

This study aims to synthesize current knowledge on whale falls, focusing on their ecological roles, successional dynamics, and contributions to deep-sea biodiversity and nutrient cycling. By integrating findings from recent studies, the study seeks to highlight research advances, identify knowledge gaps, and underscore the importance of whale falls as natural laboratories for understanding the functioning and resilience of deep-sea ecosystems.

2 Formation and Stages of a Whale Fall: Succession in Deep-Sea Oases

2.1 Initial fall and physical breakdown

When a whale dies, its carcass sinks rapidly to the ocean floor, often reaching great depths. The descent and initial deposition are influenced by the whale's size, buoyancy, and decomposition gases. Upon arrival, the intact carcass provides a massive, localized input of organic matter to the deep-sea benthos, setting the stage for a series of ecological transformations (Danise et al., 2014; Smith et al., 2014; Bolstad et al., 2023).

2.2 Mobile scavenger stage

The first stage is dominated by large, mobile scavengers such as sharks, hagfish, amphipods, and zoarcid fish. These necrophagous species rapidly consume the soft tissues, often within months to a few years, leaving behind bones and lipid-rich remains. This stage is characterized by intense feeding activity and a sharp increase in local scavenger populations, which can be observed in both modern and fossil whale falls (Danise et al., 2014; Smith et al., 2014; Bolstad et al., 2023; Ibrahim et al., 2024; Serafini et al., 2024).

2.3 Enrichment opportunist stage

As soft tissues are depleted, the whale fall enters the enrichment opportunist stage. Here, the surrounding sediments and exposed bones become colonized by dense populations of opportunistic invertebrates, including polychaete worms (notably *Osedax*), amphipods, crustaceans, and mollusks. These organisms exploit the remaining organic matter and the enriched sediments, often forming dense assemblages that can persist for months to years (Danise et al., 2014; Smith et al., 2014; Silva et al., 2021; Bolstad et al., 2023; Ibrahim et al., 2024; Serafini et al., 2024).

2.4 Sulfophilic stage

The sulfophilic stage is marked by the anaerobic breakdown of bone lipids, producing hydrogen sulfide. This chemical energy supports chemosynthetic bacteria and a specialized community of symbiotic organisms, such as chemosymbiotic bivalves and sulfur-oxidizing bacteria. The sulfophilic stage can last decades, with the composition and abundance of fauna influenced by the geochemical environment and the amount of remaining organic substrate (Amon et al., 2013; Danise et al., 2014; Onishi et al., 2018; Onishi et al., 2020; Bolstad et al., 2023).

2.5 Reef stage (long-term habitat)

In the final reef stage, after most organic material is exhausted, the remaining bones serve as hard substrate for sessile suspension feeders, including barnacles, bryozoans, corals, and tube-dwelling polychaetes. This stage can persist for years, providing a long-term habitat and contributing to local biodiversity until the bones are buried or fully degraded (Danise et al., 2014; Ibrahim et al., 2024; Serafini et al., 2024).

These stages may overlap, and their duration and community composition can vary with depth, carcass size, and environmental conditions, but together they illustrate the remarkable role of whale falls as dynamic oases in the deep ocean.

3 Ecological Importance of Whale Falls in the Deep Ocean

3.1 Nutrient input in nutrient-poor deep-sea environments

Whale carcasses deliver massive pulses of labile organic matter to the deep-sea floor, a region typically starved of nutrients. This input sustains a succession of scavengers, opportunists, and chemosynthetic organisms, increasing local biomass and altering community structure for years or even decades (Butman et al., 1995; Smith and Baco, 2003; Hilário et al., 2015; Dasgupta et al., 2024). Even smaller mammal falls, such as cow or dolphin carcasses, enrich the seafloor and support diverse assemblages, though their impact is less extensive than that of whale falls