

Social benefits are most evident where adaptation is embedded in local governance and livelihood systems. Maine's experience shows that kelp farming can diversify coastal economies and is often valued partly for ecological and ethical production practices, while broader ecosystem-approach work links the sector to alternative livelihoods and community well-being. On Canada's Pacific coast, co-designed monitoring with Indigenous stewardship organizations shows that adaptation can also strengthen social-ecological resilience by aligning harvest decisions with local knowledge, climate signals, and community priorities (Denley et al., 2025).

Across typical kelp farming regions, climate adaptation is most effective when it combines site selection, resilient seedstock, engineering upgrades, and participatory management. The evidence supports real ecological, economic, and social gains, but it also shows that benefits are context-dependent and strongest when claims remain aligned with measured outcomes.

7 Issues and Challenges in Climate Change Adaptation for Kelp Aquaculture

Climate change adaptation in kelp aquaculture is constrained not only by the direct effects of warming, acidification, storms, and disease, but also by uncertainty over how these stressors will interact across locations, species, and farming stages (Veenhof et al., 2024; Yadav et al., 2024). These uncertainties complicate decisions on site selection, breeding priorities, farm design, harvest timing, and investment planning, especially in emerging farming regions where long-term operational experience remains limited (Coleman et al., 2022; Veenhof et al., 2024).

At the same time, adaptation is not simply a technical problem. Its success depends on whether farmers can access affordable technologies, whether new systems are economically viable at commercial scale, and whether governance frameworks are flexible enough to support forward-looking responses rather than reactive coping. For kelp aquaculture, the major challenges therefore lie in managing climate uncertainty, overcoming technological and financial barriers, and building policy systems that can enable planned adaptation over long time horizons (Veenhof et al., 2024).

7.1 Risks associated with climate change uncertainties

A central challenge for kelp farming is that future climate exposure is difficult to predict with sufficient local precision for operational decisions. Ocean warming, acidification, altered seasonality, and extreme events can reduce kelp biomass, shift biochemical composition, and damage farms, but their intensity and timing vary across regions and years (Veenhof et al., 2024). More broadly, aquaculture adaptation depends on projections that are accurate enough to guide producers, because unrealistic or biased estimates of climate risk can mislead both farmers and policymakers and increase the risk of maladaptation (Maulu et al., 2021).

Uncertainty is amplified because multiple stressors often act together, while the evidence base remains uneven across stressor types and life stages. High-latitude kelps are projected to face range contractions, with risks intensified by marine heatwaves and increased freshwater and sediment inputs, yet important gaps remain in understanding how kelp microstages respond to combined stressors (Drakard et al., 2023). Risk assessments also suggest that future warming may make seaweed farming unviable in some current production regions, which means adaptation planning must account for the possibility that incremental adjustments will not always be enough (Kim et al., 2024).

7.2 Limitations regarding the adoption of adaptation technologies and investment costs

Although adaptation options such as selective breeding, diversification, improved nursery systems, and offshore expansion are widely discussed, their adoption is limited by technical complexity and cost. Reviews of climate-resilient aquaculture identify selective breeding, species diversification, and advanced systems as leading adaptation pathways, but more complex solutions generally require greater expertise and become less accessible as costs rise (Yadav et al., 2024). This constraint is especially relevant for kelp farming because resilience strategies often depend on research-intensive interventions such as breeding for tolerance, microbiome manipulation, or engineering systems suited to exposed environments (Veenhof et al., 2024).