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Fog in western coastal ecosystems: inter-disciplinary challenges and opportunities with example concepts from the Pacific Northwest, USA

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Coastal fog occurs along many of the world's west coast continental environments. It is particularly consequential during summer when an increased frequency of fog co-occurs with the seasonal dryness characteristic of most west coast climate systems, for example, in the Pacific coast of North and South America, the southwestern African coast, and southern coastal Europe. Understanding coastal fog formation and effects has consequences for many disciplines, including the physical (e.g., atmospheric science, oceanography), biological (e.g., biogeography, ecophysiology), and socio-ecological realms (e.g., Indigenous cultural knowledge, public safety, economics). Although research practices differ across disciplines, they share many of the challenges needed to advance fog science. For example, coastal fog remains difficult to reliably monitor when, where, and why it occurs, which adds difficulty to understanding fog's effects on all facets of the integrated coastal system. These shared challenges provide ripe opportunities for interdisciplinary collaboration, a template with past success in advancing fog-related science that can continue to have success in the future. In this perspectives review, we summarize the current status and frontiers of fog-related science from multiple disciplines, leveraging examples primarily drawn from the Pacific Northwest coastal region of the United States to show how interdisciplinary collaboration is needed to continue to advance our collective understanding of coastal fog formation and effects on west coast environments.

KEYWORDS

atmosphere, biogeography, collaboration, FOG, interdisciplinary science, Pacific Northwest, socio-ecological systems, west coast

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1 Introduction

Fog is a defining feature of western coastal (ocean eastern boundary) environments and is a critical source of moisture in the seasonally-dry mid-latitude regions of the Americas, Africa, and Europe, with widespread and complex effects (Figure 1). Globally, these coasts house endemic species (e.g., Dawson, 1998; Gonzales et al., 2023), productive ecosystems (e.g., Alaback, 1996), and industries that benefit from wetting and cooling effects of fog. Fog also vectorizes fungal pathogens (Shaw et al., 2021), hinders visibility (e.g., Abdel-Aty et al., 2011), contributes to aviation accidents (Gultepe, 2023), and impacts tourism and public health (Hackney et al., 1985). However, fog remains difficult to reliably predict, observe, and model on operational forecast and climate-dynamical time scales (Koračin et al., 2014; Torregrosa et al., 2014).

Multiple scientific disciplines have vested interest in building understanding of the where's, when's, and why's of coastal fog occurrence and effects. We focus on the physical sciences (forecasting, observation, measurement, and coastal meteorology and climatology), biological sciences (ecophysiology, old-growth forest conservation, biometeorology), and socio-ecological sciences (public health, indigenous perspectives, forestry, agriculture, fisheries, and forest pathogens) (Figure 2). Despite not sharing common research languages, many challenges are universal across disciplines. For example, fog is geographically variable, making it difficult to reliably monitor when and where it occurs, and, by extension, to study and predict fog formation, movement, and its socio-environmental effects. These shared challenges provide ripe opportunities for interdisciplinary collaboration, a template with past success in fog science. For example, physical controls on coastal fog formation and movement draw on explanations from both coastal meteorology and oceanography (Leipper, 1948; 1994; Samelson et al., 2021), connections that have been extended to better understand diverse phenomena including species' distributions (Weathers et al., 2020), plant water budgets (Fischer et al., 2009), and fire season fuel moisture (Emery et al., 2018). Reinforcing this collaborative approach can help answer some of the most pressing research questions surrounding coastal fog: Can we predict when and where fog occurs?; Will climate warming change fog frequency?; Does fog influence conservation of coastal biota?; How do fog and climate shape cultural knowledge systems?

Our goal is to highlight current progress, frontiers, and challenges from selected disciplines as a framework to spur interdisciplinary collaboration in global and regional fog science, supported with illustrative examples drawn from our collective research experience in the coastal Pacific Northwest (PNW), United States.

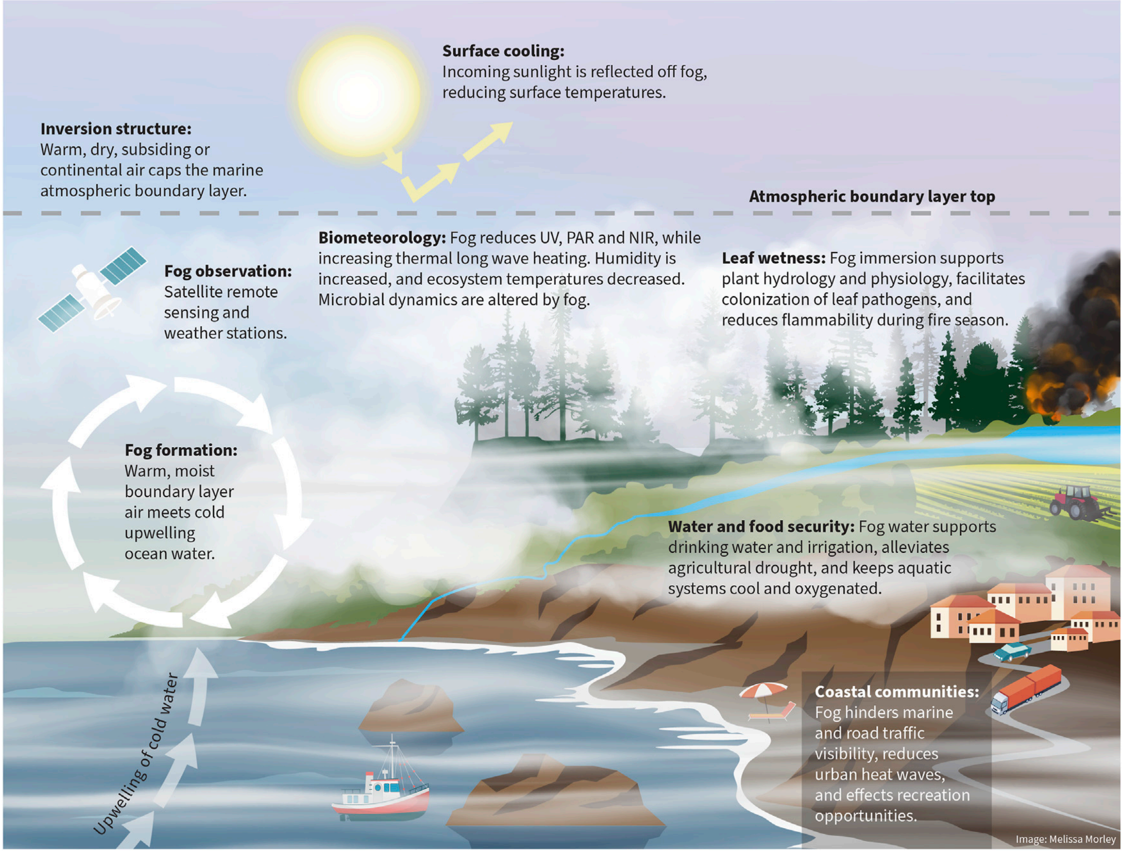

FIGURE 1
Coastal fog processes and impacts. Fog forms over the ocean and intersects with the coast as it moves landward, impacting overlapping aspects of the natural and built environment.

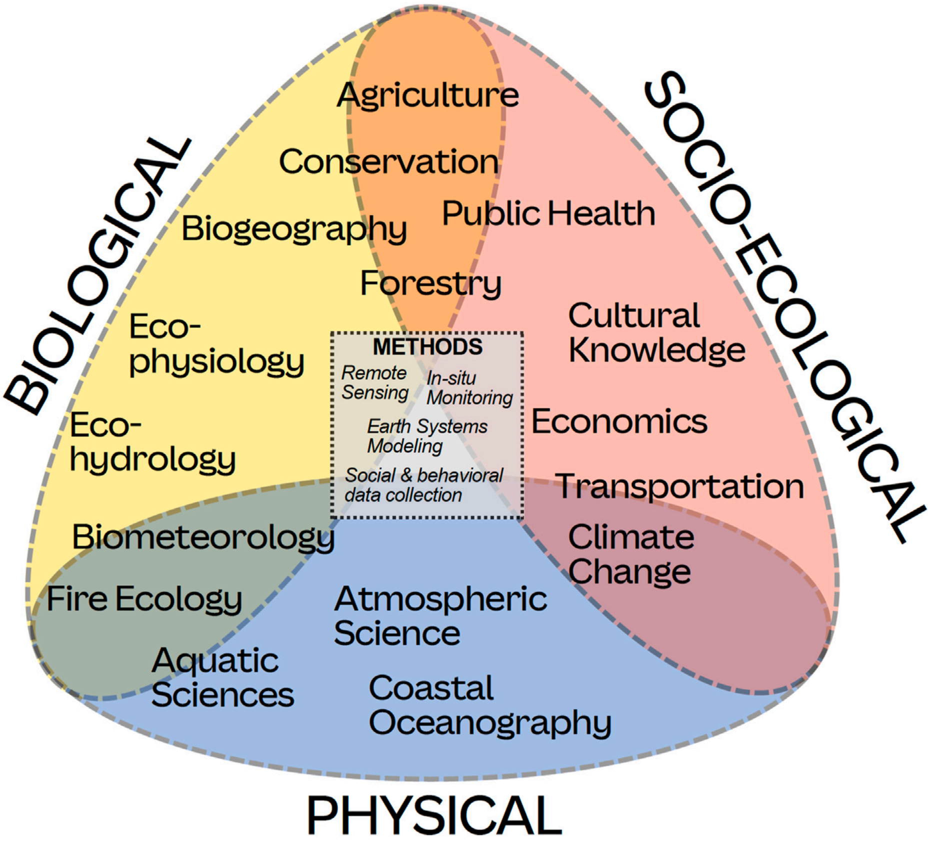

FIGURE 2
Many different disciplines are involved in fog-related research, spanning the realms of biological, socio-ecological, and physical knowledge systems. These divisions are not absolute, but interact in an often diffuse manner, mirroring the widespread impacts of fog on multiple aspects of the environment and often using common technologies and methods to monitor and study coastal fog. Some Indigenous science aspects encompass the entire figure holistically. The diversity of relevant fields creates special challenges but also exciting opportunities for interdisciplinary collaboration in fog science.

2 Uniting the interdisciplinary nature of coastal fog research and monitoring

2.1 Fog observation, measurement, and forecasting

Historically, fog detection relied heavily on naked-eye assessments, e.g., using fixed visibility markers at known distances. More quantitative methods deploy Transmissometers or Forward Scatter Sensors on weather stations, providing accurate continuous measurements of near-surface visibility and therefore fog. These can be costly and their location is biased towards urban centers that are usually warmer than surrounding areas (Baldocchi and Waller, 2014). Alternatively, satellite imagery provides large spatial coverage and repeated observations used to continuously map fog for large regions (e.g., Bendix et al., 2006; Clemesha et al., 2016; Torregrossa et al., 2016; Ran et al., 2002). However, most satellite products struggle to distinguish fog from similar atmospheric features like low-lying stratus clouds and have relatively coarse spatial resolution (often 1–4 km), making it difficult to detect geographic variability of small patches of coastal fog. Spatial gaps can be partially filled using on or near-surface cameras (e.g., Bassiouni et al., 2017; del Río et al., 2021) and supported by observational records of cloud base height and visibility (e.g., Johnstone and Dawson, 2010; Dye et al., 2020), but require extensive networks over consecutive years to draw regionally meaningful conclusions.

Fog detection alone is insufficient for characterizing fog. One common measurement is fog water deposition to the surface, which is measured by instruments such as the Standard Fog Collector (Fernandez et al., 2018) and has important applications for water resources, particularly in arid regions (Azeem et al., 2020). Research across the globe in water-scarce western coastal environments have assessed water collection rates and the feasibility of fog water for community and ecosystem consumption (Correggiari et al., 2017). Other properties of fog that can be measured include the liquid water content, droplet concentration, droplet size distribution, and fog chemistry such as concentrations of solutes like sulfur dioxide or hydrogen chloride. Such measurements are critical to understand processes such as fog water deposition rates and pollution levels. Future advances in fog observation will draw from the growing realm of machine learning, linking multi-scale and multi-source monitoring systems (e.g., satellites, cameras, and weather stations) to better predict timing and geography of fog, which can advance fog forecasting as well as research on the utilization for fog as a water resource. Cross-disciplinary collaboration with qualitative social and behavioral data collection methods can assess the outcomes of fog water collection projects, as has been done in Morocco (Ait El Kadi et al., 2024), Bolivia (Castelli et al., 2023) and Peru (Ojani, 2024) and additionally can aid in understanding cultural histories and meanings of fog.

More and better measurements will hopefully lead to a better ability to forecast fog. Fog formation and life cycles are dominated by processes at many scales, from synoptic weather patterns to local aerosol species and concentrations, making its prediction exceptionally difficult (Koračin, 2017). A lack of high-resolution fog measurements limits improvements in subgrid physics parameterizations, though recent field campaigns across the globe have made progress in extensive measurement collection of the physical and chemical properties of fog (Fernando et al., 2021).

2.2 Coastal oceanography and climatology

Fog appears along western coasts at the intersection of land, ocean, and atmosphere, driven by regional and seasonal climate norms. The driving physical processes include the trapping of moist marine air under warm, dry subsiding or continental air and above cool, upwelled coastal ocean water, with warm offshore, upstream sea-surface temperature controlling the properties of the moist trapped air (Leipper, 1948; 1994; Koračin et al., 2005, 2014; Clemesha et al., 2017; Samelson et al., 2021). Fog along western coasts is typically formed through one of two mechanisms, though other mechanisms are possible. In the first, air is advected over a cool ocean surface, typically associated with eastern ocean boundary currents, and cooled to its dewpoint. Such fog forms at the surface and grows upward. In the second, the cloud base of pre-existing low stratus descends until it reaches the surface. Samelson et al. (2021) suggest that the first mechanism is more important for coastal fog in the Pacific Northwest. Globally, it is not known which mechanism is dominant.

The characteristics of these driving elements are likely to shift under climate change, with potential consequences for the coastal fog environment that are still poorly understood. With its dependence on regional physical processes that are sensitive to global climate change, fog plays a critical intermediary role that links global change to a broad range of local impacts, from ecosystem health to public safety. Some climate-model predictions of future fog have been conducted along the PNW coast (O'Brien et al., 2013) and over the North Pacific Ocean (Kawai et al., 2018). However most widely published climate models cannot resolve coastal fog dynamics, and further developments and evaluations are nascent due to sparse long-term empirical records for validating models and the general challenge of developing reliable model predictions of regional climate change (O'Brien et al., 2013). Along the Pacific Northwest coast, Dye et al. (2020) found that coastal fog and low-level clouds over land appear to have declined since 1996 but that coastal fog and low-level clouds over the water have held steady. Such a finding highlights the need for the careful consideration of the spatial variability of fog in coastal regions. Changes in the strength of upwelling winds (Sydeman et al., 2014) or in the source waters for coastal upwelling (Rivas and Samelson, 2011) are two possible future climate evolutions that would likely affect fog.

2.3 Plant ecophysiology and ecohydrology

During fog immersion, the tall canopies of fog-adapted forests enable interception and direct absorption of water droplets deposited on leaves through foliar transport (Limm et al., 2009), and plants with an abundance of root structure at surface soil layers can draw additional moisture from fog drip (Fischer et al., 2009; Carbone et al., 2013; Baguskas et al., 2016). Northern California coastal redwoods (*Sequoia sempervirens*) attain up to two-thirds of their water from fog, while 80% of co-occurring species in redwood forests are capable of absorbing fog water (e.g., Burgess and Dawson, 2004). Coastal Oregon Douglas-fir (*Pseudotsuga menziesii*) also gain significant portions of their water budget through fog drip (Harr, 1982). By eliminating vapor pressure deficit within the upper canopy, fog modulates tree water supply and negates vertical water movement to leaves, promoting moisture retention in soil (Burgess and Dawson, 2004). Fog reduces photosynthetically active radiation by reflecting sunlight, however there is an increase in light-use efficiency as high relative humidity allows stoma to remain open for gas exchange without threatening water supply (Still et al., 2009). Potential photosynthetic gains can be counteracted by reduced leaf temperatures from fog shading, but in most cases fog remains a net benefit to photosynthesis (Oliphant et al., 2011; Berry and Goldsmith, 2020; Baguskas et al., 2021). Additionally, in Peru, coastal advection fog has supported reforestation projects that have restored soil and above-ground biomass in areas that had previously been desertified (Certini et al., 2019). Advances in understanding how fog impacts regional net carbon assimilation and water budget can come from linking satellite measurements of photosynthesis activity and evapotranspiration to high resolution fog datasets, though there is considerable uncertainty in quantifying the amount of water intercepted by the canopy or absorbed through leaves outside of the site scale.

2.4 Biometeorology

Biometeorological aspects of coastal fog integrate cell biology, physics, and atmospheric science, ultimately affecting many interacting features of the coastal system including conservation, forest health, agriculture, and public health–future collaborative research can enhance these linkages. Fog interacts with forest canopies through multiple biotic and abiotic processes linking the plants, microbes, invertebrates, and vertebrates coexisting in these systems. Canopy radiative processes are an intricate balance of the four main wavebands—ultraviolet (UV), visible/PAR, near infrared (NIR) and longwave (TIR). Turbulent processes transport trace gasses (water vapor, CO2 and methane) and biotic aerosols (spores, pollens, bacteria, small invertebrates, other microbes). In addition to ecohydrological effects (2.3), increased TIR from coastal fog can protect species sensitive to frost (Snyder and de Melo-Abreu, 2005).

Fog-related reductions in incoming UV positively affect biology, including photomorphogenesis, phototropism, and flavonoid accumulation, but overexposure can cause DNA damage, reactive oxygen species production, cell death, wilting, yellowing, and decreased photosynthesis. Plant pathogens can be negatively affected by UV-B reductions, but Section 2.6 discusses increased susceptibility of trees and plants to pathogens related to the increased leaf wetness and humidity from fog. A similar issue can be seen in insects and amphibians and their sensitivity to increased UV (e.g., Lundsgaard et al., 2020; Shi and Liu, 2021; Dong et al., 2024). Fog increases deposition of microbes in land ecosystems, and fog itself modifies the microbial floral composition (Evans et al., 2019). Fog deposition, while providing water and additional nutrients to biota, also potentially increases toxic chemicals in the food web, including transmission to humans (Weiss-Penzias et al., 2019), and reduced visibility impedes bird migration (Becciu et al., 2021). Forests can also affect the distribution of fog by fostering cooler, humid environments and emitting organic aerosols that may become condensation nuclei (Hunova et al., 2021).

2.5 Forest dynamics and conservation of old-growth forests ecosystems

Coastal PNW forest ecosystems support iconic old-growth stands, and the moist-cool productive environment of the fog zone is tightly tied to their biogeography and fire ecology. Historically, coastal Sitka spruce (*Picea sitchensis*), Douglas-fir, and shoreline lodgepole pine (*Pinus contorta* var. *contorta*), all contributed to large patches of old-growth forest interspersed with younger stands, non-forest openings, and watershed interconnectivity (Wimberley, 2002; Spies et al., 2018). Extensive logging through the 1900s liquidated much of the old forest, resulting in fragmented remnant mature and old-growth forests now highly valued for conservation and ecosystem services (Johnson, Franklin, Reeves, 2023). Fog, and the moist environment it facilitates, contributes to the productive growing conditions driving these old forests (e.g., 2.3 and 2.9) as well as the fire regimes (Agee, 1993; Spies et al., 2018) influencing their persistence. Coastal old-growth forests are regional fire refugia (Meddens et al., 2018; Krawchuk et al., 2020; Naficy et al., 2021) – locations that experience less severe or frequent fire than the surrounding landscape or region–and more broadly as disturbance refugia, including from drought stress and wind. Summer fog is intuitively an ameliorating factor of fuel moisture and flammability in these systems (Emery et al., 2018; Williams et al., 2018) though no focused research has linked coastal fog, fire, and old forests explicitly for the PNW. Coastal PNW fire regimes are typically characterized by infrequent fire with large patches of high severity fire effects (Spies et al., 2018), however finer scaled (trees and stands) fire refugia within these fires play critical roles in the persistence of older forest (Naficy et al., 2021). A more nuanced pyrogeography, including mixed severity fire regimes and Indigenous cultural burning, is increasingly being recognized as having contributed to the socio-ecological dynamics of these coastal forest ecosystems in the past, and will be important to building our understanding of socially and ecologically sustainable management of coastal forests and old growth into the future. Climate change is projected to increase fire activity (Dye et al., 2024) and shift vegetation types (Reilly et al., 2024) in coastal PNW forests, and recent heat waves exposed vulnerabilities to heat scorch and mortality where fog was not present to buffer near surface temperatures (Still et al., 2023). Future studies at the intersection of fire ecology, old forests, fog, and ecological disturbances are important investments for supporting the conservation and adaptation of old-growth forest ecosystems of the coastal fog region.

2.6 Fog and forest pathogens

Spatiotemporal patterns of fog influence plant moisture and temperature, especially foliage. Forest pathogens (microbes that cause disease in forest plants) that colonize foliage require particular environmental parameters for spore release, transport, deposition, and colonization and infection of leaves. The PNW native fungus *Nothophaeocryptopus gaeumannii* infects Douglas-fir needles, causing Swiss needle cast disease. Its distribution is controlled by fog, leaf wetness, and seasonal temperature dynamics. An active outbreak has been in effect since the late 1990s along coastal Oregon, and subsequently Washington and SW British Columbia, but is uncommon further south (Shaw et al., 2021). Winter temperature and summer leaf wetness during the spore dispersal period (May–August, especially June-July), correlate with infection (Manter et al., 2005). Mild winter temperatures allow rapid colonization of internal portions of the leaf, initiating sporophore development. The fungal development causes early leaf casting, reducing tree productivity. Fog and drizzle create extended leaf wetness periods, facilitating leaf colonization by spores, which are otherwise susceptible to dry-season desiccation. Aerial landscape disease surveys indicate that 75% of areas with visible disease occur within 18 km of the coastline (Shaw et al., 2021), where most coastal fog occurs. Given the conservation, commercial, and recreational role of Douglas-fir in the PNW, reliable spatiotemporal mapping of fog is critical to consider pathogen effects now and in the future.

2.7 Public health and safety

Climate change impacts various aspects of human wellbeing, but health impacts of fog in the context of changing climates have not received extensive attention from researchers. Both mental and physical health may be impacted by fog or its absence. For instance, fog can be hypothesized to contribute to depression. Yet while seasonal affective disorder has been extensively studied, the specific impacts of fog have not. Fog reduces transportation visibility (road, water, rail, and air), leading to injurious or fatal accidents (Abdel-Aty et al., 2011; Fultz and Ashley, 2016). Many coastal communities have poor road networks for evacuation during natural disasters, which may be particularly difficult to navigate in foggy conditions (Dye et al., 2021). It's plausible that fog has negative respiratory health impacts, especially when fog is contaminated by smoke or other pollutants (Hackney et al., 1985). Fog may also alleviate heat-related illness, especially in elderly people during hot summers (Gershunov et al., 2011, cited in Torregrosa et al., 2014).

Accessing drinking and irrigation water through fog "harvesting" raises innovative research questions involving household water and food insecurity and their impacts on multiple aspects of human health. Survey tools for measuring household food and water insecurity make it possible to study potential relationships between fog and both of these constructs, which are fundamental to human wellbeing (Young et al., 2019; Brewis et al., 2020). Thus the potential links between fog and public health are multiple, under-studied, and ripe for advancement.

2.8 Indigenous perspectives on and responses to fog

Across cultures, people see fog as an important factor impacting their wellbeing, navigational abilities, and environments. Environmental anthropologists focus on how humans experience climate change and respond to changing environments, particularly in ways that impact their wellbeing, local ecosystem processes, and climate change itself. Traditional ecological knowledge (TEK), also known as Indigenous local knowledge, is of particular interest because it is based on thousands of years of close co-existence with local ecologies.

In a recent collaborative project, local indicators of climate change were collected by anthropologists through qualitative interviews and focus groups at 48 sites globally, across different climate zones and livelihood strategies, with clouds and fog identified as climate-impacted elements in 15 sites (Reyes-García et al., 2023, 2024a, b). This collaboration is a model for future studies that aim to collect fog-related TEK in western coastal settings.

Integrating TEK into fog research can be accomplished through forms of community-based participatory research that are co-led by Indigenous councils, elders, and researchers, and by ensuring that non-indigenous researchers involved in such partnerships are sensitive to the multiple meanings that fog can carry. Human experiences and responses are mediated by meanings, and entities carry multiple meanings, adding complexity to social-environmental systems. Fog has been an important entity for Indigenous North Americans since time immemorial, with roles in stories about the sea, salmon, and human gender relations. Indigenous Canadians tell a story of a woman whose brothers did not allow her to "be who she truly is," a sea lover and swimmer. Raven made fog so she could disappear into the sea and be left alone (King, 2021). Tlingit peoples maintain a story in which Raven's wife ran away, escaping because "she was the fog." She ran into the water, and all the salmon she had dried followed her (Alaska Native Knowledge Network, 2006).

Fog is known by Indigenous peoples to keep waters cool and better oxygenated for salmon, supplemented by controlled fires to create smoke, which also blocks sun from overheating waters and maintains oak savanna (National Park Service, 2023). Indigenous Californians and Nevadans recognized that long-lasting winter fog impacts respiratory health, referring to it as *pogonip* or "white death" (Alonzo, 2019). Fog is also a metaphor for forgetting trauma, as in the documentary "The Thick Dark Fog" (Vasquez, 2011) examining Indigenous North Americans' memories of abuse at childhood boarding schools, and as a metaphorical barrier created by settler colonialism preventing Indigenous peoples from learning and knowing the orature of their ancestors (Park, 2023).

To further illuminate perspectives on fog among Indigenous peoples, research should combine archival, ethnohistorical, and ethnographic research in close collaboration with Tribes, First Nations and other Indigenous groups. Recent scholarship offers guidelines for inclusive science that contributes to climate change adaptation efforts in ways that recognize histories of settler colonialism and reduce negative impacts of climate change on vulnerable peoples (Hernandez, 2022).

2.9 Forestry, agriculture, and fisheries

Agriculture is strongly tied to the coastal fog belt's influence on species distributions (Franklin and Dyness, 1988). In the PNW coastal fog zone, Sitka spruce, western hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*) dominate, transitioning to Douglas-fir further inland. However, higher-value Douglas-fir is the preferred forest plantation species, even in the fog zone, where it overlaps with prevalence of Swiss needle cast infestations that reduce the tree's productivity and economic value (2.6). In California, coastal redwood is the preferred plantation species in the fog belt because of its high timber value as a timber species and natural association with fog. Food crop agriculture benefits from dry-season fog immersion, increasing water (+50%) and light (+70%) use efficiency in commercial farms (Baguskas et al., 2018). By increasing stream base flow and reducing water temperatures in the warm, dry season, fog cover positively impacts salmon productivity (Sawaske and Freyburg, 2015; Torregrosa et al., 2019). Salmon support a robust fisheries, culinary, and tourism industry across the region and have since time immemorial been a keystone species for North America's west coast Indigenous peoples and ecosystems (Colombi and Brooks, 2012) but face multiple population pressures, including increased water temperatures (Wainwright and Weitkamp, 2013), that could be further affected by changing fog cover.

3 Conclusion and future collaborative perspective

Nearly all aspects of the coastal socio-environmental system are linked to fog. Its initial physical formation over the ocean and movement landward leads to fog as an integral part in the ecohydrological cycle of coastal ecosystems, with heightened importance during dry seasons, maintains a prominent role in Indigenous experience, and impacts agriculture, health, and conservation. A widespread, collaborative approach is needed to build these socio-environmental linkages across disciplines and peoples, many of which are discussed here, combining disciplinary knowledge and experience bases to tackle the shared challenges that will push fog science forward.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

AD: Conceptualization, Supervision, Visualization, Writing–original draft, Writing–review and editing. SR:

Conceptualization, Visualization, Writing–original draft, Writing–review and editing, Supervision. Sd: Conceptualization, Writing–original draft, Writing–review and editing. AI: Conceptualization, Writing–original draft, Writing–review and editing. YJ: Conceptualization, Writing–original draft, Writing–review and editing. JK: Writing–original draft, Writing–review and editing, Conceptualization. MK: Writing–original draft, Writing–review and editing, Conceptualization. KM: Writing–original draft, Writing–review and editing, Conceptualization. LO: Writing–original draft, Writing–review and editing, Conceptualization. KP: Writing–original draft, Writing–review and editing, Conceptualization. RS: Writing–original draft, Writing–review and editing, Conceptualization. DS: Writing–original draft, Writing–review and editing, Conceptualization. CS: Writing–original draft, Writing–review and editing, Conceptualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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