

Balancing on the Edge: Lessons from Peruvian Mangrove Ecosystems under Climate Change Pressure

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Equilibrio al límite: lecciones de los manglares peruanos frente a la presión del cambio climático

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Globally, mangrove ecosystems are among the most productive and valuable coastal environments, and yet they are also among the most vulnerable to both natural variability and anthropogenic pressure (Donato *et al.*, 2011; Alongi, 2014). The mangroves located on Peru's northern Pacific coast constitute a paradigmatic example of a highly dynamic ecosystem, whose structure and functioning are closely defined by hydrological, geomorphological and biogeochemical processes (Pérez *et al.*, 2017; Twilley *et al.*, 2018). Understanding the mechanisms governing their response to environmental forcing (such as extreme hydrological events) is therefore essential for effective management and long-term conservation.

Peruvian mangroves are subjected to a wide range of natural disturbances, including seasonal variability in precipitation, fluctuations in river discharge and tidal dynamics, as well as anthropogenic stressors such as unregulated resource extraction, deforestation, eutrophication and sewage release (Pérez *et al.*, 2017; Pérez *et al.*, 2020). Interaction between these drivers results in pronounced spatial and temporal heterogeneity, rendering mangrove systems particularly sensitive to environmental change. Such sensitivity underscores the need for comprehensive environmental diagnostics, with particular emphasis on the physicochemical characterization of the water column and the geochemical properties of subtidal sediments, which together regulate habitat quality and ecosystem functioning (Donato *et al.*, 2011; Asante *et al.*, 2024).

In this context, high-resolution characterization of both the water column and sedimentary environments provides a critical baseline for evaluating ecosystem health and for developing realistic climate change impact scenarios (Alongi, 2014; Sanders *et al.*, 2016). The geomorphological setting of mangrove systems, together with their characteristic sedimentological properties, organic matter content, water residence time and ambient temperature, jointly regulate redox conditions, nutrient cycling and carbon accumulation (Sanders *et al.*, 2016; Pérez *et al.*, 2017). These biogeochemical processes exert direct control over benthic communities and the ecosystem services they support, including fisheries resources of high ecological, social and economic value (Kristensen *et al.*, 2008; Lee *et al.*, 2014).

Numerous studies of Peruvian mangroves have used these ecosystems as natural laboratories in order to assess how hydrological regimes and estuarine geomorphology influence the geochemical conditions of subtidal sediments and the physicochemical variability of bottom waters (Pérez *et al.*, 2017; Pérez *et al.*, 2018a). In addition, research has highlighted the role of mangrove vegetation in mitigating the impacts generated by unregulated anthropogenic activities, such



as aquaculture and waste inputs (Pérez *et al.*, 2018b; Pérez *et al.*, 2020). Collectively, these integrative approaches have enabled the identification of key processes governing ecosystem resilience and vulnerability under contrasting environmental conditions. Based on the results observed, it is possible to formulate two hypothetical climate change scenarios, each of which implies a markedly different ecological trajectory for Peruvian mangrove ecosystems (Figure 1).

Under a scenario of reduced precipitation, a significant decrease in the discharge of Peru's northern rivers would be expected. This reduction would limit the export of nutrients and carbon from the mangrove system, favoring their accumulation within estuarine sediments (Passos *et al.*, 2021; Asante *et al.*, 2024). Therefore, primary production in channels and tidal creeks would intensify due to elevated nutrient availability, leading to increased biochemical oxygen demand in both the water column and surface sediments (Kristensen *et al.*, 2008; Alongi, 2009). The establishment would be likely of more acidic, highly reducing and persistently hypoxic to anoxic conditions, facilitating the dominance of opportunistic and stress-tolerant species, while constraining the persistence of taxa sensitive to oxygen depletion (Kristensen *et al.*, 2008; Passos *et al.*, 2021). Such conditions could severely

impair the recruitment and survival of benthic resources of socioeconomic significance, including bivalves, crustaceans and penaeid shrimp, particularly when compounded by ongoing overexploitation (Dubuc *et al.*, 2019; Zhan *et al.*, 2023).

Conversely, under a scenario of intensified precipitation, a substantial increase in river discharge would enhance the transport of sediments, nutrients, and carbon toward the coastal ocean, reducing their retention within the mangrove ecosystem (Pérez *et al.*, 2017; Naidu *et al.*, 2022). Both scenarios are consistent with the natural variability characteristic of northern Peru, which is influenced by recurring El Niño and La Niña events —phenomena which, in recent years, have increased in frequency (Reyes *et al.*, 2024).

The predominance of brackish conditions in surface water and sediment, together with increased hydrodynamic forcing, would limit autochthonous primary production, due to nutrient dilution and light limitation. In addition, increased erosion of mangrove-colonized areas and the physical disruption of sedimentary habitats would hinder the establishment of benthic communities (Alongi 2009; Dubuc *et al.*, 2019). Such a scenario would be characterized by low organic enrichment and reduced carbon accumulation, ultimately diminishing secondary

CLIMATE CHANGE SCENARIOS FOR PERUVIAN MANGROVES

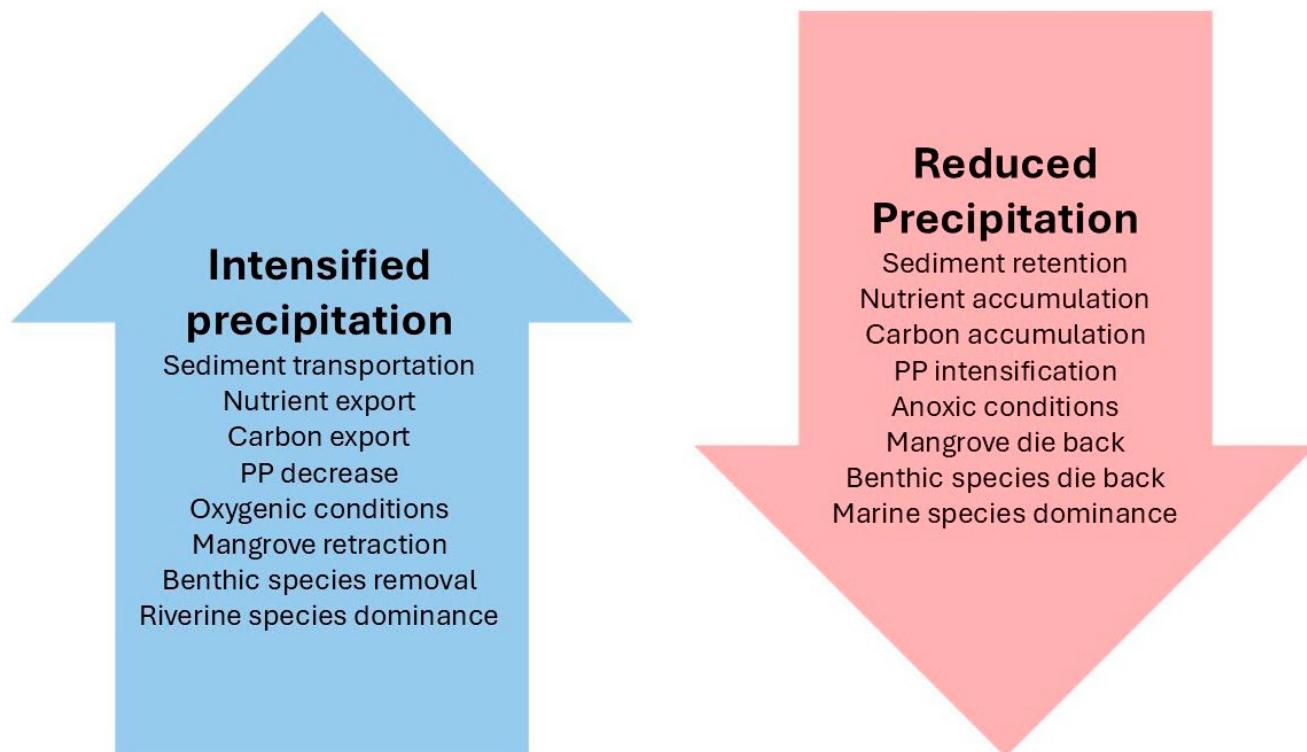


Figure 1. Two climate change scenarios for Peruvian mangrove ecosystems

production and destabilizing trophic interactions within the ecosystem (Alongi, 2014; Lee *et al.*, 2014). Crucially, the current ecological integrity of Peru's mangrove ecosystems is reliant upon the natural alternation between wet and dry seasons, which acts as a regulatory mechanism, balancing carbon accumulation and hydrodynamic flushing (Pérez *et al.*, 2017; Pérez *et al.*, 2021). While the dry season promotes sedimentary carbon retention and autochthonous production, the wet season facilitates a form of natural «flushing» or «detoxification», through enhanced water exchange and sediment redistribution. The permanent establishment of either of these extreme scenarios, as projected under the influence of climate change, would therefore compromise the stability of benthic subsystems and erode the resilience of mangrove ecosystems (Kristensen *et al.*, 2008; Alongi, 2014).

Taken together, Peruvian mangrove ecosystems exemplify the delicate equilibrium between hydrology, geochemistry, human intervention and biological structure in tropical mangrove estuaries. In order to anticipate ecosystem responses to climate change and anthropogenic pressure, the strengthening of long-term, integrated biogeochemical monitoring and

reconstruction efforts in wetlands will be crucial (Pérez *et al.*, 2020; Aponte *et al.*, 2025). Such knowledge offers a robust scientific foundation for the adaptive management strategies required to conserve biodiversity, sustain ecosystem services and safeguard the socioeconomic resources upon which local communities depend.

Authorship contribution

AP: Conceptualization, writing: original draft, writing: review, and editing.

HA: Visualization, writing: review, and editing.

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Potential conflicts of interest

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AI declaration

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