Climate Change Driven Direct and Indirect Influences on Kelp Forests

Joan Doe

Introduction

Climate change poses critical and potentially detrimental effects on various aspects of natural ecosystems such as kelp forests. Kelp forests are important ecosystems in temperate ocean climates, composed of large brown algae that are generally found in relatively shallow, cool water near the coast and provide a multitude of ecological benefits. Facilitating high biodiversity and primary productivity, kelp forests create whole communities, supporting species in all trophic levels (Andrews et al. 2014). Therefore, it is important to assess the possible consequences a changing climate might have on kelp forest ecosystems.

In addition to a steady rise in temperatures, an increase in dramatic weather variations such as El Niño and the Pacific Decadal Oscillation (PDO) are predicted to influence ocean climate (Wernberg et al.). An increase in carbon dioxide concentrations and ocean water temperatures provide a need for concern due to the expanse of habitat loss that these changes can initiate. In recent years the attention to climate change's possible effects on kelp has increased due to a gap in knowledge on the subject. While many studies focus on acidification's effect on calcareous species, it's influence on kelp forests is not as widely studied. Although, it is known that along with direct effects on kelp reproduction and productivity, indirect consequences through herbivores and competitors can be influenced by climate change as well.

This review will evaluate the scientific studies completed that examine the direct and indirect effects of warming and ocean acidification on various species of brown algae. It will begin with the direct effects of a changing climate and move through the various indirect interactions between species that may be influenced as well.

Direct Effects of Temperature Increase

Across multiple studies, researchers have found evidence towards temperature's direct effect on algae. In one study they found that a species of kelp, *Eckionia radiata*, had a greater loss in kelp biomass but no change in effective quantum yield with an increase in temperature (Provost et al. 2017). Effective quantum yield was found by using a Pulse Amplitude Modulation Fluorometer to measure the photosynthetic health of the kelp (Provost et al. 2017). In comparison, another study by Andrews et al. evaluated the effects of increased temperatures on early post-settlement stages of *Scytithalia dorycarpa*. They discovered that settlement densities of germlings increased at temperatures 15 and 18°C and little survived at temperatures above 23°C (Andrews et al. 2014). Additionally, increased temperature was found to significantly decrease the percentage of fertilized germlings (Andrews et al. 2014).

The difference in experimental procedure could explain the studies slight differences and provide an insight onto the localized effect of temperature. The focus on the early life and reproduction of kelp under a range of temperatures identifies the vulnerable life stages (Andrews et al. 2014). Additionally, Provost portrays that kelp biomass loss could be exasperated by physiological stress that temperature induces (Provost et al. 2017). Therefore, the conclusion that kelp survivorship and reproduction can be directly altered by an increase in ocean temperatures can be accepted.

Although, there is a cause for further studies to be conducted on the direct effects of temperature on kelp due to the limited research on the subject and that only a small subset of species have been evaluated. Kelp is highly diverse and encompasses a large group of algae species important in determining how kelp responds to an increase in temperature. It is also important to note that kelp of the same species might acclimate to higher temperatures differently based on past life histories. Short term experiments have suggested that *L. ochroleuca* and *Saccorhiza polyschides* contain the ability to change metabolic processes in response to rises in ocean temperature (Franco et al. 2015). This could account for additional variability across different algae's response to temperature changes.

Direct Effects of Ocean Acidification

Research studying the direct effect of decreased pH on algae survival portrays the pattern that algal growth is unaffected by slight changes in pH. *Sargassum linearifolium*, a species of brown algae, was found to have no change in survivorship when subjected to water with higher acidity (Poore et al. 2013). Similar to Poore's findings, the species *Eckionia radiata* had no reaction to decreased pH (Provost et al. 2017). Although, it has been found in previous studies that pH can alter growth rates, concentrations of nitrogen in tissues, and creation of secondary metabolites in many primary producers (Poore et al.). Therefore, the question wether changes in pH directly influence the physiological or reproductive aspects of kelp remains to be sufficiently answered. Due to predicted changes in climate additional studies should be conducted regarding the possible effects on kelp forests.

Indirect Effects of Temperature Increase

The driving factor that enables kelp forests to be able to support a wide range of species is that they are primary producers. These species are the foundation for energy and are thus consumed by various primary consumers. Through this interaction kelp survivorship can be indirectly effected by competition and herbivory. Therefore, changes in temperature affecting competitors or herbivores could influence kelp indirectly.

<u>Competitors</u>

Algal turfs are are composed of turf-forming algae and inhibit the recruitment of kelp (Provost et al. 2017). Algal turfs have been found to be favored in a warming climate when compared to colder temperatures (Provost et al. 2017). As temperatures rise and algal turfs become more adept to handling the climate, kelp forests are predicted to decline. Turf forming algae especially those composed of filaments of cyanobacteria and benthic algae prevent establishment of kelp (Connell et al. 2013). Therefore, algal turfs which were once subordinate to kelp forests will become increasingly prevalent in the future in correlation with rising ocean temperatures.

Multiple ecological factors influence the growth of algal turf which complicates the task of identifying temperature's specific role. The 'kelp-turf phase shift' could be initiated by higher nutrient availability through pollution of costal waters (Connell et al. 2013). This strong correlation should be properly managed through careful experimental procedure and could influence results of field observations. Due to the many aspects that can affect algal turf expansion the precise role of temperature increase requires further study to reach a definite conclusion.

Primary Consumers

Indirect influences on kelp can also include herbivory by a multitude of species. Through both lab and field observations there was found to be an increase in kelp biomass lost to herbivory (Franco et al. 2015, Provost et al. 2017). There are many different species that consume kelp although only a few have been studied under temperature increases such as urchins and some species of herbivorous fish. Urchins are both found to have higher population densities and grow faster at higher temperatures (Franco et al. 2015, Provost et al. 2017).

Several researchers have determined that the disappearance of kelp forests is due to the tropicalization phenomenon. The trend follows a replacement of kelp with organisms characteristic to tropical areas due to an increase in ocean temperature and various heatwave occurrences (Vergés et al. 2016, Wernberg et al. 2016). Video field data on the eastern Australian coast conducted over a 10 year period and 0.6 °C temperature rise displays a large increase in herbivory by tropical species new to the area (Vergés et al. 2016). Tropical species of sea urchin, *Tripneustes gratilla*, was found to consume kelp at 1.6 times the rate of the temperate species, *Centrostephanus rodgersii* (Vergés et al. 2016). The establishment of these new ecological species create altered ecosystems and suppress the ability for kelp forests to reestablish themselves (Wernberg et al. 2016).

Additionally, changes in long-term weather patterns such as El Niño and La Niña critically impact the ocean temperature in certain areas. These patterns change various currents and impact the flow of warm and cold water to some areas. The Leeuwin current which carries warm water from the tropics down the west of Australia is an example of a force which is heavily influenced by patterns such as El Niño (Wernberg et al. 2016). Major climate anomalies can be created from these shifts in ocean currents. The resulting dramatic heatwaves enhance the consequences of ocean warming on ecosystems such as kelp forests. Future predictions of the climate state that these occurrences are expected to increase in frequency and intensity (Wernberg et al. 2016). Therefore, a greater understanding of the complex effects these incidents have is critical in the protection of kelp forest ecosystems.

Secondary Consumers

Additionally, through the food web secondary and tertiary consumers can also effect kelp survival through a top down control of populations. Increase in temperature can change predation habits on primary consumers which then could influence kelp survival. There is limited data on these interactions due to it's complexity and difficulty to accurately assess. It has been found that eastern rock lobsters (*Sagmariasus verreauxi*) consume less long-spined sea urchin (*Centrostephanus rodgersii*), a predator to kelp, when subjected to temperature increases (Provost et al. 2017). However, not only do sea urchins increase in growth they are preyed on less by rock lobster. Kelp forests can thus can be dramatically effected by trophic cascades stimulated by changes in temperatures. Although, further research should be conducted to establish a wider range of knowledge on trophic interactions with kelp under increased temperatures.

Indirect Effects of Ocean Acidification

Competitors

In addition to warming temperatures, higher acidity also influences competitors and consumers resulting in indirect consequences. Ocean acidification can enhance the fitness of agal turfs due to their ability to take advantage of an increased carbon dioxide concentration (Connell et al. 2013). Corresponding with the biology of agal turf, it was found that there was on average an increased area of turf in acidified conditions (Provost et al. 2017). Algal turf's ability to take advantage of the rising CO2 levels shifts the ecological advantage to turfs. In contrast, kelp differs in resource limitation through only depending on nutrient availability. Therefore, increasing CO2 levels in combination with nutrient availability will only benefit the expansion of turfs. Algal turfs, through establishing themselves over limited substrate, reduces the ability for kelp forests to recolonize. This control over limited space by algal turfs further decreases the population density of kelp.

Primary Consumers

There has not been many studies on the effect of herbivorous grazers under acidic conditions and the conclusion on their influence has not been entirely agreed upon. In one study ocean acidification was found to have no effect on urchin growth (Provost et al. 2017). Although, it has also been presented through models that calcareous grazers, such as urchins would be sparse in acidic conditions (Connell et al. 2013). Calcareous organisms utilize calcium carbonate (CaCO3) in their own structure. Ocean acidification reduces the concentration of CaCO3 available and this increases solubility of calcareous structures (Connell et al. 2013). Heightened vulnerability of these organisms corresponds with the models predicting a decrease in populations of calcareous individuals. A study on the interaction between *Sargassum linearifolium* and *Peramphithoe parmerong*, an marine herbivore, revealed that when the algae was subjected to both decreased pH increased temperature feeding rates increased (Poore et al. 2013). Therefore, due to the complexity of the interconnected web of marine species and their various reactions to a changing climate without further research it is difficult to state the definitive affect primary consumers would have on kelp.

Conclusion

Predictions of future ocean conditions display an increase in both temperature and acidity which present possible disastrous consequences to many marine organisms including kelp forests. Kelp provides the foundation for a complex ecosystem which contains high biodiversity and acquisition of carbon which supports many species across all trophic levels. This ecological landscape can be altered by the changing climate in a multitude of ways.

An increase in temperature has been found to significantly effect the reproduction of kelp along with germling survivorship. The direct effects of ocean acidification is not completely known, with future research required to throughly assess the relationship. Indirect temperature influences include that competition with algal turfs increases due to their superiority in a warmer climate. When conducting field research on agal turfs the influence of pollution should not be overlooked. Increased nitrogen availability through synthetic fertilizers have a dramatic affect on algal growth. Therefore, in order to study solely the affect of temperature and acidification on algal growth careful considerations must be made. Herbivory has been found to increase as well through primary consumers and decrease in predation of secondary consumers. Indirect effects of ocean acidification on kelp forests is widely unknown but there is evidence supporting a shift to algal turfs and a possible decrease in calcareous grazers.

Although, there is much more known today about the effects of climate change on kelp forests there is still a wide gap in scientific knowledge on the subject. Kelp forests are a highly diverse and complex environment with many species interacting with the algae both directly and indirectly. To fully understand the scope of the effect of climate change, many of these species interactions and how they change with a changing climate need to be further studied. The scientific information would not only be highly beneficial economically through protection of fish stock for fisheries but also help understand how to protect the highly beneficial ecosystem.

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