6 Case Study: Climate Adaptation Practices in Typical Kelp Farming Regions

6.1 Overview of the case study region and climate change characteristics

China, especially its northern production centers such as Shandong and Liaoning, remains the world's largest kelp farming region and therefore offers the clearest case for examining climate adaptation in commercial cultivation. At the same time, newer farming regions in the North Atlantic, such as Maine and Scandinavia, are increasingly important because they combine rapid industry expansion with strong exposure to changing coastal conditions. Across these regions, warming, shifting seasonality, and growing environmental variability are now central constraints on farm productivity and planning (Hu et al., 2021).

Climate risk is not limited to gradual warming. Evidence from China shows that *Saccharina japonica* is already among the most thermally sensitive cultivated macroalgae, and projected warming under future emissions scenarios is expected to increase heat stress across many aquaculture zones. Broader synthesis across kelp systems also shows that ocean warming reduces kelp growth, reproduction, and survival across life stages, while combined warming and acidification often intensify these effects (Roethler et al., 2025).

In practice, climate impacts also emerge through indirect and region-specific pathways. In Sanggou Bay, anomalous environmental change was linked to microbiome disruption and disease outbreaks in farmed kelp, indicating that climate stress can amplify biological hazards rather than acting only through physiology. On Canada's Pacific coast, marine heatwaves advanced bryozoan outbreaks on giant kelp, showing that warming can shift the timing and severity of epibiotic pressure in ways relevant to harvest scheduling and site choice (Zhang et al., 2024; Denley et al., 2025).

High-latitude and offshore-facing regions are not insulated from these threats. Reviews from the northeast Pacific indicate that future kelp performance will be shaped not only by temperature, but also by salinity, sediment load, and light, with important gaps remaining for vulnerable microscopic stages. More generally, ocean warming has already altered the structure and distribution of kelp ecosystems in many parts of the world, even though some populations remain locally stable over decadal scales (Smale, 2019; Drakard et al., 2023).

6.2 Implementation process of adaptation strategies and key technical measures

Adaptation in kelp farming generally begins with risk recognition, followed by adjustments in siting, seedstock, farm design, and seasonal operations. In China, proposed responses to climate pressure include preserving wild and cultivated germplasm, selecting sites suited to changing environmental conditions, breeding stress-resistant cultivars, and adopting innovative cultivation models. Similar ecosystem-based guidance from Europe and North America emphasizes climate resilience, protection of wild genetic diversity, and management systems that account for environmental carrying capacity (Hu et al., 2021).

Site selection is a first-line adaptation because local exposure strongly shapes farm vulnerability. Chinese reviews identify the selection of suitable cultivation sites under changing conditions, including possible expansion into more offshore spaces, as a major response to warming and other coastal pressures. Canadian case evidence similarly shows that adaptive management can favor cooler and more wave-exposed sites, while reducing harvests in warmer years and shifting harvest earlier when seasonal warming arrives unusually soon (Hu et al., 2021; Denley et al., 2025).

A second implementation pathway is biological improvement of farm stock. Recent experimental work suggests that thermal priming of *Saccharina latissima* gametophytes can increase subsequent sporophyte growth by up to 30% and extend tolerance under heat stress, indicating a practical crop enhancement route for warming seas. Genomic work on southern Chinese *S. japonica* cultivars further indicates that adaptation to relatively high seawater temperature involves changes in amino acid metabolism, sugar metabolism, osmotic regulation, and innate immune responses, supporting selective breeding for thermal resilience (Figure 2).

A third pathway is engineering adaptation. Because sheltered nearshore space is limited, offshore cultivation is increasingly proposed as a climate adaptation option, but it requires more robust infrastructure. Engineering analyses