). Recovery assessment of a refined-oil impacted and fire ravaged mangrove ecosystem. *Environmental Monitoring and Assessment*, *127*(1-3), 353-362. https://doi.org/10.1007/s10661-006-9285-7

OzCoast. (2016). Changes in mangrove areas. https://ozcoasts.org.au/indicators/biophysical-indicators/mangrove_areas/

Padonou, E.A., Gbaï, N.I., Kolawolé, M.A., Idohou, R., & Toyi, M. (2021). How far are mangrove ecosystems in Benin (West Africa) conserved by the Ramsar Convention? *Land Use Policy*, *108:* 105583. https://doi.org/10.1016/j.landusepol.2021.105583

Page, S.E., Siegert, F., Rieley, J.O., Boehm, H.-D.V., Jaya, A., & Limin, S. (2002). The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*, *420*(6911), 61-65. https://doi.org/10.1038/nature01131

Pandey, K., & Ghosh, S.K. (2018). Modelling of parameters for forest fire risk zone mapping. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII-5*, 299-304. https://doi.org/10.5194/isprs-archives-XLII-5-299-2018

Queiroz, L. de S., Rossi, S., Calvet-Mir, L., Ruiz-Mallén, I., García-Betorz, S., Salvà-Prat, J., & Meireles, A.J. de A. (2017). Neglected ecosystem services: Highlighting the socio-cultural perception of mangroves in decision-making processes. *Ecosystem Services*, *26*, 137-145. https://doi.org/10.1016/j.ecoser.2017.06.013

Rahman, M., Ullah, R., Lan, M., Sumantyo, J.T.S., Kuze, H., & Tateishi, R. (2013). Comparison of Landsat image classification methods for detecting mangrove forests in Sundarbans. *International Journal of Remote Sensing*, *34*(4), 1041-1056. https://doi.org/10.1080/01431161.2012.717181

Reddy, C.S., Bird, N.G., Sreelakshmi, S., Manikandan, T.M., Asra, M., Krishna, P.H., Jha, C.S., Rao, P.V.N., & Diwakar, P.G. (2019). Identification and characterization of spatio-temporal hotspots of forest fires in South Asia. *Environmental Monitoring and Assessment*, *191*(Suppl. 3): 791. https://doi.org/10.1007/s10661-019-7695-6

Ribeiro, R. de A., Rovai, A.S., Twilley, R.R., & Castañeda-Moya, E. (2019). Spatial variability of mangrove primary productivity in the neotropics. *Ecosphere*, *10*(8): e02841. https://doi.org/10.1002/ecs2.2841

Robbins, A.M.J., Eckelmann, C.M., & Quiñones, M. (2008). Forest fires in the Insular Caribbean. *Ambio*, *37*(7/8), 528-534. https://doi.org/10.1579/0044-7447-37.7.528

Roces-Díaz, J.V., Santín, C., Martínez-Vilalta, J., & Doerr, S.H. (2021). A global synthesis of fire effects on ecosystem services of forests and woodlands. *Frontiers in Ecology and the Environment*, *20*(3), 170-178. https://doi.org/10.1002/fee.2349

Sadeer, N.B., Mahomoodally, M.F., Gokhan, Z., Rajesh, J., Nadeem, N., Kannan, R., Nabeelah Bibi, S., Fawzi, M. M., Gokhan, Z., Rajesh, J., Nadeem, N., Kannan, R.R.R., Albuquerque, R,D.D.G. & Pandian, S. K. (2019). Ethnopharmacology, phytochemistry, and global distribution of mangroves-a comprehensive review. *Marine Drugs*, *17*(4), 231-231. https://doi.org/10.3390/md17040231

Saoum, M.R., & Sarkar, S.K. (2024). Monitoring mangrove forest change and its impacts on the environment. *Ecological Indicators*, *159*, 111666. https://doi.org/10.1016/j.ecolind.2024.111666

Shivanna, K.R. (2022). Climate change and its impact on biodiversity and human welfare. *Proceedings of the Indian National Science Academy*, *88*(2). https://doi.org/10.1007/s43538-022-00073-6

Siegert, F., Ruecker, G., Hinrichs, A., & Hoffmann, A.A. (2001). Increased damage from fires in logged forests during droughts caused by El Niño. *Nature*, *414*(6862), 437-440. https://doi.org/10.1038/35106547

Siikamaki, J., Sanchirico, J.N., & Jardine, S.L. (2012). Global economic potential for reducing carbon dioxide emissions from mangrove loss. *Proceedings of the National Academy of Sciences*, *109*(36), 14369-14374. https://doi.org/10.1073/pnas.1200519109

Sil, Â., Azevedo, J.C., Fernandes, P.M., Regos, A., Vaz, A.S., & Honrado, J.P. (2019). (Wild)fire is not an ecosystem service. *Frontiers in Ecology and the Environment*, *17*(8), 429-430. https://doi.org/10.1002/fee.2106

Silveira, M.V.F., Silva-Junior, C.H.L., Anderson, L.O., & Aragão, L.E.O.C. (2022). Amazon fires in the 21st century: The year of 2020 in evidence. *Global ecology and biogeography*, *31*(10), 2026-2040. https://doi.org/10.1111/geb.13577

Singh, S. (2022). “Forest fire emissions: A contribution to global climate change.” *Frontiers in Forests and Global Change*, *5*. https://doi.org/10.3389/ffgc.2022.925480

Sinsin, C.B.L., Bonou, A., Salako, K.V., Gbedomon, R.C., & Kakaï, R.L.G. (2023). Economic valuation of mangroves and a linear mixed model-assisted framework for identifying its main drivers: a case study in Benin. *Land*, *12*(5), 1094-1094. https://doi.org/10.3390/land12051094

Slocum, M.G., Platt, W., Beckage, B., Panko, B., & Lushine, J. (2007). Decoupling natural and anthropogenic fire regimes: a case study in Everglades National Park. *Florida Natural Areas Journal*, *27*(1), 41-55. https://doi.org/10.3375/0885-8608(2007)27[41:DNAAFR]2.0.CO;2

Smith, S.M., Newman, S., Garrett, P.B., & Leeds, J.A. (2001). Differential Effects of surface and peat fire on soil constituents in a degraded wetland of the Northern Florida Everglades. *Journal of Environmental Quality*, *30*(6), 1998-2005. https://doi.org/10.2134/jeq2001.1998

Smith, T.J., Foster, A.M., Tiling-Range, G., & Jones, J.W. (2013). Dynamics of mangrove-marsh ecotones in subtropical coastal wetlands: fire, sea-level rise, and water levels. *Fire Ecology*, *9*(1), 66-77. https://doi.org/10.4996/fireecology.0901066

Smyth, C. (2020). *The impacts of bushfires on coastal and marine environments: A review and recommendations for change*. West End, Queensland: Australian Marine Conservation Society. https://www.marineconservation.org.au/wp-content/uploads/2020/03/Bushfire-Report_February-2020_Final-full-for-web-1.pdf

Sojinu, O.S., Sonibare, O.O., & Zeng, E.Y. (2010). Concentrations of polycyclic aromatic hydrocarbons in soils of a mangrove forest affected by forest fire. *Toxicological & Environmental Chemistry*, *93*(3), 450-461. https://doi.org/10.1080/02772248.2010.532130

Song, S., Ding, Y., Li, W., Meng, Y., Zhou, J., Gou, R., Zhang, C., Ye, S., Saintilan, N., Krauss, K.W., Crooks, S., Lv, S., & Lin, G. (2023). Mangrove reforestation provides greater blue carbon benefit than afforestation for mitigating global climate change. *Nature Communications*, *14: 756*. https://doi.org/10.1038/s41467-023-36477-1

Song, Y., Xu, C., Li, X., & Oppong, F. (2024). Lightning-induced wildfires: an overview. *Fire*, *7*(3), 79-79. https://doi.org/10.3390/fire7030079

Spalding, M.D., McIvor, A.L., Beck, M.W., Koch, E.W., Möller, I., Reed, D.J., Rubinoff, P., Spencer, T., Tolhurst, T.J., Wamsley, T.V., van Wesenbeeck, B.K., Wolanski, E., & Woodroffe, C.D. (2013). Coastal ecosystems: a critical element of risk reduction. *Conservation Letters*, *7*(3), 293-301. https://doi.org/10.1111/conl.12074

Sydney Institute of Marine Science (2020) 'Potential *impacts of bushfires on our marine environment: Contaminants and toxic effects of ash to marine* ecosystems', https://www.sims.org.au/news/94/bushfire-impact-statement Accessed 4 July 2024.

Taillardat, P., Friess, D.A., & Lupascu, M. (2018). Mangrove blue carbon strategies for climate change mitigation are most effective at the national scale. *Biology Letters*, *14*(10), 20180251. https://doi.org/10.1098/rsbl.2018.0251

Tasnim, F., Kamrujjaman, M., & Khan, T. (2023). Structural changes in mangroves of Sundarban in Bangladesh: effects of climate change and human disturbances. *Modeling Earth Systems and Environment*, *9*(3), 3553-3566. https://doi.org/10.1007/s40808-023-01699-1

Taufik, M., Setiawan, B.I., & Lanen, V. (2018). Increased fire hazard in human-modified wetlands in Southeast Asia. *Ambio*, *48*(4), 363-373. https://doi.org/10.1007/s13280-018-1082-3

Temmerman, S., Horstman, E.M., Krauss, K.W., Mullarney, J.C., Pelckmans, I., & Schoutens, K. (2023). Marshes and mangroves as nature-based coastal storm buffers. *Annual Review of Marine Science*, *15*(1), 95-118. https://doi.org/10.1146/annurev-marine-040422-092951

Thampanya, U., Vermaat, J.E., Sinsakul, S., & Panapitukkul, N. (2006). Coastal erosion and mangrove progradation of Southern Thailand. *Estuarine, Coastal and Shelf Science*, *68*(1-2), 75-85. https://doi.org/10.1016/j.ecss.2006.01.011

Thoha, A.S., Saharjo, B.H., Boer, R., & Ardiansyah, M. (2018). Characteristics and causes of forest and land fires in Kapuas District, Central Kalimantan Province, Indonesia. *Biodiversitas Journal of Biological Diversity*, *20*(1), 110-117. https://doi.org/10.13057/biodiv/d200113

Thom, D., & Seidl, R. (2015). Natural disturbance impacts on ecosystem services and biodiversity in temperate and boreal forests. *Biological Reviews*, *91*(3), 760-781. https://doi.org/10.1111/brv.12193

Tian, K., Wang, Z., Li, F., Gao, Y., Xiao, Y., & Liu, C. (2021). Drought events over the Amazon River Basin (1993-2019) as detected by the climate-driven total water storage change. *Remote Sensing*, *13*(6), 1124-1124. https://doi.org/10.3390/rs13061124

Trejo, D.A.R. (2008). Fire Regimes, Fire Ecology, and Fire Management in Mexico. *AMBIO: A Journal of the Human Environment*, *37*(7), 548-556. https://doi.org/10.1579/0044-7447-37.7.548

Turco, M., Rosa-Cánovas, J.J., Bedia, J., Jerez, S., Montávez, J.P., Llasat, M.C., & Provenzale, A. (2018). Exacerbated fires in Mediterranean Europe due to anthropogenic warming projected with non-stationary climate-fire models. *Nature Communications*, *9*(1), 1-9. https://doi.org/10.1038/s41467-018-06358-z

Tyukavina, A., Potapov, P., Hansen, M.C., Pickens, A.H., Stehman, S.V., Turubanova, S., Parker, D., Zalles, V., Lima, A., Kommareddy, I., Song, X.-P., Wang, L., & Harris, N. (2022). Global trends of forest loss due to fire from 2001 to 2019. *Frontiers in Remote Sensing*, *3*. https://doi.org/10.3389/frsen.2022.825190

Underwood, E.C., Klinger, R.C., & Brooks, M.L. (2019). Effects of invasive plants on fire regimes and postfire vegetation diversity in an arid ecosystem. *Ecology and Evolution*, *9*(22), 12421-12435. https://doi.org/10.1002/ece3.5650

Unnikrishnan, S., Singh, A., & Kharat, M.G. (2012). The role of mangroves in disaster mitigation: a review. *International Journal of Environment and Sustainable Development*, *11*(2), 164. https://doi.org/10.1504/IJESD.2012.049180

Urquhart, G.R. (2009). Paleoecological record of hurricane disturbance and forest regeneration in Nicaragua. *Quaternary International*, *195*(1-2), 88-97. https://doi.org/10.1016/j.quaint.2008.05.012

Vogt, J., Alfred, de J., Hugo, C., Diego, M., Marco, M., & Paulo, B. (2016). A global drought observatory for emergency response. *EGU General Assembly Conference Abstracts*, EPSC2016-2582.

Wang, M., Sun, Y., Zeng, H., Wu, W., Deng, L., & Tu, P. (2022). Distribution of black carbon in sediments from mangrove wetlands in China. *Frontiers in Forests and Global Change*, *5*. https://doi.org/10.3389/ffgc.2022.989329

Ward, M., Tulloch, A., Radford, J.Q., Williams, B.A., Reside, A.E., Macdonald, S.L., Mayfield, H.J., Maron, M., Possingham, H.P., Vine, S.J., O'Connor, J.L., Massingham, E.J., Greenville, A.C., Woinarski, J.C.Z., Garnett, S.T., Lintermans, M., Scheele, B.C., Carwardine, J., Nimmo, D.G., Lindenmayer, D.B., Kooyman, R.M., Simmonds, J.S., Sonter, L.J., & Watson, J.E.M. (2020). Impact of 2019-2020 mega-fires on Australian fauna habitat. *Nature Ecology & Evolution*, *4*(10), 1321-1326. https://doi.org/10.1038/s41559-020-1251-1

Williams, A.P., Abatzoglou, J.T., Gershunov, A., Guzman-Morales, J., Bishop, D.A., Balch, J.K., & Lettenmaier, D.P. (2019). Observed impacts of anthropogenic climate change on wildfire in California. Earth's *Future*, *7*(8), 892-910. https://doi.org/10.1029/2019EF001210

Williams-Jara, G.M., Espinoza-Tenorio, A., Monzón-Alvarado, C., Posada-Vanegas, G., & Infante-Mata, D. (2022). Fires in coastal wetlands: a review of research trends and management opportunities. *Wetlands, 42:* 56. https://doi.org/10.1007/s13157-022-01576-0

Wu, L., Taylor, M.P., & Handley, H.K. (2017). Remobilisation of industrial lead depositions in ash during Australian wildfires. *Science of the Total Environment*, *599-600*, 1233-1240. https://doi.org/10.1016/j.scitotenv.2017.05.044

Zhang, X., Xu, Y., Xiao, W., Zhao, M., Wang, Z., Wang, X., Xu, L., Luo, M., Li, X., Fang, J., Fang, Y., Wang, Y., Oguri, K., Wenzhöfer, F., Rowden, A.A., Mitra, S., & Glud, R.N. (2022). The hadal zone is an important and heterogeneous sink of black carbon in the ocean. *Communications Earth & Environment*, *3:* 25. https://doi.org/10.1038/s43247-022-00351-7