International Journal of Molecular Ecology and Conservation, 2026, Vol.16, No.1, 22-30
http://ecoevopublisher.com/index.php/ijmec

Case Study Open Access

Whale-Fall Ecosystems in the Deep Sea Ecological Succession, Biodiversity, and Biogeochemical Significance

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International Journal of Molecular Ecology and Conservation, 2026, Vol.16, No.1 doi: 10.5376/ijmec.2026.16.0003
Received: 10 Jan., 2026
Accepted: 08 Feb., 2026
Published: 28 Feb., 2026

Preferred citation for this article:
Li M.M., 2026, Whale-fall ecosystems in the deep sea ecological succession, biodiversity, and biogeochemical significance, International Journal of Molecular Ecology and Conservation, 16(1): 22-30 (doi: 10.5376/ijmec.2026.16.0003)

Abstract This study systematically analyzes the formation process and ecological succession stages of whale falls, including initial descent, mobile scavenger stage, enrichment opportunist stage, sulfophilic stage, and reef stage, elucidating their roles in maintaining deep-sea biodiversity and nutrient cycling. Key findings highlight that whale falls not only significantly enhance local productivity and species richness but also share ecological and evolutionary links with other deep-sea chemosynthetic environments such as hydrothermal vents and cold seeps, serving as “stepping stones” for species dispersal and adaptive radiation. The crucial functions of whale falls in biogeochemical processes, including carbon sequestration, sulfur cycling, and nitrogen and phosphorus cycling, are also emphasized. However, with the intensification of anthropogenic activities such as whaling, deep-sea mining, bottom trawling, and climate change, the frequency and ecological functions of whale falls are increasingly under threat.
Keywords Whale falls; Deep-sea ecosystems; Biodiversity; Nutrient cycling; Biogeochemistry

1 Introduction

Whale falls, the term for sunken whale carcasses and the ecosystems they create, represent unique and vital habitats in the deep-sea environment. These massive organic inputs deliver concentrated pulses of nutrients to the otherwise food-limited deep ocean, supporting a succession of specialized biological communities and driving significant ecological processes (Smith and Baco, 2003; Smith et al., 2015; Chen and Wang, 2020).

A whale fall is defined as the process and aftermath of a whale carcass descending to the ocean floor, where it forms a localized ecosystem rich in organic matter. These oases provide a substantial energy source for a diverse array of deep-sea organisms, including scavengers, chemosynthetic bacteria, and highly specialized fauna such as bone-eating worms and snails (Smith et al., 2015; Chen and Wang, 2020; Li et al., 2022). Whale falls are considered biodiversity hotspots, supporting thousands of individuals and dozens of species, many of which are new to science or exhibit evolutionary novelties (Smith et al., 2015; Sumida et al., 2016; Chen and Wang, 2020; Li et al., 2022).

The ecological significance of whale falls was first speculated upon in the 19th century, but it was not until the late 20th century that direct observations confirmed their role as unique deep-sea habitats. The discovery in 1989 of a chemoautotrophic community on a whale skeleton in the northeast Pacific marked a turning point, leading to a surge in research and the identification of similar communities in other ocean basins and even in the fossil record dating back 30 million years (Butman et al., 1995; Smith and Baco, 2003; Smith et al., 2015).

Studying whale falls is crucial for understanding deep-sea biodiversity and nutrient cycling. These carcasses act as stepping stones for the dispersal of chemosynthetic organisms, facilitate adaptive radiation, and contribute to the maintenance and connectivity of deep-sea ecosystems (Smith et al., 2015; Sumida et al., 2016; Shimabukuro et al., 2019). The decomposition of whale biomass drives complex successional stages, from scavenger-dominated to chemosynthetic communities, profoundly influencing carbon flux and biogeochemical cycles in the deep ocean (Goffredi et al., 2008; Smith et al., 2015; Chen and Wang, 2020; Amendola et al., 2021; Li et al., 2022).