*General Article*______________________________________ *Chapter – 10*

KELP FOREST: ECOLOGICAL SIGNIFICANCE AND RESTORATION PROSPECTS

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Abstract

Kelp, the sequoia of oceans encompasses approximately 25% of the global coastal expanse. The submerged ecosystem characterized by brown algae (Kelp) that flourish within a depth ranging from 0 to 50 meters forms the Kelp Forest. These underwater forests are renowned for their exceptional productivity and dynamic nature. Kelp forests are distributed across the globe, spanning the Pacific, Atlantic, Indian, and Arctic coastal oceans, excluding Antarctica. Kelp forests offer a variety of benefits to society (encompassing food, energy, recreational resources, and coastal protection), nutrient cycling, and carbon sequestration. Kelp demonstrates an exceptional growth rate, exceeding that of land-based plants by over 30 times. As a result, a single acre of kelp forest has the capacity to absorb up to 20 times more carbon dioxide (CO_2) from the atmosphere compared to terrestrial forest. The ecosystem of kelp forests primarily revolves around the kelp, detritus, and the plankton-based food chain. Approximately 80% of kelp production enters the coastal ecosystem as detritus, which can take various paths, such as washing up on beaches, sinking to the seafloor, or being consumed and decomposed. Kelp forest ecosystems and the valuable services they provide are experiencing declines on a global scale, particularly in areas characterized by elevated seawater temperatures and rapid warming. In response to threats, marine managers are taking action to restore and mitigate these declines. Academic researchers have played a significant role in the restoration of kelp ecosystems. Various methods, such as transplanting, seeding, grazer control, and the implementation of artificial reefs, are actively used to restore kelp populations, with the choice of method depending on the underlying causes of decline. However, future restoration efforts may need to undergo significant changes to keep pace with the escalating rate of environmental change.

Keywords: Kelp, Brown algae, Climate change, Seagrass

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Introduction

Kelp, the green lungs of the oceans, cover a quarter of the world's coastline. The order Laminariales, a group of brown algae commonly referred to as kelp, are critical foundation species of the planet. The production of kelp per unit area is the counterpart of intensively managed agricultural areas and tropical rainforests, making them one of the planet's most teeming primary producers. The kelp forest is an underwater forest environment that typically develops between 0 and 50 meters of water and has a high kelp density. Identical to forests on land, these are the ecosystems that constitute brown algae(seaweed) in place of trees and are characterized by both a canopy and an understorey (Verges and Campbell, 2020). They store and cycle significant volumes of CO_2 and are the third most productive system in the world (Filbee-Dexter & Wernberg, 2020). The worth of kelp forests is projected to be $US 684 billion annually worldwide through direct exploitation, harvesting and indirect contributions to monetarily valued businesses like fishing and tourism (Eger *et al*., 2021). Kelp forests boost the productivity of nearshore habitats by acting as a source of food and habitat for a range of different species. The preferable conditions to thrive on are a hard substrate typically rocks or sand, light (minimum yearly irradiance dosage > 50 E m^2), and a nutrient-rich environment (nitrogen and phosphorus). The process of oceanographic upwelling, which transports cool water rich in nutrients from the bottom to the mixed surface layer of the ocean, is known to relate to regions of prolific kelp forests. The morphological structure of kelp thallus (body or plant structure of kelp) is specialized to aid in its ability to survive and expand in aquatic environments. The holdfast, the stipe, and the blade or lamina are its three basic components. The holdfast, which is the bottom part of the thallus, acts as an anchor to secure the kelp to rocks or other seafloor materials. It is made up of a mass of haptera, which resemble roots and exude a gooey fluid that aids the kelp in remaining securely attached to the substrate even in the presence of powerful water currents. The stipe, which extends from the holdfast and resembles a long, flexible stem, supports, and raises the rest of the thallus above the ocean floor. The leaf-like portion of the kelp thallus is called the blade, often referred to as the lamina. It grows laterally from the top of the stipe and serves as the kelp's primary photosynthetic organ. In addition to these primary components, the kelp thallus may also have pneumatocysts, which are bladder-like structures occupied by gas that is located within the stipe or at the base of the blade. They give kelp buoyancy, assisting it to stay upright and nearer to the water surface where it can utilize sunlight for photosynthesis.

Distribution

Kelps are mostly found in arctic and temperate waters throughout the planet. Laminaria, one of the most prevalent genera, is primarily connected to both sides of the Atlantic Ocean as well as the coasts of China and Japan; Ecklonia, on the other hand, is found in Australia, New Zealand, and South Africa; and Macrocystis, which is widespread in the Southern Ocean archipelago, the Northeastern and Southeast Pacific Oceans, and in isolated patches near Australia, New Zealand, and South Africa. The northeastern Pacific, from north of San Francisco, California, to the Aleutian Islands, Alaska, has the highest diversity of kelps (>20 species) (Verges and Campbell, 2020).

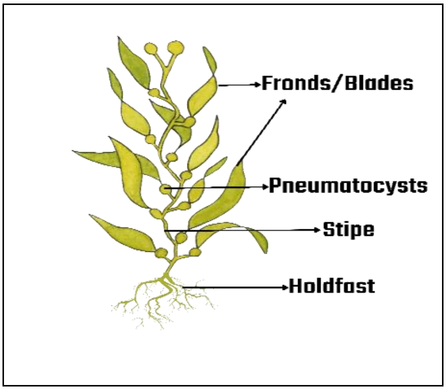

Fig1. Morphological structure of Kelp

Fig 2. Kelp Forest

(Source:https://fishreef.org/2022/03/sea-cave-restores-cold-water-kelp-forests/)

Life Cycle

Kelp can reproduce both sexually (egg fertilization) and asexually (kelp fragments). Large fronds known as sporophyte blades have sorus tissue that is developed enough to release zoospores or meiospores for sexual reproduction, which get settled in 48 hours. Initiating with the microscopic stage, followed by the gametophyte stage where the settled spores shed their flagella and are used for locomotion. Spores transform into male and female gametophytes during the gametophyte stage. Male antheridia or female oogonium are produced as the cells undergo sexual differentiation. In contrast to the female oogonium, which is utilized to generate eggs, the male antheridia produce sperm. A zygote is created when the generated sperm fertilizes an egg. Once the egg is fertilized, the diploid zygote divides, grows into a small juvenile sporophyte that is generated basally as the blade expands, eventually becomes the holdfast that serves as the kelp's anchor, and eventually matures into a sporophyte that is utilized to begin new reproduction (Visch *et al*., 2019).

Importance

Numerous environmental services provided by kelp forests, including protection of shorelines, nitrogen cycling, and commercial fishing, are worth billions of dollars each year (Bennett *et al*., 2016). People from different continents and times have valued vast kelp forests considerably. Archaeological research reveals how kelp forests helped early Americans go southward about 20,000 years ago (Erlandson *et al*., 2007). Since the 8th century, Japanese, Korean, and Chinese economies have relied heavily on kelp harvesting as well as other associated plants and animals in the Northwest Pacific, where they are consumed for food and livelihood. Since ancient times, kelp has been used in Europe to produce soda ash, treat ailments caused by iodine deficiency, and as a fertilizer to boost crop yields (Kain & Dawes, 1987). Alginate, also known as algin from alginate-yielding seaweeds, is a common food additive as well as a component in medicine and bioengineering. In the 20th and 21st centuries, kelp forests have taken over as the primary source of alginate. Around the world, kelp forests serve as habitat for significant abalone, lobster, reef fish, and kelp fisheries. Furthermore, kelp forests' high production rate allows them to supply oxygen, remove carbon dioxide from the atmosphere, and lessen marine nutrient pollution (Filbee-Dexter & Wernberg, 2020; Eger *et al*., 2023).

Role in Climate Change Mitigation

Kelp forests could reduce the negative effects of climate change through two possible ways. First, kelp forests account for a sizable amount of the global budget of organic carbon with their substantial standing biomass, rapid production rate, and global distribution. Even though most kelp lives on shallow rocky reefs where carbon cannot be retained, detached kelp (40–80% of total biomass) is frequently transferred to other environments where carbon sequestration is possible (for example, in deep coastal sediments). Second, kelp photosynthesis increases the pH of the surrounding water by absorbing dissolved inorganic carbon during the day which may assist in reducing ocean acidification (Verges and Campbell, 2020). Inorganic carbon makes up more than 2000 mol kg^{-1} of seawater in the oceans, while organic carbon makes up 35 to 150 μmol kg^{-1} of seawater (Ould and Caldwell, 2022). Through photosynthesis, the biological carbon pump incorporates carbon into biomass, which is then transported to depth by sinking through the water column. Seasonal variations in ocean carbon stores are 5% (McGuire *et al*., 2009). In the case of macroalgae, dissolved organic carbon (DOC) makes up around 52% of the exported carbon, while particulate organic carbon (POC) makes up the remaining 48% (Ould and Caldwell, 2022). Due to the chemical composition of detrital material determining the rate of degradability, rates of DOC and POC differ across macroalgae species. Carbon from *Palmaria spp*. (red macroalgae) remineralizes more easily than *Desmarestia* (brown macroalgae). POC is recycled in significant amounts in shelf seas (for example, as beach cast material); nonetheless, a large majority of the POC is exported beyond the continental shelf and sinks to depth. While the more resistant DOC fraction is still accessible to microbial mixotrophs and heterotrophs, it is exported to depth with more ease. A balance between carbon fixation and remineralization determines the effectiveness of the ocean's biological carbon pump (Passow and Carlson, 2012). Less POC is carried to depth and, consequently, less is buried for long-term storage when remineralization proceeds more quickly. In fact, a deepening of only a few tens of metres can account for changes in atmospheric CO_2 concentrations of between 10 and 30 ppm (Roth *et al*., 2014). As the oceans warm, it is predicted that the remineralization depth will increase (and the sequestration flux depth will increase). As a result of the significantly lower temperatures and oxygen levels at deep, where these detrital carbon sources are exported (and eventually assimilated inside stable sedimentary reserves), this is considered to be long-term carbon storage (Ould and Caldwell, 2022). Recent research estimated that 153 Tg C yr^{-1} (0.153 Gt) of macroalgae carbon is sequestered in deep-sea sediments, with 14 Tg C yr^{-1} (0.014 Gt) buried in shelf sediments and an additional 6.2 Tg C yr^{-1} (0.0062 Gt) buried from macroalgae growing in soft sediments (Krause-Jensen and Duarte, 2016). Although there are considerable differences between species and places, these estimates still exceed the total amount of carbon buried by salt marshes, mangroves, and seagrasses put together. It has been calculated that by 2100, we must remove between 640 and 950 Gt of CO_2 from the atmosphere, or roughly 8 to 12 Gt of CO_2 every year (Luderer *et al*., 2018). This will allow us to stay under the 1.5^{o} C limit of world temperature increase. The measured capacity of macroalgae to meet the targets by 0.1732 Gt yr^{-1}, or between 1.44% and 2.17% per annum is substantiated by their propensity to flourish on rocks rather than in sediments. The capacity to scale up biomass production through aquaculture, should not be discounted; however, it also shouldn't be superficially exaggerated (Ould and Caldwell, 2022).

Threats

In globally distributed environment, kelp forests have been put forth on decline stage now (Rogers-Bennett & Catton, 2019). The cause of decline varied from regional stressors like pollution to global effects like climate change (Wernberg *et al*., 2019). Early kelp forest reductions in the 1800s were associated with sea urchin population growth, which erupted possibly by the eradication of urchin predators from the environment. Threats like direct kelp harvesting or significant urban water pollution were the main causes of subsequent kelp population decrease in the 20^{th} century (Coleman *et al*., 2008). These stressors are still important for managing the kelp ecosystem today, but they are also influenced by climate change, with a variety of negative effects. The kelp population has experienced significant contractions because of elevated water temperatures and marine heatwaves pushing them over their physiological preferences and limits. The extension of the range of herbivorous sea urchins, which can overgraze entire forests and form urchin barrens, has also been made easier by warmer seawater temperatures. This phenomenon has been observed in most kelp-producing nations. A similar decrease in kelp forests towards the warmer limit of their distribution has also recently been linked to temperature-driven changes in the ranges of herbivorous fishes (Zarco-Perello *et al*., 2017). Such significant losses have a severe impact on the environment and the economy. For instance, kelp losses have resulted in the closure of kelp, sea urchin, abalone, lobster, and other fisheries in numerous parts of the world.

Restoration

With the loss of kelp forest habitats and the associated ecosystem services, marine managers are acting in response by attempting to halt and reverse these declines. Restoration of kelp forests has been done for more than 300 years and has taken place in 16 different nations by a wide range of societal sectors, including academia, governments, communities, indigenous groups, and companies. The practice of kelp restoration was introduced in Japan in the 1700s and has subsequently taken off globally. Japan has the longest and most extensive history of kelp forest management in the world, with more than 700 documented restoration initiatives since the 1970s (Eger *et al*., 2022). In the past, managing kelp forests was a passive activity in which managers concentrated on enhancing environmental or physical conditions, such as by enhancing water quality, limiting kelp harvest, or protecting species that support kelp forests. In addition to lowering human pressures and increasing populations of animals that support kelp forests, marine protected areas (MPAs) have been successful in doing so (Caselle *et al*., 2015). The United Nations (UN), which has designated 2021–2030 as the "Decade of Ecosystem Restoration" and the "Decade of Ocean Science for Sustainable Development," oversees the greatest efforts. In addition to providing necessary ecosystem services, protecting biodiversity, and ensuring food security, are separate but related activities urging a global focus on renewing marine and other ecosystems (Waltham *et al*., 2020). The goals of both UN efforts may be achieved by restoring kelp forests.

Restoration Methodologies

There are four basic active restoration techniques for kelp population: transplanting, seeding, grazer control, and artificial reefs; the method chosen depends heavily on the reason for the drop.

Transplanting

Typically, to transplant kelp, the holdfast is attached to an artificial substance, which is then lowered into the water with the hope that it would migrate to the benthos or serve as a seed source and habitat for new plants. For example, holdfasts are glued to the rock, attached to small concrete blocks or stones, tied to ropes, attached to already-existing holdfasts, and attached to mesh mats that are themselves anchored to the seafloor or to artificial substrata (Marzinelli *et al*., 2009). Scalability and how effectively the plant can adhere to the seafloor are the main drawbacks of each of these methods. Since kelp must be physically transplanted, manual installation will probably be too expensive for large-scale restoration operations. The use of laboratory-cultured gametophytes that are connected to small stones (i.e., gravel), cultivated in the lab, and then distributed into the ocean is part of a novel technique being developed under the name "green gravel," which shortens deployment time by eliminating the need for divers and boosts scalability. The advantage of transplanting is that it brings plants into the ecosystem and improves the surroundings so that new recruits can thrive (Layton *et al*., 2019). Therefore, transplanting might be the first crucial step to create source populations that later self-produce.

Seeding Kelp Populations

The act of "seeding" entails spreading and/or growing the juvenile life stages of kelp in the ocean, including seeds, gametophytes, propagules, and zoospores. Less emphasis has been paid to seeding kelp populations than to transplanting. This might be because of the extraordinarily high mortality of kelp propagules and the perceived benefit of concentrating on sporophytes, where survival is enormously higher. In projects that have used seeding, the propagules have often settled on the sea floor by being weighted to the bottom of mesh bags packed with fertile kelp blades (Westermeier *et al*., 2014). Since divers are required to install and remove the bags from the ocean, these efforts have only little results and have continued to take a lot of time.

Removing Competitor

Despite of variety of methods for removing kelp competitors from the sea floor, the removal of kelp competitors from the sea floor has received very little attention. While some of these techniques, like a chain spun by wave action, can be maintained without ongoing input, others, like manual or mechanical removal, need a significant amount of labour. Whatever the method, large-scale scraping of the benthos is probably unworkable in most nations and places, therefore this strategy will probably only be used at small-scale transplant sites where displacing rivals may help to establish the desired kelp population (Eger *et al*., 2022).

Grazer Control

The removal of the animal manually from the intended restoration area or its exclusion is the main method for controlling grazers. This may involve killing sea urchins with quicklime, crushing, moving, or harvesting them (Piazzi & Ceccherelli, 2019).

Artificial Reefs

Although they are utilized more frequently in afforestation projects than in restoration ones, this is nevertheless a widely employed strategy. Therefore, artificial reefs are erected in environments that previously lacked kelp (for example, on a sandy substrate, as is typical). In Japan and Korea, the use of artificial reefs for afforestation is common, but there is more opposition elsewhere (Tickell et al., 2019).

Future Restoration Methodologies

Even though environmental change has historically been rather slow, future restoration strategies may need to shift considerably to keep up with the pace of changing climatic conditions. For instance, choosing specific kelp genotypes for restoration may have significant benefits, either through selective breeding, direct genetic modification, or adopting kelps that have withstood harsh occurrences (Coleman & Wernberg, 2020). The establishment of seed banks on land to protect genetic material that may otherwise vanish is being taken into consideration (Layton & Johnson, 2021). Adding beneficial microbes to kelp microbiomes can improve the kelp's resistance to stresses and the success of restoration efforts. Increasing beneficial interactions between kelps and other species is essential for restoration success more generally. Additionally, although still only a theory, the employment of autonomous robots such as those created to eradicate crown-of-thorns sea stars on the Great Barrier Reef could continuously eliminate urchins over vast geographic areas. Any automated and remote method, nevertheless, must be carefully weighed against any potential threats to other ecosystem components, such as threatened or endangered species (like abalone). Future management strategies should focus on reducing the overfishing of important species, sedimentation, and pollution rates, and eventually working to limit or even reverse greenhouse gas emissions that are warming the oceans beyond the physiological tolerances of some species.

Conclusion

Beyond the realms of marine life, kelp forests stand as remarkable ecosystems, showcasing high productivity and biodiversity while providing a multitude of essential ecosystem services. Furthermore, kelp forests play a crucial role in sequestering a significant amount of carbon contributing to the blue carbon stock and assisting in mitigating climate change. Multiple climatic and non-climatic stresses have contributed to the degradation of kelp. Fortunately, attempts to actively restore kelp populations around the world have increased because of the rising concern and awareness. Different strategies are being researched and put into practice robustly. The promising restoration efforts tend to revive kelp forests guaranteeing the preservation of their priceless contributions to the health and well-being of humankind. Overall, keeping the relevance of kelp forests in view in terms of their capacity to fight climate change, and the wide range of ecosystem services they offer, it is required to count kelp forests as an ecosystem of prime value.

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