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Fire ecology in marine systems

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Wildfire byproducts enter into the oceans via terrestrial and atmospheric routes. They pose a challenge to the sustainability of marine ecosystems, especially under the current increase in fire activity. Research is needed to unravel the dynamics between wildfires and marine life, and the oceans' potential to mitigate wildfire emissions.

Wildfires as a marine disturbance

Wildfires represent prevalent ecological disturbances in a variety of terrestrial ecosystems, encompassing boreal and warm temperate forests, Mediterranean shrublands, tropical savannas, and grasslands [1]. Within these ecosystems, a substantial proportion of the byproducts generated by wildfires, including ashes, smoke, and sediments, find their way into the ocean through both terrestrial pathways (runoff and rivers) and atmospheric dispersion (aerosols) (Figure 1). Wildfires are not a recent phenomenon but have occurred over extensive geological timescales, marked by activity peaks during the Carboniferous and Permian periods and later in the Cretaceous, coinciding with elevated atmospheric oxygen concentrations [2].

Presently, global biomass burning, primarily attributed to wildfires, results in the annual generation of 40–250 Mt of charcoal, often referred to as black carbon (BC) [3]. The broad temporal and spatial significance of wildfires highlights their fundamental role in shaping Earth's dynamics, including their influence on the world's oceans. However, the role of fire byproducts in marine ecosystems remains unexplored.

Our hypothesis is that wildfires significantly impact the ecology of oceans. Specifically, we expect that wildfire byproducts: (i) enhance nutrient transport from land to sea; (ii) alter marine chemistry and carbon and nutrient cycling; (iii) alter phytoplankton productivity; and (iv) have effects (both positive and negative) on the oceanic biota (from microbes to mammals). We briefly review the little research performed on these topics and call for further research. Thus, we provide a foundational framework for future research on marine fire ecology.

Biological consequences

Similar to terrestrial ecosystems, wildfires are likely to generate both winners and losers in marine environments. While they can cause substantial harm, they also have the potential to boost nutrient availability, increase ecosystem productivity, and create unique environmental conditions that may support less competitive species. However, the nature and extent of these effects remain unknown.

The introduction of fire byproducts into marine ecosystems predominantly influences primary producers, notably phytoplankton. The responses of phytoplankton to wildfire ashes and aerosols often resemble the effects of exogenous iron (Fe) input from sources such as dust deposition or volcanic ash, resulting in increased algal blooms and red tide occurrences in the ocean [4,5] or alterations in phytoplankton composition [6]. For instance, the extensive Indonesian wildfires of 1997 induced red tides that extended across the Indonesian archipelago over 2 months [7]. These red tides, accompanied by oxygen depletion, led to significant mortality among phytoplankton, zooplankton, and benthic organisms and were considered responsible for coral mortality that occurred along a 400-km stretch in the Mentawai Islands. Similarly, during the unprecedented Australian fires of 2019–2020, iron-rich aerosols initiated a protracted phytoplankton bloom in the Pacific Southern Ocean, lasting 4 months and surpassing previous records [8]. This huge photosynthetic event had the potential to sequester a substantial portion of the carbon emissions from the fires, underscoring the critical role of marine ecosystems in mitigating fire emissions. While there is growing evidence of the importance of wildfire emissions in shaping marine phytoplankton dynamics, our understanding of the broader implications for trophic interactions and the carbon budget remains limited, except for the few instances mentioned. The long-term significance of these processes, particularly in regions where fires are frequent, irrespective of extreme fire years, remains largely uncharted. We propose that their importance is likely to hinge on the availability of other macronutrients in the specific oceanic regions where aerosols are deposited. Specifically, we predict that, in aquatic ecosystems with ample availability of other macronutrients, the addition of iron will have a negligible impact on carbon fixation rates, while in ecosystems where iron is a limiting factor, Fe fertilization will significantly enhance carbon fixation.

In addition, phytoplankton blooms redirect the flow of organic matter through fecal pellets and higher trophic groups (including zooplankton and nekton). Although there are only a limited number of studies examining the impacts of fire byproducts on other taxa (Table 1), the regular inflow of external materials through dust deposition plays a crucial role in the formation and maintenance of regions rich in zooplankton. These regions, in turn, provide an ideal environment for the growth of fish larvae, ultimately benefiting the populations of larger predators, such as tropical tuna. [9]. It would also be important to delve into the functional and adaptive responses to gain a comprehensive

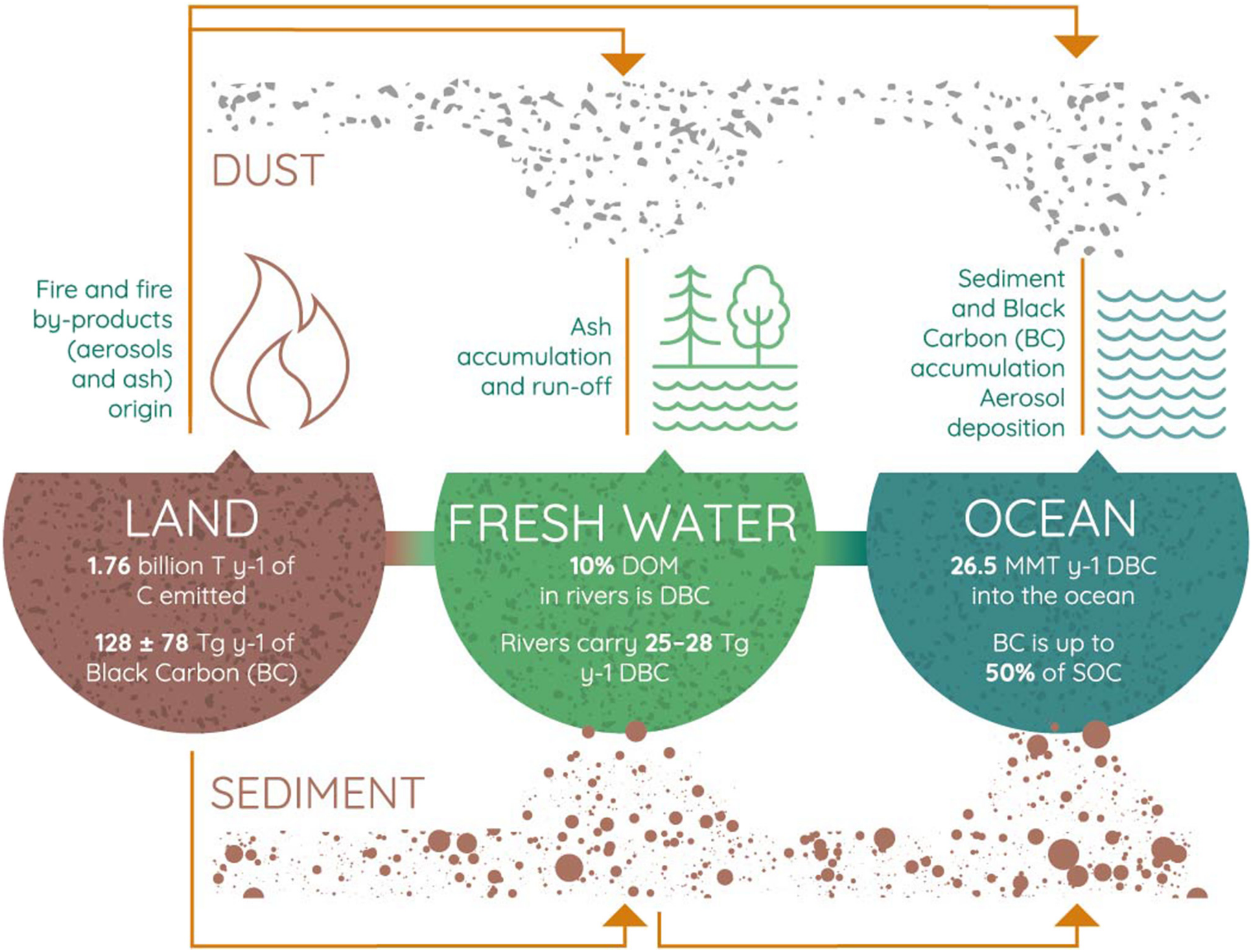

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Figure 1. Schematic representation of the interaction between land (where fires occur), freshwater and the atmosphere (where fire byproducts are transported), and the ocean. The values refer to the production of carbon (C) and black carbon (BC) during fires. It also illustrates the concentrations of dissolved BC (DBC) and dissolved organic matter (DOM) that are transported through rivers, as well as the quantities of DBC that are released into the ocean. When wildfires occur on coastal systems, they may impact the ocean directly without going through freshwater systems. Sources: [1–4,8,11,12] and references therein.

understanding of the mechanisms that uphold biodiversity in 'fire-prone' marine ecosystems.

Oceans as sinks of carbon from fires

BC, or charcoal, is a product of incomplete biomass combustion, known for its high resistance to degradation. Wildfires play a pivotal role in perpetuating not only the persistence of soil organic carbon (SOC), specifically pyrogenic carbon (pyrogenic C), but also the presence of recalcitrant BC in aquatic ecosystems [10]. It is noteworthy that ~50% of BC in sediments undergoes degradation within 3 years, while the remaining half may endure for millennia [3]. This wide spectrum of variability is contingent on wildfire-specific attributes and environmental factors. BC is mobilized from soils as dissolved BC (DBC) and transported to the ocean through river systems (Figure 1). Approximately 6% of the carbon sequestered in marine sediments is of pyrogenic origin [10]. The deposition and accumulation of BC have significant implications for the carbon cycle, functioning as a geological carbon sink over extended timescales. The lateral flux of BC from soil to watersheds and subsequently to the ocean mostly occurs during periods of heavy rainfall. However, it is essential to emphasize that ~80% of BC generated by vegetation tends to remain in its local ecosystem, with the remaining 20% having the potential to reach the ocean [8].

Moreover, it is challenging to precisely quantify the specific contribution of BC to

Table 1. Examples of responses to wildfires in marine biota

Species group	Response	Mechanism	Refs
Phytoplankton	Increase of marine phytoplankton production in iron-limited waters	Increase of soluble bioessential trace metals (e.g., iron)	[4,5,12]
Phytoplankton	Increased dinoflagellate abundance (genera *Gonyaulax* and *Prorocentrum*)	Increase of detrital and ash particles	[6]
Coral	*ca* 100% mortality	O_2 depletion in water column due to red tide bloom underpinned by the availability of iron	[7]
Seagrasses (several species)	Decrease of vertical growth and horizontal expansion	Limited light	[13]
Bottlenose dolphins (*Tursiops truncatus*)	Irregular lung function that leads to hematological and serum biochemical changes	Smoke inhalation	[14]
Sea otter (*Enhydra lutris*)	Differences in gene transcription profiles and clinical anomalies (e.g., dental diseases)	Exposure to fire-generated hydrocarbon products	[15]

the total annual organic matter burial in the ocean, considering that the ocean receives organic matter from diverse sources beyond BC. Continental platforms are repositories of ~90% of the organic carbon (OC) buried in the ocean. They act as effective filters and traps for natural and anthropogenic materials originating from terrestrial environments. Notably, the ocean stores an estimated 2300 Pg of inorganic carbon in the upper 1 m of sediment, with 75% in abyssal zones [11]. This is the largest pool of sediment C stocks globally, 2.3 times higher than the 1 m of terrestrial soils.

Concluding remarks: future research directions

Wildfires have played, are playing, and will continue to play a pivotal role in terrestrial, freshwater, and marine ecosystems, profoundly shaping the Earth's system. Foreseeable trends point to a global increase in fire activity, largely attributed to human-induced global warming, resulting in a greater deposition of fire-related materials in marine ecosystems. Presently, our understanding of how fires impact marine ecosystems is primarily anecdotal (Table 1).

In addition to remote sensing studies [4,5], field surveys after fire to monitor changes in water quality and marine biota are required to improve our understanding of wildfire impacts on marine ecosystems. They are essential to gauge the scale and duration of disruptions and to pinpoint the susceptibility of the affected marine habitats. Furthermore, controlled laboratory experiments, where fire ash and dust are introduced at regulated concentrations, would provide us with invaluable insights into the intricate dynamics of marine communities. These experiments would allow us to measure the direct effects on various species such as fish, coral, and plankton, yielding a more mechanistic understanding of post-fire marine ecosystem dynamics. This research is instrumental in guiding conservation efforts and strategies for ecosystem recovery.

A crucial yet underexplored area of research involves quantifying the role of marine microbes and phytoplankton in the capture of carbon emissions from wildfires. This not only enhances our comprehension of global biogeochemical cycles but also aids in refining the global carbon budget. Thus, it is essential to integrate this aspect into global carbon models while also enhancing our ability to quantify carbon transfer to the ocean through runoff and sedimentation.

To gain a comprehensive understanding of the impact of wildfires on our planet, we need to address the ecology of fire in the marine environment. This would enrich our knowledge of the interconnected systems that constitute the Earth.

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Declaration of interests

The authors declare no conflict of interest.

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