

## **Carbon Sequestration Job: Kelp Wanted, Sea Urchins Need Not Apply!**

“Where’s my drink? My Diet Dr.Kelp?! Don’t tell me you forgot my drink (Hillenburg, 1999)!” While this Bikini Bottom customer may have had a slight overreaction to Spongebob forgetting his drink, he certainly is right about one thing: we can’t forget the (Diet Dr.) kelp! Kelp forests are unassuming ecosystems doing more than meets the eye; they support high levels of both primary and secondary production, form structurally diverse microhabitats, and aid in buffering coastal erosion (Steneck et al., 2002). Perhaps most importantly, kelp forests are a significant carbon sink, helping to sequester excess anthropogenic carbon and combat climate change (Filbee-Dexter & Wernberg, 2020). However, these forests face many threats, with the most significant being herbivory (Estes et al., 2010). In particular, purple sea urchins (*Strongylocentrotus purpuratus*) have developed a real taste for kelp, and are chowing down across mid-latitude coasts faster than you can say she sells sea shells by the sea shore (Pearse, 2006). Not all hope is lost though, as an unlikely hero provides an otter-ly adorable solution to urchin-driven kelp forest loss.

### **Kelp Forests: A Brief Background**

Boasting impressive sizes, with some growing as tall as 150 feet under the water’s surface, as well as expansive ranges, including the North American Atlantic and Pacific Coasts, UK, Japan, and surrounding the Aleutian Islands, kelp forests provide an important habitat for many aquatic species (Steneck et al., 2002). While they are taxonomically simple, composed predominantly of only 20 species of brown algae, kelp forests are simultaneously structurally diverse, typically featuring three tiered- layers of vegetation – a small, medium, and large size variety of kelp (Steneck et al., 2002). This vegetational complexity allows kelp forests to harbour predators amongst their canopies, foster nursery habitats in their understories, and support a variety of low-light adapted species (Steneck et al., 2002). Additionally, kelp forests respond quickly to disturbance, offering an important buffer against coastal storms and related erosion (Steneck et al., 2002). Evidently, kelp forests support a high level of biodiversity due to their physical structure alone, but are also particularly important for secondary production. They are a direct source of energy for kelp consuming organisms, as well as an indirect energy source in detritus-based food webs, where kelp fragments drift to the benthos and are consumed by microbes (Steneck et al., 2002).

### **The Sea Urchin Problem**

Kelp ecosystems exist in a stable state paradigm, wherein they are either highly productive kelp forests, or urchin-dominated barrens, devoid of any vegetation (Pearse, 2006). Urchin barrens are most common in mid-latitude areas, where sea urchin herbivory is the driving cause of kelp deforestation, and the shift from forest to barren typically requires external damage to kelp (Pearse, 2006). Normally, sea urchins are stationary inhabitants in kelp forests, feeding on kelp litter that has detached from living plants (Pearse, 2006). However, when kelp is damaged (e.g. by storm events), urchins will begin to forage on establishing kelp recruits, effectively preventing the reestablishment of the forest state (Pearse, 2006). Recently, there has been both a significant increase in extreme coastal weather events due to climate change, as well

as human capture of urchin predators through fishing activities over the last century (Steneck et al., 2002; Wright et al., 2021). Together, these impacts have led to increasing kelp damage, an overabundance of urchins, greater kelp consumption, reduced disturbance response of kelp, and a subsequently, a growing ratio of barrens to forests (Steneck et al., 2002; Estes et al., 2010). Along the Californian coast alone, it is estimated that up to 95% of kelp forests have transitioned into urchin-barrens – creating serious problems for carbon uptake (McPherson et al., 2021).

In terms of productivity, kelp forests fix up to four times as much inorganic carbon as their sea urchin barren counterparts via photosynthesis, and account for nearly 3% of global blue carbon sequestration (Estes et al., 2010; Filbee-Dexter & Wernberg, 2020). Despite their contribution to carbon sequestration, kelp forests have often been overlooked as a viable carbon sink in favour of accreting coastal vegetation, such as mangrove forests or seagrass beds (Filbee-Dexter & Wernberg, 2020). These ecosystems predominantly accumulate carbon in their soils and sediments, while kelp forests, which are typically situated on rocky coastlines, store carbon in their own biomass (Filbee-Dexter & Wernberg, 2020). Yet, kelp forests are estimated to sequester more than 170 teragrams of carbon per year (Wright et al., 2021; Bayley et al., 2021)! With the proportion of barren habitat increasing significantly in mid-latitude areas due to human-mediated urchin population booms, combined with the current anthropogenic undervaluing of the importance of kelp forests in global carbon sequestration, these habitats are at risk. How can we control urchin densities to promote kelp growth, and thus, increase carbon uptake? Well, the answer may surprise you, but one potential solution is sea otters!

### **Sea Otters to the Rescue**

Prior to their overhunting in the late 19<sup>th</sup> century, sea otters (*Enhydra lutris*) were abundant across many of the same rocky coastal ecosystems where kelp forests are found today, filling roles as both keystone species and ecosystem engineers (Dean et al., 2000; Estes et al., 2010). Namely, sea otters ensured the maintenance of kelp forests by consuming mass amounts of the otherwise dominant primary consumers, purple sea urchins (Estes et al., 2010). However, when their population sizes were reduced to below “ecologically effective sizes” by hunters, sea otters were no longer able to control sea urchin populations or initiate a related trophic cascade by doing so, which helped to promote sediment deposition and decrease coastal erosion (Estes et al., 2010). Sea otters are equally as dependent on kelp forests as these areas are on them, relying upon the forests for shelter from predators, like sharks, a source of prey, and nursery habitats (Nicholson et al., 2018). Thus, the 19<sup>th</sup> century decline in sea otters, followed by an increase in sea urchins, and subsequent decrease of kelp forest habitat, acted as a positive feedback loop, negating the ability of both sea otters and kelp forests to fulfill their original ecological roles (Estes et al., 2010).

Since the initial loss of sea otters, many marine conservationists and scientists have been working to help their populations rebound, and through these efforts have discovered correlations between kelp forest area and sea otter survival rates, sea otter presence and urchin barren presence (**Fig 1**), as well as sea otter presence and net primary productivity of kelp forests (Dean et al., 2000; Estes et al., 2010; Wilmers et al., 2012). Aquariums, such as the Monterey Bay Aquarium in California, have already experienced great success with otter reintroduction

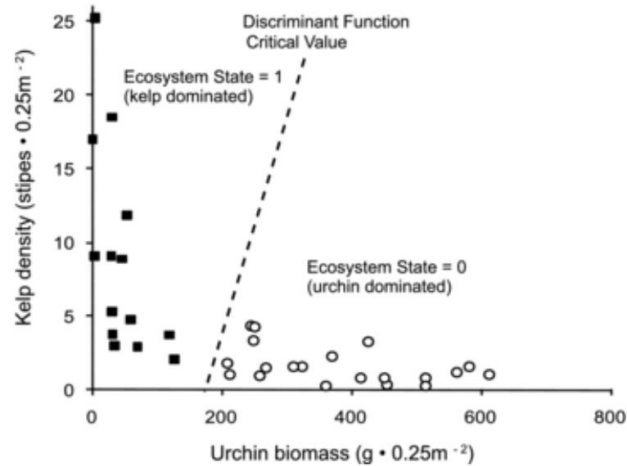
programs and related sea urchin control (Monterey Bay Aquarium, 2019). Most of the young otters participating in this program have experienced little to no time in natural environments before being released to the wild, as they were rescued as stranded pups, or born in the facility (Monterey Bay Aquarium, 2019). Majority of the older otters were rescued following serious injuries and had already established a “home range territory” before arriving, meaning that upon re-release, these adults were likely to seek said territories (Monterey Bay Aquarium, 2019).

The staff at Monterey Bay realized that this conundrum presented a unique opportunity; older female otters could act as surrogates for the younger otters during their stay in the aquarium, so that when they were all released to the wild, pups would have learned adequate survival skills from their surrogates, but lack “site fidelity” (Monterey Bay Aquarium, 2019). Why is this important? Well, majority of urchin barrens along the Californian coast are lacking otters, likely because the mammals have already set their territories in productive kelp forests. However, young pups who have no set territory, will simply remain where they are released – meaning they provide a potential solution to controlling urchin populations across many uninhabited barrens (Monterey Bay Aquarium, 2019). Additionally, the aquarium has discovered that otters released from this program between 2002-2016, as well as their wild-bred offspring, currently account for more than half of the total population in Elkhorn Slough (**Fig 2**), a degraded estuary nearby Monterey Bay (Monterey Bay Aquarium, 2019). This demonstrates that surrogate-reared otters and their kin are able to survive equally as wild as wild otters, supporting the Monterey Bay reintroduction program as a viable solution to increasing otter populations across mid-latitude urchin barrens.

### **Getting by With a Little Kelp From our Friends**

With climate change at the forefront of many minds, carbon uptake solutions are of critical importance – especially those that are not land or resource-intensive, like blue carbon sinks including kelp forests (Filbee-Dexter & Wernberg, 2020). All in all, these ecosystems face a multitude of threats, ranging from commercial harvesting to natural storm damage, but none are as great as human-mediated sea urchin herbivory across the mid-latitudes (Estes et al., 2010). By controlling sea urchin populations, otters ensure that kelp forests do not experience phase shifts into urchin barrens, allowing for continued kelp growth, and thus, maximum carbon sequestration at local scales (Wilmers et al., 2012). With evidence of successful otter reintroduction programs across the mid-latitudes, as well as demonstrated positive correlations between otter presence and phase shift transitions from urchin barrens to kelp forests, it would be otter nonsense not to pursue this as a potential solution!

## Appendix



**Figure 1:** This graph plots average annual kelp density against average annual purple sea urchin biomass across 436 sites along the Aleutian archipelago from 1987-2006. Circles indicate low-density sea otter populations ( $<6/km$ ), while squares represent high-density sea otter populations ( $>6/km$ ), displaying a positive correlation between high-density otter populations and kelp density, as well as a negative correlation between high-density otter populations and urchin biomass (Estes et al., 2010).



**Figure 2:** An otter raised in the Monterey Bay Aquarium's surrogate program being released into Elkhorn Slough for the first time (Monterey Bay Aquarium, 2019).

## References

- Bayley, D., Brickle, P., Brewin, P., Golding, N., & Pelembe, T. (2021). Valuation of kelp forest ecosystem services in the Falkland Islands: A case study integrating blue carbon sequestration potential. *One Ecosystem*, 6, 1-26. doi:<https://doi.org/10.3897/oneeco.6.e62811>
- Dean, T., Bodkin, J., Jewett, S., Monson, D., & Jung, D. (2000, June). Changes in sea urchins and kelp following a reduction in sea otter density as a result of the Exxon Valdez oil spill. *Marine Ecology Progress Series*, 199, 281-291. doi:10.3354/meps199281
- Estes, J., Tinker, M., & Bodkin, J. (2010, May). Using ecological function to develop recovery criteria for depleted species: sea otters and kelp forests in the Aleutian Archipelago. *Conservation Biology*, 24(3), 852-860. doi:<https://doi.org/10.1111/j.1523-1739.2009.01428.x>
- Filbee-Dexter, K., & Wernberg, T. (2020, July). Substantial blue carbon in overlooked Australian kelp forests. *Scientific Reports*, 10, 12341. doi:<https://doi.org/10.1038/s41598-020-69258-7>
- Hillenburg, S. (Director). (1999). *Spongebob Square Pants* [Television series]. USA: Nickelodeon.
- McPherson, M., Finger, D., Houskeeper, H., Bell, T., Carr, M., Rogers-Bennett, L., & Kudela, R. (2021). Large-scale shift in the structure of a kelp forest ecosystem co-occurs with an epizootic and marine heatwave. *Communications Biology*, 4, 298. doi:<https://doi.org/10.1038/s42003-021-01827-6>
- Nicholson, T., Mayer, K., Staedler, M., Fujii, J., Murray, M., Johnson, A., ... Van Houtan, K. (2018, February). Gaps in kelp cover may threaten the recovery of California sea otters. *Ecography*, 41(11), 1751-1762. doi:<https://doi.org/10.1111/ecog.03561>
- Pearse, J. (2006, November). Ecological role of purple sea urchins. *Science*, 314(5801), 940-941. doi:10.1126/science.1131888
- Sea otter rescue and research (2021). In *Monterey Bay Aquarium*. Retrieved from <https://www.montereybayaquarium.org/stories/sea-otter-rescue-and-research>
- Steneck, R., Graham, M., Bourque, B., Corbett, D., Erlandson, J., Estes, J., & Tegner, M. (2002, December). Kelp forest ecosystems: biodiversity, stability, resilience and future. *Environmental Conservation*, 29(4), 436-459. doi:<https://www.jstor.org/stable/44520631>
- The feel-good science behind sea otter surrogacy (2019). In *Monterey Bay Aquarium*. Retrieved from <https://www.montereybayaquarium.org/stories/the-feel-good-science-behind-sea-otter-surrogacy>
- Wilmers, C., Estes, J., Edwards, M., Laidre, K., & Konar, B. (2012, September). Do trophic cascades affect the storage and flux of atmospheric carbon? An analysis of sea otters and

kelp forests. *Frontiers in Ecology and the Environment*, 10(8), 409-415.  
doi:<https://doi.org/10.1890/110176>

Wright, L., Pessarrodona, A., & Foggo, A. (2021, October). Climate-driven shifts in kelp forest composition reduce carbon sequestration potential. *Research Square*, 1.  
doi:[10.21203/rs.3.rs-957301/v1](https://doi.org/10.21203/rs.3.rs-957301/v1)