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Management of *Dosidicus gigas*, a large, pelagic predator in the eastern North Pacific Ocean

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Abstract

The Humboldt squid (*Dosidicus gigas*) has been expanding its geographical range in the eastern North Pacific Ocean over the past 20 years. This species of squid has advanced from the most southern part of their native range, off the Chilean coast, northward to southern Alaska. This expansion of a fast-growing pelagic predator is concerning and should be evaluated. *Dosidicus gigas* has been known to negatively affect native species of fish populations, such as Pacific hake (*Merluccius productus*), when expanding its range. The effects of an establishment of a D. gigas population in Pacific Canadian waters on both ecological systems as well as commercial fisheries should be assessed to develop management plans to protect native species and commercial fisheries. The reduction of potential effects of *D. gigas* establishment on native species of the eastern North Pacific is essential to conserving current native populations. A complete list of trophic interactions between *D. gigas* and species native to the eastern North Pacific is still underdeveloped. To qualitatively assess what is driving the migratory behaviour of *D. gigas*, the physiological, reproductive, and ecological traits of the species are reviewed here. The results indicate that warming water temperatures, reproductive plasticity, and prey/predator interactions are the leading causes thought to be driving *D. gigas* northward.

1. INTRODUCTION

SCIENTISTS have found that Climate Change has shown to affect a variety of natural ecosystems around the world including marine ecosystems [1]. One of the effects of Climate Change is the alteration of geographical distributions of organisms throughout the globe [2]. This has been documented in the North Sea as marine fishes are moving northward with the warming of water temperatures resulting from Climate Change [2]. The shift in distribution Northward was present in commercially fished species such as Atlantic cod (*Gadus morhua*) and common sole (*Solea solea*) as well as fish species that are not commercially fished such as scaldfish (*Arnoglossus laterna*) and snakeblenny (*Lumpenus lampretaeformis*) [2].

The Humboldt squid (*Dosidicus gigas*) is an abundant oceanic predator [3] that has been steadily expanding its range since the late 1990s [4]. *Dosidicus gigas* was once endemic to the Humboldt Current System (HCS) of south and central America but is now observed as far north as Central California (Figure 1) [3]. Few occasions of *D.*

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gigas stranding have been observed as far north as British Columbia, Canada (BC) and Alaska [4]. This unprecedented and sudden change in distribution has deemed *D. gigas* a highly migratory predator that must be managed to avoid negative effects on native ecosystems should it become established in Canadian waters.

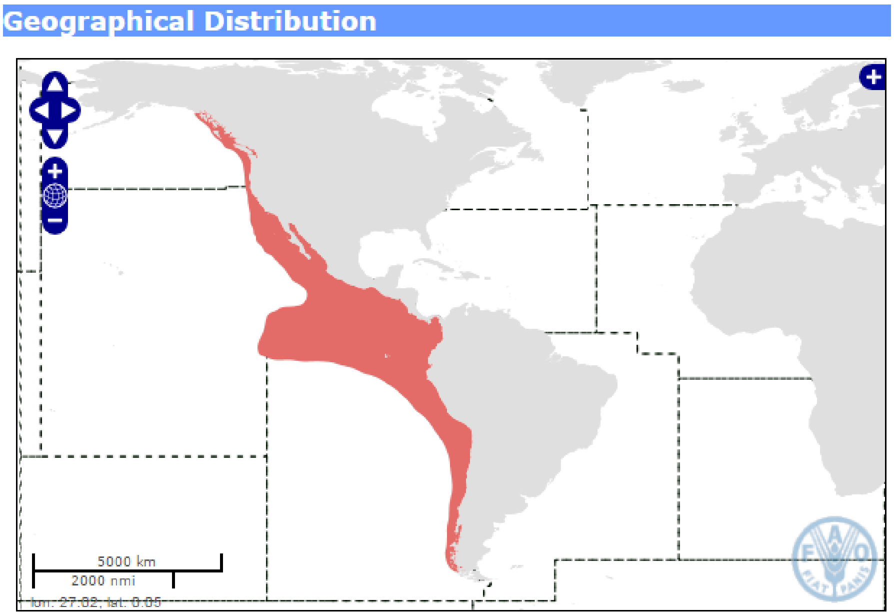

Figure 1: *The current geographical distribution of Humboldt Squid (Dosidicus gigas) in the Eastern Pacific. FAO 2015 [5].*

The first large migration of *D. gigas* was seen in Monterey Bay in 1997/98 after a strong El Niño occurrence [6]. After 1998, *D. gigas* sightings were rare off the coast of California until 2002 when the squid were present in large numbers after a weak El Niño event [6]. *Dosidicus gigas* have been present near Monterey Bay ever since 2002 [6]. Thus it can be inferred that an indirect effect of El Niño events contributed to the establishment of *D. gigas* along the Californian coast [6]. In 2009, large numbers of *D. gigas* washed up on the shores of BC [7]. In the years to follow, *D. gigas* was a rare sight off the coast of BC [8], similar to the events that took place in Monterey Bay ten years prior.

2. Ecology and Biology of *D. gigas*

To better understand the reasons behind the first large migration and what to expect if *D. gigas* begins to become established in Canadian waters, a review of their basic biology and ecology is required. The diet of *D. gigas* varies on prey availability [9]. In the California Current System (CCS) the diet of the squid varies based on habitat use and geographical location [9]. The main dietary components of *D. gigas* in the CCS were analyzed from stomach content samples and were found to be two species of lanternfish (*Tarletonbeania crenularis*, *Stenobrachius leucopsarus*) [9]. Many other species were also present in the stomachs of these squid including crustaceans, Pacific herring (*Clupea pallasii*), Pacific hake (*Merluccius spp.*), Pacific sardine (*Sadinops sagax*), salmon (*Salmonidae spp.*), rockfish (*Sebastes spp.*), flatfish (*Pleuronectidae spp.*), and other cephalopods including its own species [9]. The wide diversity of diet can be observed among individuals within the same school of *D. gigas* [9].

The diet of *D. gigas* off the coast of BC has been found to be different than the diet of *D. gigas* in the CCS [9, 7]. Multiple stranding events occurred in late 2009 off the west coast of Vancouver Island, BC which provided the opportunity for their stomach contents to be analyzed [7]. After stomach analysis of the stranded *D. gigas* it was evident that the main prey species were *C. pallasii* and *S. sagax* [7]. Other prey species in the eastern North Pacific Ocean included Dungeness crab (*Metacarcinus magister*), Coho salmon (*Oncorhynchus kitsuch*), and kelp greenling (*Hexagrammos decagrammus*) [7]. Even though *D. gigas* is a generalist predator, it is also prey for many species [3]. Large sharks, North Pacific Spiny Dogfish, tunas, billfish, and marine mammals such as sperm whales, pilot whales, porpoises, sea lions, and seals are known to predate on most life stages of *D. gigas* [3, 10].

Dosidicus gigas is a fast growing squid that can reach 0.75 metres within the first year of its life [3]. They live for one to two years and reproduce only once in their life time with the potential to produce up to 32 million eggs [3]. Reproduction occurs year round and peaks during the summer of the southern hemisphere (October through January) [3, 10, 11]. Recent work has shown that *D. gigas* is capable of switching reproductive patterns. After the El Niño that took place in 2009, the squid population around the Gulf of California seemed to collapse [12]. Typically *D. gigas* reproduce near shore at around 1.5 years old [3]. Shortly after 2009 the squid were found reproducing further north and offshore at a younger age of six months and a smaller size of 30 centimetres [12]. This faster reproductive pattern saw positive returns as the *D. gigas* population near the Gulf of California doubled by 2011 [10, 12].

Dosidicus gigas are known to spend most of their time in the Oxygen Minimum Zone (OMZ) at depths of around 200–700 metres [13]. The squid undergo diurnal vertical migrations between dusk and dawn to hunt [13]. The OMZ that the Humboldt squid occupy has been steadily approaching the surface over the past 50 years [13]. The average depth of the OMZ changed from 638 metres in the 1950s to 500 metres in 1997 [13]. Physiological changes in temperature, oxygen availability, and water pressure that the squid experience daily suggest that abiotic factors may not be the direct driving force in the *D. gigas* vagrant behaviour [13].

3. Reasons behind range expansion in *D. gigas*

Dosidicus gigas have moved their geographical distribution northward from the Humboldt Current System (HCS) in South and Central America to as far north as Alaska [3]. *Dosidicus gigas'* variation in physiological adaptations and reproductive patterns make the abiotic factors of their range expansion harder to determine. The OMZ where *D. gigas* spends most of its time has been approaching the surface in recent years [13]. This change in OMZ depth is thought to be largely due to the effects of Climate Change and could benefit *D. gigas* as a predator by changing prey distribution [13]. El Niño events are thought to increase deoxygenation of ocean water and cause the OMZ to occur at shallower depths [13]. This effect will become more prevalent in northern latitudes with increasing water temperatures [13]. As prey move north to stay at a deeper OMZ in warm temperatures, *D. gigas* will likely follow resulting in a migratory pattern.

The reproductive patterns of *D. gigas* appear to change with warmer water temperatures [12]. The faster reproductive pattern would make a more adaptive population of *D. gigas*. Species with faster life histories are known to shift their distribution more than species with longer generation times [2]. Due to increasing ocean temperatures, the reproductive peak of *D. gigas* could extend into September and February in the South Pacific. Work with stable isotopes show that all *D. gigas* captured at northern latitudes are in fact from one origin close to the Gulf of California [14]. This recent work shows that large and varying migration patterns of a single population can be responsible for the distribution changes of *D. gigas*. The abiotic fluctuations that accompany El Niño events seem to affect *D. gigas* on a population level rather than individually.

4. Implications of *D. gigas* range expansion

Many problems could arise with the establishment of *D. gigas* into Pacific Canada. One trophic interaction that is known to occur is a decline of Pacific hake (*Merluccius productus*) with an increase of *D. gigas* [6, 15]. Dietary evaluation of *D. gigas* shows that there would be pressure on economically important fish species such as Pacific herring (*Clupea pallasii*), Pacific sardine (*Sardinops sagax*), and salmon to a small extent [9]. The predatory activity of *D. gigas* would compete with local predators such as harbour porpoise (*Phocoena phocoena*), harbour seal (*Phoca vitulina*), salmon (*Oncorhynchus spp.*), and shark species. Alternatively, *D. gigas* would be a prey item for larger predators in the eastern North Pacific Ocean [3, 10].

The landings of Pacific sardine (*S. sagax*) in Pacific Canada have been declining since 2006 [16]. Over the last 6 years the landings of *S. sagax* in British Columbia declined from 22,000 tonnes in 2010 to 0 tonnes in 2013 [16]. The Pacific herring (*Clupea pallasii*) is an economically and ecologically important species off the Pacific coast of Canada [17]. *Clupea pallasii* is preyed upon by multiple species in the local area and is very abundant close to shore [17]. The regions of Pacific Canada that land the most herring are the Strait of Georgia (SOG) and the Prince Rupert District (PRD) [17]. The SOG produces much higher amounts of herring due to a large local population [17]. The Pacific hake (*M. productus*) total allowable catch (TAC) for 2013/2014 was set at 87,000 tonnes [18]. As *M. productus* is a ground fish, it is caught by bottom trawling [18]. Management would be needed to protect these commercially important fish species if *D. gigas* becomes established in the eastern North Pacific.

5. Management actions and future work

There are management steps that can be taken to reduce the likelihood that an establishment of *D. gigas* will drastically affect the abundance of ecologically and economically valuable marine species. Anthropogenic mediated Climate Change is not something that can be fixed immediately but must always be considered a top priority. Reducing the burning of fossil fuels and methane production from activities like cattle farming can help slow the production of greenhouse gases that contribute to Climate Change.

After reviewing the research that shows a strong correlation between warmer El Niño events and large migrations in *D. gigas*, there is evidence that suggests potential negative consequences of Climate Change can lead beyond simple range expansion if not remedied promptly.

Should *D. gigas* successfully establish itself in Pacific Canada some economically important fish must be managed to avoid overexploitation and local extinction. The *S. sagax* fishery is small, sensitive, and declining and steps should be taken if a new voracious predator is present in local waters. Having a healthy *S. sagax* population helps the ecosystem stay stable by supporting higher trophic levels that prey on *S. sagax* [16]. Larger *S. sagax* populations would also reduce top-down cascading effects on lower trophic levels and potentially prevent the establishment of a *D. gigas* population [19]. The *C. pallasii* fishery should remain open but should consider cutting the TAC by a significant amount in the event of a *D. gigas* establishment. Extra attention should be paid to the SOG region as it is the southernmost region that would most likely see the largest amount of migrating *D. gigas*.

The expansion of *D. gigas* overlaps with the range of North Pacific hake (*Merluccius productus*). Since the increase in *D. gigas* in Californian waters there has been a coincidental decline in *M. productus* [6]. The coincidence may provide evidence for the presence of a top-down trophic pressure from *D. gigas* on *M. productus* [19, 15]. The predatory pressure of *D. gigas* could change the distribution and abundance of *M. productus* [15]. Similar effects of *D. gigas* are present on rockfish species in the same habitat [15]. It is recommended that the amount of bottom trawling in all fisheries is drastically reduced. The reduction of bottom trawling will help Pacific hake and long-lived, slow growing rockfish populations remain stable as they are often caught as by-catch.

Since 2003 the global *D. gigas* fishery has grown from 400,000 tonnes per year to over 900,000 tonnes [20]. The fishing pressure on *D. gigas* has been most prevalent in Chile and Peru and has been recently increasing in Central America and Mexico [5, 21]. The increasing pressure on *D. gigas* from fishing mortality in combination with climatic change and El Niño events may help explain the drastic range expansion. It could be that southern fishing pressure is lowering the genetic variability in *D. gigas* and possibly creating two distinct populations. Other types of fishing involving large pelagic species could also help explain the change in distribution of *D. gigas*. The abundance of large tuna species, billfish, sharks, and mackerel have declined due to overfishing in the temperate Pacific [22]. The reduction in large pelagic predators, including toothed whales, provided a mesopredator release for *D. gigas* [3, 6, 19]. The juvenile *D. gigas* are directly released from predation by the removal of large pelagic predators while the adult *D. gigas* are released from predation as well as competition for food resources [3, 6, 19].

A recent analysis of *D. gigas* off the coast of BC has shown high levels of paralytic shellfish toxins in D. gigas tissue [7]. High levels of toxins would make *D. gigas* inedible for humans and other animals. If toxin concentrations are not consistent for all *D. gigas* in the area, then there is a possibility to open a fishery for *D. gigas* in Pacific Canada to help manage its effect on the local ecosystem. The current *D. gigas* fishery has been growing in recent years and is exported to places such as Asia and eastern

North America [5, 21].

6. Conclusion

With large migrations of *D. gigas* occurring in congruence with El Niño events, there is evidence that warmer ocean temperatures have some positive effect on *D. gigas* movement to the North. Other marine species have also changed their own geographical distributions in response to increasing ocean temperatures [2]. The prevention of anthropogenic mediated increases in ocean temperature is imperative to conserving local and native ecosystem structures.

The interactions between *D. gigas* and local species in the eastern North Pacific Ocean must be better understood to properly evaluate and manage the effects that a possible establishment would have on the ecosystem. *Dosidicus gigas* should be studied as a predator as well as a prey item in trophic food webs. The removal of large pelagic predators must be avoided to prevent the establishment of foreign predators such as *D. gigas*.

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