AN ABSTRACT OF THE THESIS OF

Toby N. Harbison for the degree of Master of Science in Marine Resource Management presented on June 3, 2021

Title: Assessing the Impact of Fishery Bait on Spatiotemporal Variation in the Feeding Ecology of Dungeness Crab (*Cancer magister*) Using Stable Isotopes, Gut Content Analysis & Fishermen Interviews

Abstract approved: ___________________________________________________

Sarah K. Henkel

The commercial Dungeness crab (*Cancer magister*) fishery is Oregon’s largest trap-based fishery. Each year, crab vessels discard millions of pounds of bait, including squid, razor clams, and sardines, into the near-coastal ocean. Although the fishery season typically runs from December 1st through August 14th, most landings occur within the first six weeks of the open season. Regional and seasonal variation in Dungeness crabs’ δ¹³C and δ¹⁵N stable isotope (SI) composition and gut contents across multiple sex and size classes were assessed to investigate the potential consumption of discarded bait by the crabs. Stable isotope mixing models were employed to approximate possible spatiotemporal variability in bait contribution to Dungeness crab diets. Additionally, fishermen interviews were conducted to determine the bait species utilized in the fishery as well as the regional and seasonal distribution of bait inputs into the marine system. The δ¹³C and δ¹⁵N signature of crabs collected during four seasons (December 2019, March-April 2020, June-July 2020, and October 2020) across three regional study areas showed highly significant regional and seasonal variation. Tissues of female crabs sampled in the springtime across multiple sites contained increased δ¹⁵N ratios compared to all other seasons, which could be indicative of trophic enrichment through bait consumption. Fishermen interviews...
indicated that the types and amounts of bait used vary over the course of the commercial fishery season, but not substantially between regions. Overall, the results demonstrated the complex and dynamic nature of coastal food webs and the importance of considering multiple habitats over time when evaluating trophic relationships.
Assessing the Impact of Fishery Bait on Spatiotemporal Variation in the Feeding Ecology of Dungeness Crab (*Cancer Magister*) Using Stable Isotopes, Gut Content Analysis & Fishermen Interviews

by
Toby N. Harbison

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Major Professor, representing Marine Resource Management

Dean of the College of Earth, Ocean, and Atmospheric Science

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Toby N. Harbison, Author
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CHAPTER 1: BACKGROUND ON THE FISHERY AND FEEDING ECOLOGY OF DUNGENESS CRAB (*CANCER MAGISTER*)

1. Introduction

The Dungeness crab, *Cancer magister*, consistently supports the most profitable commercial fishery in the state of Oregon. Every year, commercial Dungeness crab fishermen add thousands of pounds of organic material to the state’s coastal waters in the form of bait. And yet, despite the economic importance of this abundant species, the ecological impact of bait subsidies on this abundant species’ feeding ecology has not previously been studied. This study sought to assess spatiotemporal variation in Dungeness crab diets through stable isotope analysis, gut content analysis, and fisherman interviews. I hypothesized that these analyses would provide evidence for seasonal shifts in dominant food sources, characterized by peak bait consumption in the winter and early spring, cannibalism in the spring and early summer, and reliance on organic matter in the late summer and autumn. I also assessed the relationships between stable isotope values and sex, carapace width, and location on the coast. Fisherman interview data was used to assess spatiotemporal variation in fishing strategies that could impact the isotopic composition of bait subsidies to the coastal system.

2. Section Overview

This thesis explores my hypothesis in four parts. Chapter One provides background information pertinent to feeding ecology of Dungeness crabs and other marine decapods. It also explores stable isotope and gut content analysis as tools to infer trophic relationships as well as the impacts of adding organic materials to marine systems. Readers should come away from Chapter One with more questions than they started with, not because of a lack of clarity, but because it engages the creative, problem-solving portions of their brain.
Chapter Two delves into knowledge gained about how bait use strategies within the Oregon commercial Dungeness crab fishery impact the spatiotemporal distribution of bait discards off the Oregon coast. The chapter is formatted as an essay with the intention of using portions of the text and information as the basis for a research project proposal down the line. The interviews were originally designed to collect basic information about bait use to determine the inclusion and exclusion of certain bait types in the stable isotope mixing models, and yet conducting the interviews revealed an entire master’s thesis project worth of potential analyses that has reached inception here. The crabbers were unexpectedly forthcoming with tricks of their trade and excited to hear the results of the interview, stable isotope, and gut content analyses. In the future, Chapter 2 will be adapted into a newsletter written for fishermen and members of the public explaining the project and research results. This newsletter will be distributed by the Oregon Dungeness Crab Commission and Oregon Sea Grant.

A manuscript exploring the impacts of seasonal variation in Dungeness crab diets on $\delta^{13}C$ and $\delta^{15}N$ through values through stable isotope and gut content analysis constitutes Chapter Three. As this manuscript is intended for publication, it follows the standard format for peer reviewed research, with an abstract, introduction, methods, results, discussion, and conclusion. The paper seeks to answer three main questions. First, do $\delta^{13}C$ and $\delta^{15}N$ isotope values from Dungeness crabs collected in winter 2019 and spring through autumn 2020 provide evidence for seasonal fluctuations in the crabs’ trophic niche? Second, can the results of stable isotope mixing models support the hypothesis that the carbon and nitrogen sources for Dungeness crabs shift seasonally among bait from the commercial fishery, cannibalism, and wild, benthic prey? And third, what can the combination of stable isotopes and gut contents tell us about specific Dungeness crab prey species? Each of these questions tests not only an ecological hypothesis,
but the chosen methods as well. Stable isotopes offer powerful tools for inferring information about trophic dynamics, and yet those tools must be used carefully and thoughtfully to draw valid conclusions. Gut content analysis also has its strengths and weaknesses, which will be explicitly discussed. The final chapter, Chapter 4, contains a summary of the major findings within the three previous sections and ideas for future research.

3. The Oregon Dungeness Crab Fishery

Management and regulation of the commercial Dungeness crab fishery has changed little since it began in San Francisco in 1848 (ODFW 2021). In the early 1900s fishermen could legally keep any male crab over six inches long and commercial harvest was closed in the autumn. Today, the US West Coast states manage the fishery according to the “3S” system: size, sex, and season. Because all the Dungeness crabs that range from Central California to Alaska comprise a single population (Jackson et al. 2018), fisheries management agencies in California, Oregon, and Washington collaboratively develop management strategies through the Pacific States Marine Fisheries Commission Tri-State Dungeness crab process (PSMFC 2012).

Oregon permits harvest on male crabs over 6 ¼ inches for commercial fishermen and over 5 ¾ inches for recreational users (ODFW 2021). The State enacted a limited-entry system of 465 permits starting in the 1995-96 season, which has now been reduced to 424 permits. Beginning in 2006-07, the Oregon applied additional pot limits of 200, 300, or 500 pots per fish ticket (Davis et al. 2017). Generally, the season runs from December 1st through August 14th, although the fishery does not open until the male crabs grow into their post-molt bodies and attain at least 23-25% meat fullness, depending on the region. The presence of harmful algal blooms (HABs), whale entanglement in crabbing gear, and price negotiations have also delayed or temporarily closed the fishery mid-season in some years. A small commercial bay fishery also
operates in the fall when the ocean fishery is closed. The bay fishery lies outside the scope of this project. In the ocean fishery, fishing effort is highly concentrated in December, January, and early February; accordingly, bait discards peak during that time as well. Fishermen land most of the annual catch within the first six weeks of the fishery season (Dewees et al. 2004).

Historically, Dungeness crab landings have fluctuated in decadal cycles (see Figure 1), although this cyclical trend has broken down over the last several decades (Botsford et al. 1982; Botsford and Lawrence 2002), when average landings have increased (Richerson et al. 2020). Between 2007 and 2014, Oregon landings averaged 16.7 million pounds per year. The 2015 to 2020 average rose to 19.3 million pounds with similar levels of effort, indicating increased production during that period. Researchers have presented various hypotheses to explain these fluctuations (Armstrong at al. 2010; Rasmuson 2013; Johnson et al. 1986; Botsford 2001; Shanks 2013; Shanks and Roegner 2007), generally citing environmental and oceanographic rather than fishery related drivers. One pertinent theory is that density-dependent prevalence of cannibalism may also contribute to population fluctuations (Fernandez 1999; Higgins et al. 1997; Shanks 2013).

Annual harvest generates an average revenue of approximately 40 million dollars. Ex-vessel value, or total profit to fishermen, reached an all-time high of 74.2 million dollars during the 2017-18 season. Both market forces and catch led to that dramatic increase in revenue. In most years, the Dungeness crab fishery generates more profit than any other single species fishery in Oregon or on the West Coast more broadly. On a global scale, large crustaceans (with carapace width >10cm) have gained significance as a commercial species over the past ~75
years; worldwide catch has quintupled since 1950 (Anderson et al. 2011). Despite its economic significance, the fishery has never been the subject of a formal stock assessment, although evidence suggests that catch generally serves as a sufficient proxy for legal sized male abundance (Richerson et al. 2020).

The fishery requires millions of pounds of bait each year. The Oregon Department of Fish and Wildlife (ODFW) collects information about the types of bait Dungeness crab fisherman use. According to those records, clam, squid, herring, sardines, and mackerel constitute the most frequently used bait types. The main purpose of this research is to assess how this bait impacts Dungeness crab diets and Oregon’s near-coastal benthic ecosystem at large. Some commercial crab pots allow the captured crabs to eat the bait, while others contain an enclosed bait box that prevents bait access. In either case, commercial fishers toss used bait
overboard after they collect their catch and re-bait the pots with fresh meat before setting them. This procedure increases food availability for Dungeness crabs and other marine organisms. In the Gulf of Maine (Grabowski et al. 2009; Saida et al. 2002) and Western Australia (Waddington and Meeuwig 2009), researchers have found evidence that bait inputs from trap-based commercial lobster fisheries influence the feeding dynamics of lobsters in those regions.

This thesis provides a first step in exploring the hypothesis that bait subsidies could be the mechanism behind the consistently high landings in the commercial Dungeness crab fishery despite increased effort: landings have averaged 17.3M pounds per season 1998-9 to 2017-8 versus the previous two-decade seasonal average of 9.6M pounds (Davis et al. 2017). Previous studies have investigated the impact of adding organic material to marine ecosystems (Waddington and Meeuwig 2009; Wassenberg and Hill 1987; Ramsay et al. 1997; Groenewold and Fonds 2000; Dempster et al. 2002; Castro et al. 2005; Catchpole et al. 2006; Tuya et al. 2006) including organic detritus from trawlers (Dayton et al. 1995; Groenewold and Fonds 2000) and aquaculture (Cancemia et al. 2003; Yi Zhou et al. 2006; Vita et al. 2007), but this dynamic has not previously been studied within the Dungeness crab fishery. According to Boudreau & Worm (2012), “we are only beginning to understand the role that decapods play in marine ecosystems, and how exploitation [through fisheries] might modify this role.”

4. Ontogeny & Diet

Baseline knowledge on the distribution, life history, and behavior of Dungeness crabs provides essential context for understanding how discarded bait might impact their feeding. The geographic range of Dungeness crab, *Cancer magister*, extends from approximately Point Conception, CA, in the south to Unalaska, AK, in the Aleutian Island chain in the north (Schmitt 1921; MacKay 1943; Butler 1961). The exact range varies according to the relationship between
spawning and oceanographic conditions such as the timing of the spring transition (Richerson et al. 2020; Shanks and Roegner 2007), driving crabs north and south slightly at the borders of their range from year to year. No previous studies have specifically addressed comparative latitudinal variation in Dungeness crabs’ diets.

The species inhabits shallow estuaries and the intertidal zone up to depths of at least 180m (Armstrong 1984). Adult crabs prefer sandy-mud substrates (Karpov 1983; Lawton and Elner 1985), while some juveniles prefer to inhabit eelgrass beds or shell litter substrates (Stevens and Armstrong 1984). Dungeness crab diets shift with ontogenetic changes in development (Jensen et al. 1998) and habitat. These life history stages display clear seasonality, and therefore could potentially interact with seasonal variations in caloric subsidies from the commercial fishery. Mating coincides with female molting in the spring and summer (MacKay 1942; Cleaver 1949; Poole and Gotshall 1965). Females can store sperm for months to years before extrusion, fertilization, and brooding, usually between October and March in Oregon (Waldrom 1958). Not all females molt, mate, and/or brood every year (Swiney et al. 2003). Those who are brooding can carry upwards of two million fertilized eggs beneath their abdominal flap until they hatch between December and April in Oregon (Reed 1969; Gregory 1976). Hatch timing varies across the range. Evidence suggests that female crabs eat minimally to not at all while brooding. In Alaska, ovigerous females bury themselves (Stone and O’Clair 2002) and display reduced foraging behaviors (Schultz and Shirley 1997). 90.3% of egg-carrying Cancer polyodon females, a phylogenetically similar species to Cancer magister, had empty guts in two Chilean estuaries (Cerdal and Wolff 1993).

After hatching, oceanographic forces carry larval Dungeness crab offshore as they develop through five zoeal phases (Reed 1969; Gregory 1976). Larvae use the natatory hairs on
their maxillipeds, modified legs that the crabs use for feeding, to consume both zooplankton and phytoplankton (Gregory 1976). Hartman and Letterman (1978) found diatoms in the guts of Dungeness crab zoea. Those zoea metamorphose into megalope in the early spring, often around the spring transition, when a predominant upwelling begins off the Oregon coast (Armstrong 1984). Tidal currents transport megalope into nearshore waters in the late spring and early summer, where they live in high concentrations. These dense groupings of Dungeness crab megalope attract predators such as gray whales (Dunham and Duffus 2002), rockfish (Prince 1972), and salmon (Botsford and Lawrence 2002). After approximately one month, megalope molt into juveniles and often recruit into estuaries, which act as protective nursery grounds with abundant prey and relatively few predators (Gunderson et al. 1990).

Juvenile crabs spend significantly more time in estuaries that adults, who tend to make brief forays into estuarine environments to feed and then return to the ocean (Curtis and McGaw 2008). These differences in habitat utilization, and thus feeding, likely impact the carbon and nitrogen stable isotope ratios in their tissues. The weak osmoregulatory ability of Dungeness crabs could explain the tendency of adult crabs to limit time spent in estuaries. Dungeness crabs in a controlled environment were more likely to eat in low salinity environments while experiencing starvation, suggesting that adult crabs might venture into estuaries only when calories in the ocean are scarce (Curtis et al. 2010). They will stop moving completely and hug their appendages tightly to their bodies above 36.2 ppt and below 15.5 ppt (Sugarman et al. 1983). A tagging study conducted by Collier (1983) did not show any specific pattern of movement within adult Dungeness crab population in the ocean, however, some evidence suggests that male crabs tend to travel greater distances than females (Stone and O’Clair 2001). Stone and O’Clair (2001) found that female Dungeness crabs in Fritz Cove, Southeast Alaska
typically only ranged ~1.5 km outside the cove while their male counterparts ranged ~7.2 km. Contrastingly, in British Columbia, Smith and Jamieson (1991) found that male Dungeness crabs moved an average of 288 meters/day while females moved an average of 419 meters/day. *Cancer magister* generally spawn offshore, which could be a major motivator for adult female crabs to venture into deeper waters.

Overall, the most frequently noted prey taxa for post-metamorphic Dungeness crabs include crustaceans (including conspecifics), bivalves, fish, and gastropods. However, authors have reported a variety of additional dietary sources, including diatoms (Jensen and Asplen 1998), algae, polychaetes, and foraminifera. See Table 1 for a list of Dungeness crab trophic sources reported in literature. Some controversy exists regarding the degree of resource partitioning and optimal foraging displayed by Dungeness crabs (Stevens et al. 1982). Many authors describe crabs as opportunistic feeders; Gotshall (1977) asserted that “Dungeness crab populations are apparently not limited by the abundance or scarcity of particular foods because they are non-specific feeders that readily adjust to various foods” (Armstrong et al. 1984). And yet, Steven et al. (1982) notes that crabs in Grays Harbor, WA, might preferentially consume *Crangon* spp. and avoid polychaetes given their relative densities within the estuary.

Additionally, evidence indicates ontogenetic shifts in resource exploitation as crabs grow, although the specific food sources eaten at different sizes varies across studies.

Dungeness crabs occupy an influential role in both benthic food webs and the larger ecosystem, moving back and forth between estuaries and the coastal ocean. They act as predators and prey. Numerous species opportunistically eat Dungeness crab, including bald eagles, octopus, leopard sharks, otters, and marine fishes, although predation decreases as the crabs mature into their adult stage. The crabs are more vulnerable earlier in life. Dungeness crab
megalope provide an especially important food source for salmon populations. Several studies suggest that there might be a relationship between intensive predation by Coho and chinook salmon on megalope and declines in Dungeness crab landings in Northern California and Oregon (Orcutt et al. 1976; Reilly 1983). Botsford et al. (1982) found a cyclic covariance between Dungeness crab and salmon population abundances. Predation by the crabs on other benthic organisms also plays an important role in the population dynamics of prey species. After heavy recruitment into estuaries, juvenile Dungeness crabs have decimated local prey populations, including *Transennella* spp in Bodega Bay, CA (Ruiz 1989), and Coos Bay, OR (Asson-Batres 1986), and *Mya* sp. in Grays Harbor, WA (Palacios 1994). “Experimental studies have shown that decapods influence the structuring of benthic habitat, occasionally playing a keystone role by suppressing herbivores or space competitors” (Boudreau and Worm 2012). Complex life history means it is likely that Dungeness crabs affect a range of habitats and prey species over their life cycle (Boudreau and Worm 2012).

Many authors report cannibalism between (MacKay 1942; Butler 1954; Gotshall 1977) and within age class (Jacoby 1983; Karpov 1983; Fernandez et al. 1993a, b,1994). Botsford and Hobbs (1995) said that field data indicates females exhibit higher rates of cannibalism than males. According to an analysis conducted by Stevens et al. (1982) in Puget Sound, WA, other Dungeness crabs were the most frequently occurring single species in the guts of other Dungeness crabs. The evidence suggested that cannibalism occurred more frequently in crabs <60 mm CW than crabs > 60 mm CW (Stevens et al. 1982). In the species *Cancer polyodon*, approximately 10% of juvenile crabs in each cohort are cannibalized. In Oregon, a significant amount of cannibalism has been documented within commercial Dungeness crab pots.
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Using an approximate cannibalism/predation factor of 6.8% (Tegelberg 1972), the Oregon Dungeness Crab Commission estimates that the crabs cannibalize 56,000 pounds of softshell crab per year in those pots (Davis et al. 2017).

Rates of cannibalism appear to be cyclical rather than constant, peaking during periods of dense juvenile recruitment into estuaries. Fernandez et al. (1993) hypothesized that cannibalism explains recruitment failure of subsequent megalopae cohorts in habitats saturated by older young of the year (YOY) crabs. Cannibalism has also been suggested to generate cyclic fluctuations in the abundance of Dungeness crab in the California fishery (Botsford and Wickham 1978; Higgins et al. 1997). Shanks et al. (2010) report a density dependent relationship between larval abundance and subsequent fishery yield. They found that when the number of megalopae was at or below 100,000 caught per year in their light traps, numbers of larvae are a good predictor of catch, however, the relationship between larval abundance and yield is non-linear beyond that point. Cannibalism on larval recruits by larger Dungeness crabs could partially explain this relationship, acting as a cap on population growth.

Although most of the literature regarding Dungeness crab diets primarily considers carnivory, Jensen and Asplen (1998) suggested that filamentous diatoms, eelgrass epiphytes, and algae could provide food during periods of prey scarcity or intense competition between densely recruited juveniles. They observed early instar crabs feeding on eelgrass epiphytes in Puget Sound. MacKay (1942) reported algae as the fourth most important food source for Dungeness crabs in British Columbia, behind crustaceans, bivalves, and polychaetes. Several researchers have cautioned against ignoring sand in gut contents, suggesting that crabs could eat it on purpose to capture calories from epibenthic microalgae (Jensen and Asplen 1998; Haefner 1990). Cerdal & Wolff (1993) observed at least five macroalgae species in Cancer polyodon guts in a
Chilean bay, including *Gracilaria* sp., *Polysiphonia* sp., *Ulva* sp, an unidentified Phaeophyta, and an unidentified Rhodophyta. According to Antonio et al. (2012), coastal benthic macroinvertebrates, including crabs, utilized microalgae, terrestrial leaf litter, and riverine particulate organic matter as food sources in shallow waters of the Tango Sea off Japan. Additionally, the Mediterranean crab *Pachygrapsus marmoratus* shifts seasonally between carnivory and herbivory, taking advantage of numerous food sources (Cannicci et al. 2007).

The example of *P. marmoratus* indicates that crab diets vary seasonally, reflecting the complex and dynamic nature of trophic inputs at the terrestrial-marine interface. Physical mixing in estuaries and primary production in coastal waters drives fluctuations in the sources of organic materials (Hughes et al. 2000; Antonio et al. 2012) available for benthic organisms to eat. An analysis of seasonal variation in the trophic niches of three decapod species, *Upogebia africana*, *Callichirus kraussi*, and *Palaeomon peringueyi*, in the Kowie River Estuary of South Africa indicated that their diets shifted temporally according to changes in food availability. Kennish (1997) found that seasonal variation in food availability impacted the reproductive output and body condition of an herbivorous crab, *Grapsus albolineatus*, off Hong Kong. All these examples relate to species that spend most of their lives within estuaries. Researchers have focused less research on seasonal variation in the feeding behaviors of species, like *Cancer magister*, that primarily inhabit estuaries as juveniles but then travel back and forth into the ocean as adults.

Sex-dependent differences in feeding behaviors could also impact seasonal variation in the isotopic composition of Dungeness crab tissues. *Cancer magister* researchers have paid relatively little attention to differences in dietary dynamics between male and female crabs, however, Cerdal and Wolff (1993) hypothesized that observed disparities between male and
female *Cancer polyodon* diets are related to sex-specific behaviors for increasing reproductive success. At a site in Guayacan, Chile, 80% of female guts but only 49% of male guts contained the infaunal mollusc species *Tagelus dombei*. A higher percentage of male guts contained small epibenthic Anomura. Cerda and Wolff suggested that these heterogeneous diets were the result of relatively mobile male crabs protecting a “harem” of sedentary female crabs (Orensanz and Galucci 1988; Wolff and Soto 1992). The mobile males would be more likely to graze on readily available prey at the surface of the benthos, while the females would be more likely to stay in one place and spend the time to dig up *Tagelus dombei* from within the sediment.

Although this territorial harem-forming behavior has not been documented in *Cancer magister*, female Dungeness crabs do form dense brooding aggregations across their range (Diamond and Hankin 1985; Armstrong et al. 1987; O’Clair et al. 1996; Scheding et al. 2001), burying themselves in sediment and reducing feeding and foraging. Stone and O’Clair (2002) documented female Dungeness in Southeast Alaska entering a period of relative inactivity during the winter and early spring at around 16m depth, especially if they were carrying eggs, moving to shallower waters (~10m) during larval hatching and phytoplankton blooms between April and June, and then heading towards deeper waters (<107.3m) starting in July. They hypothesized that the females moved into deeper water in the late summer to search for food, which was less abundant in shallow waters after larval recruitment and the springtime spike in primary productivity. Male crabs have also been observed burying themselves in sediment, although to a lesser degree, likely to avoid predation (Stone and O’Clair 2002).

On a global scale, fisheries discards increase the availability of organic material to benthic communities (Britton and Morton 1994). These food subsidies impact ecosystem functioning in numerous ways, including increasing secondary productivity (Groenewold and
Fonds 2000; Ramsay et al. 1997), reducing consumption of natural prey species (Waddington and Meeuwig 2009), and transporting biomass from pelagic to coastal systems (Grabowski et al. 2009). Additionally, numerous authors have hypothesized that fisheries discards increase the abundance of benthic scavengers (Furness et al. 1988; Berghahn 1990; Wassenberg and Hill 1990; Kaiser and Spencer 1996; Ramsay et al. 1997). Research on trap-based commercial lobster fisheries in Maine and Western Australia found that bait subsidies have altered the trophodynamics of lobsters in those regions (Grabowski et al. 2009; Saila et al. 2002; Waddington and Meeuwig 2009). Grabowski et al. (2009) asserted that herring bait “augmented lobster populations” at a heavily fished site in the Gulf of Maine. The tissue of lobsters at that site had a higher $\delta^{15}$N value than at a control site that was closed to fishing, suggesting consumption of higher trophic level food. Gabrowski et al. (2009) also found that lobsters feeding on herring bait reached a harvestable size more quickly than those who ate a diet of natural benthic prey in a controlled environment. Fisheries discards are often spatiotemporally variable (Rijnsdorp et al. 1996). According to Polis et al. (1996), bait subsidies must be frequent and predictable in order impact consumer populations.

5. Stable Isotope Analysis

The combination of stable isotope and gut content analysis has become a common and useful tool for understanding trophic relationships (Kolts et al. 2013). Gut content analysis can be especially helpful in determining what organisms have been eating over short timescales (hours prior to capture), identifying seasonal diet variability (Divine 2017), and determining differences in dietary preference of a single species across multiple habitat types. This approach does have some drawbacks, however, especially with quantifying soft-tissue prey (worms, etc.), which tends to be digested more quickly than prey with “hard parts” (shells, cartilage, etc.).
Researchers can easily underestimate soft prey types (Hyslop 1980) due to this shortcoming. Additionally, Dungeness crabs grind their prey into small fragments that are difficult to impossible to identify. Even if a prey species is identifiable, it can be challenging to determine how many individuals of that species are present in the gut (Kolts et al. 2013). Stable isotope analysis can provide more information about assimilated proportions of food sources, dietary preferences over weeks to months (Hobson 1999), and food-web relationships (France 1996; 1996; Michener and Schell 1994). Numerous laboratory and field studies indicate that δ¹³C isotope ratios of a specific organism reflect those of their prey and that predators have an average of 3‰ δ¹⁵N nitrogen isotope enrichment from their prey (Cocheret de la Moriniere et al. 2003; Rau et al. 1983; Michener and Schell 1994; Fry 1983; Schoeninger and DeNiro 1984; Cabana and Rasmussen 1994). Read together, carbon and nitrogen isotope ratios provide useful information for understanding feeding pathways (Peterson et al. 1985; Ehleringer et al. 1986; Peterson and Fry 1987; Nyssen et al. 2002).

Those who employ stable isotope analysis (SIA) to assess trophic relationships and patterns of resource consumption must be aware of its limitations to avoid drawing unsound conclusions. According to Boecklen et al. (2011), in some instances ecologists have used SIA problematically by relying too heavily on literature for key model parameters like fractionation factors (sometimes referred to as trophic enrichment factors), ignoring “multiple sources of variation in isotopic signatures” beyond those being tested, and making over-generalized inferences about diverse systems. They suggest that more laboratory experiments are needed to generate more precise values describing isotopic transfer between sources and consumers. My study was designed to capture multiple factors contributing to variation in isotopic signatures of Oregon’s Dungeness crabs, including size, sex, region, and season. And indeed, some of the
most noteworthy findings from the study resulted from these considerations (especially regarding region and season), highlighting the complexity of the SIA landscape and the habitat-specific nature of stable isotope values.

One of the most notable challenges with using stable isotope analysis in this study is the uncertainty surrounding fractionation values. In the original conceptualization of this project, \( \delta^{13}C \) and \( \delta^{15}N \) mixing models would be used to assess seasonal shifts in resource variation across multiple regions. These models would be constructed using benthic prey species identified from literature and sorted from bean trawl samples off Newport, OR, 2011-2016 by Henkel and common commercial Dungeness crab fishery bait species identified using ODFW data and fishermen interviews carried out by Harbison. Bait was obtained from commercial crabbers, field collection, and a fish processor (Pacific Seafoods, Inc.) in Newport, OR. These baits varied in provenance and were, for the most part, not native to Oregon waters. Creating robust mixing models requires fractionation values for Dungeness crab, which are unknown.

Here, despite the cautions from Boecklen et al. (2011), I used literature to estimate fractionation values. Resultant information on resource partitioning determined by the included models should therefore be considered approximate rather than precise. This procedure still provides a step forward towards a greater understanding of benthic food webs on the Oregon coast, with the understanding that more precise results could be acquired if Dungeness crab fractionation values are measured through laboratory experiments in the future. For now, we will rely on the following guidelines presented by numerous authors: \( \delta^{13}C \) in animals usually remains within \( \sim 1\% \) of their diet and \( \delta^{15}N \) increases by \( \sim 3\% \) per trophic level (DeNiro and Epstein 1978; Michener and Schell 1994; Post 2002).
Dungeness crab tissue turnover rates are also unknown, which adds another layer of uncertainty to the analysis. Changes in $\delta^{13}C$ and $\delta^{15}N$ composition following shifts in a consumer’s diet depends on specific tissue’s turnover rate (Gannes et al. 1998). In crustaceans, molting cycles, water temperature, diet composition, and size class could all influence turnover rates as well (Kangas 2000; Møller et al. 2008). In one experimental study on blue swimmer crabs, *Portunus pelagicus*, which reside in intertidal estuaries around Australia and New Caledonia, researchers assessed diet assimilation over a period of 9 weeks and found that even among the youngest, fastest growing crabs, isotopic signatures did not “stabilize and become representative of their food source” during that time (Møller et al. 2008). This lagged relationship suggests that *P. pelagicus* tissues require >9 weeks to turnover. In the present Dungeness crab study, wild samples were collected in December 2019, March/April 2020, June/July 2020, and October 2020, ~8 to 14 weeks apart. Gut contents of any given sample were expected to be representative of the concurrent sample season, while stable isotope values were expected to be representative of the previous season, ~12 weeks prior.

6. References


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CHAPTER 2: INVESTIGATING COMMERCIAL DUNGENESS CRAB BAIT USE STRATEGIES THROUGH FISHERMAN INTERVIEWS

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1. Introduction

To discern the extent to which bait subsidies from the commercial Dungeness crab fishery in Oregon alter the Dungeness crab feeding ecology, an understanding of spatiotemporal variation in the types and amounts of bait that fishermen use is required. The Oregon Department of Fish and Wildlife (ODFW) collects information about bait use in logbooks. That data provides an overall snapshot of the primary bait species used, including an approximation of the total number of pounds of each species deployed per year. However, it offers only a coarse understanding of bait use strategies and the spatiotemporal distribution of bait subsidies into the coastal system. I interviewed twenty-four commercial Dungeness crab fishermen with home ports spanning the entire Oregon coast to gain a more detailed understanding of bait usage, paying particular attention to practices that could dynamically alter the input of externally sourced organic material to coastal benthic communities. The results of these interviews guided my choices about which types of bait to include in the stable isotope mixing models presented in the next chapter. The combination of these interviews and the subsequent stable isotope and gut content analysis constitute a first step in answering the larger question of whether bait alters the trophodynamics of Dungeness crab.

2. Background

On a global scale, fisheries discards increase the availability of organic material to benthic communities (Britton and Morton 1994). These food subsidies impact ecosystem functioning in numerous ways, including increasing secondary productivity (Groenewold and Fonds 2000; Ramsay et al. 1997), reducing consumption of natural prey species (Waddington and Meeuwig 2009), and transporting biomass from pelagic to coastal systems (Grabowski et al. 2009). Additionally, numerous authors have hypothesized that fisheries discards increase the
abundance of benthic scavengers (Furness et al. 1988; Berghahn 1990; Wassenberg and Hill 1990; Kaiser and Spencer 1996; Ramsay et al. 1997). However, such discards are often spatiotemporally variable (Rijnsdorp et al. 1996) and bait subsidies must be frequent, predictable, and sufficiently large in magnitude in order impact consumer populations (Polis et al. 1996). Research on trap-based commercial lobster fisheries in Maine and Western Australia found that bait subsidies impact the feeding strategies of lobsters in those regions (Grabowski et al. 2009; Saila et al. 2002; Waddington and Meeuwig 2009). Grabowski et al. (2009) asserted that herring bait “augmented lobster populations” at a heavily fished site in the Gulf of Maine. The information gained from interviewing Oregon fishermen may prove useful when determining if bait inputs from the commercial Dungeness crab fishery are sufficient in magnitude to increase secondary productivity in crab populations.

Unfortunately, biometric data on Dungeness crab populations prior to the inception of commercial exploitation in 1948 does not exist. That lack of information makes it difficult to determine how human activities may have altered the crabs’ natural feeding strategies. When researching lobsters in the Gulf of

Figure 2: Commercial Dungeness crab fishing effort per 5km block in the 2012-2013 season in Oregon. Source: Oregon Dungeness Crab Fishery Bioeconomic Model, 2017, based on unpublished ODFW logbook data.
Maine, Grabowski et al. (2009) addressed this issue by sampling at two sites: one that was exposed to trap-based fishing effort and another where fishing was prohibited. The “fishing free” site acted essentially as a control with which to compare nitrogen enrichment through herring bait consumption. In Oregon, fishing effort is widely distributed throughout the coastal zone, though patchy in terms of intensity (Figure 2). Oregon does have five “no-take” marine reserves that are managed by the Oregon Department of Fish and Wildlife, including Redfish Rocks near Port Orford, OR, Cape Perpetua just south of Yachats, OR, Otter Rock north of Newport, OR, Cascade Head along Lincoln City, OR, and Cape Falcon near Cannon beach, OR. However, using crabs from one or more of these reserves as control specimens would have limited to unknown effectiveness because of the reserves’ relatively small size and the tendency of Dungeness crabs to move greater distances alongshore than the length of these reserves (Hildebrand et al. 2011) with variable site fidelity. Crabs could easily fill their stomachs with bait discards in a heavily fished area and then scurry into a reserve or area with less fishing effort.

In Australia, Waddington & Meeuwig (2009) used a mass balance model to approximate lobsters’ caloric needs, their secondary productivity, and the proportion of that productivity that could be accounted for by bait subsidies. They calculated that the magnitude of bait inputs varied significantly across regions and seasons according to changes in fishing effort, with a maximum caloric contribution of 35% from bait. My thesis contributes knowledge about Dungeness crab diets that can be used to develop accurate mass balance models in the future. Numerous authors have suggested that previous diet studies underestimate crab utilization of soft prey items including polychaetes, algae, and other organic detritus due to the limitations of gut content analysis. These prey items prove difficult to identify because they lack remnant hard structures.
Calculating the maximum proportion of bait-derived calories contributing to Dungeness crab productivity requires a solid grasp of the calories available from other sources (i.e. wild prey, algae, cannibalism) and crab feeding preferences, which are currently not well understood. This study investigates the presence or absence of evidence for seasonal variability of bait consumption through both gut content and stable isotope analysis (explained in detail in the next chapter), based on the knowledge that fishing effort (and therefore bait subsidies) is highly concentrated in December, January, and early February. Fishermen land most of their annual catch within the first six weeks of the fishery season (Dewees et al. 2004). This study will add detail to currently available data on fishing effort and strategies.

The type and amount of effort in the fishery, dictated by state regulations, relates directly to the type and amount of bait utilized by fishermen. The US West Coast states manage the commercial Dungeness crab fishery according to the “3S” system, size, sex, and season. Oregon permits commercial harvest on male crabs over 6 ¼ or ~159mm (ODFW 2021). Female and sub-legal males are returned to the ocean if caught, which means they have more opportunity to consume bait within multiple traps than legal sized males. The State of Oregon also restricts effort by granting a maximum of 424 permits per year, although the actual number of tickets in use if often below that maximum. Those permits are tiered, with pot limits of 200, 300, or 500 pots per fish ticket (Davis et al. 2017). Generally, the season runs from December 1st through August 14th, although the fishery does not open until the male crabs grow into their post-molt bodies and attain at least 23-25% meat fullness, depending on the region. The presence of harmful algal blooms (Moore et al. 2020), whale entanglement in crabbing gear, and price negotiations have also delayed or temporarily closed the fishery mid-season in some years.
(Lebon et al. 2018). A small commercial bay fishery also operates in the fall when the ocean fishery is closed.

The Oregon Department of Fish and Wildlife collects fishery logbooks that contain information about the types and amounts of bait that fishermen use per season. According to that data, the most frequently used bait types include squid (~1.1M lbs./season), clams (~900K lbs./season), sardines (~500K lbs./season), mackerel (~300K lbs./season), and lesser quantities of “other fish,” mink, tuna, rockfish, chicken, herring, anchovy, black cod, hake, halibut, and salmon (Bostrom et al. 2018). Fishermen use a variety of baiting equipment, including bait jars, chew bags, and bait pins (see Figure 3). All these tools are clipped or zip-tied inside the crab pots. The bait jars have tiny holes that allow the scent of the bait to waft out into the water without allowing captured crabs to eat the bait once inside the pots. Other organisms, like benthic amphipods, do enter the jars and feed on the bait. Chew bags and bait pins, on the other hand, allow the crabs to consume bait once they enter the pot.

This chapter dives “into the weeds” about the types of bait crabbers use, how they use it, and whether those strategies vary regionally (or port to port) within the State of Oregon, providing context for the stable isotope analysis to come. It offers a first step in offering the following questions: could regional variability in bait use could translate to differences in

Figure 3: Commonly used commercial Dungeness crab baiting gear. Clockwise from the top right: “Scotty” jar, bait jar, chew bag and bait pin. Other bait vessels not shown include the bait cage & pitcher.
isotopic ratios within crabs across sites? How are the broader ecological impacts of commercial
bait discards shaped by fishing strategies?

3. Methods

I collaboratively crafted interview questions about bait use geared towards commercial
Dungeness crab fishermen with input from career fishermen Robert Eder of Newport, OR, and
the Oregon Dungeness Crab Commission (ODCC). The survey asked about the types, amounts,
and spatiotemporal distribution of bait subsidies to Oregon’s coastal ocean (the complete survey
is included in the Appendix). The questions were uploaded into the online survey platform
Kobotoolbox. This strategy gave participants the option of completing the survey online or over
the phone. The ODCC then sent an email with a link to the survey to every commercial
Dungeness crab fisherman in Oregon on their listserv. Concurrently, fishermen were contacted
for phone interviews using Dr. Henkel’s fisherman contact list. At the end of each interview, I
asked the fisherman to suggest other potential participants and provide their phone number(s).
Most of the participant recruitment took place through this “snowball” method. Seven surveys
were filled out online by participants, while 17 were conducted over the phone, for a total of 24
responses.

After the interviews were complete, the data was downloaded as a .csv file from
Kobotoolbox. The .csv file contained binary, categorical, and text string responses arranged as a
table. Handwritten notes were also typed up and saved as a text file associated with the dataset.
Each fisherman was given a unique identifier and their names were removed from the dataset for
privacy. The binary data (relating to types of bait used and months of fishery participation) was
extracted from the main dataset and transferred to a .csv format. It was then uploaded into R
Studio and run through a hierarchical clustering algorithm using Ward’s distance to assess the
degree of dissimilarity between each binary string. This algorithm output six groupings of fishermen with similar bait use strategies as well as a cluster dendrogram. Home port and bait type information for the fishermen in each group was recorded to identify patterns.

Next, the degree of correlation between each binary string was used to create a network connectivity visualization in R. This visualization showed participants with similar bait type usage as relatively close together and participants with dissimilar bait type usage as farther apart, providing another avenue to assess trends. Both the hierarchical clustering analysis and the correlation network analysis were used to assess regional port specific trends in bait use strategy. The three regions, “North,” “Central,” and “South,” were determined by splitting the Oregon coast into thirds by latitude. Non-binary quantitative data was then summarized as mean values with associated standard deviations and compared to the ODFW preassessment document. Lastly, the ecological ramifications of the information contained within the survey results were assessed through literature review.

4. Results

Within the group of twenty-four fishermen interviewed, the three most common bait types were squid, rockfish, and razor clams. 100% of the fishermen used squid, 87.5% used rockfish, and 75% used razor clams. See Figure 4 for a complete break-down of the most

![Dungeness Crab Fishery Baits](image)

**Figure 4:** The percentage of interview respondents in each group who reported using each of the categories of bait that were asked about in the interview.
frequently used bait types. A notable difference between ODFW data about major bait types used and these interview results was the variation in the significance of rockfish bait to the fishery. ODFW reported only minimal use of rockfish, whereas rockfish was the second most frequently used bait according to this analysis. Interviewees also reported using other types of bait that were not included in the ODFW report, including Dover sole, bonito, lingcod, canned tuna, sablefish, canned cat food, dogfish, deer carcasses, pigs’ ears, and shad. Additionally, the reported values of bait used by each fisherman came to 3.11±1.94 lbs per pot and 35,000±12,431.63 lbs per season on average. 58.33% of respondents indicated that they never reuse bait when resetting crab pots, 33.33% said that they reuse bait less than half the time, and 8.33% said they reuse bait about half the time. All the fishermen indicated that they toss their used bait overboard into the ocean, either immediately after pulling the pot or after exiting their primary fishing grounds. Those who discarded bait after leaving their primary fishing grounds chose to avoid dropping discards near their pots, fearing that the availability of excess bait in the area would disincentivize crabs from entering the pots.

The number of respondents who engage in the fishery, the types and amounts of baits used, and the baiting methods employed vary over the course of the season. All the respondents reported that they start crabbing as soon as the season opens, which generally occurs in December or early January, and continue harvesting.

![Fishery Participation by Month](image)

*Figure 5: Percent of respondents who participate in the fishery during each open season month in a typical year.*
at least through February. The number of respondents who participate in the fishery declines each month starting in March, and by June-August only ~30% of the fishermen I interviewed continue to crab. Figure 5 shows the percentage of respondents who typically fish in each open season month (December-August). As effort decreases, the types and amounts of bait the respondents use concurrently shift. 79% of interviewees stated that their bait use strategy changes over the course of the season. The most frequently occurring explanation for this variation was availability of baits species (41.6%). Respondents also cited competition as a motivating factor for using more bait at the beginning of the season (both in terms of types and amounts) to draw crabs to their pots rather than those of other crabbers. 29.2% indicated that they include more fish in their pots in the early season, including rockfish and tuna, in addition to clams and squid. By the end of the season, they tend rely on clams and/or squid alone. One crabber linked the increased dependence on clams later in the season to longer soak times, asserting that clams remain in the pots longer than fish or squid. Additionally, several crabbers reported using more hanging bait and chew bags, which enable crabs to eat the bait in the pots, in addition to bait jars, which restrict access to bait, at the beginning of the season and bait jars alone as the season progresses. One interviewee provided his general bait recipe, which consists of 1lb clams and 1lb squid in a bait jar and 4-5lbs fish in a chew bag at the season opener and 0.5lbs clams and 0.5lbs squid at the end of the season. 96% of respondents used both a closed bait method (bait jar and/or box) and an open bait method (chew bag and/or bait pin) at some point during the season. One fisherman reported using only squid in closed bait jars.

Additionally, fishermen indicated several strategies pertaining to depth and distance from port where they set their pots and how long they leave those pots in the water. The minimum, maximum, and mean pot depths were 2 fathoms, 125 fathoms, and 29.89 fathoms, respectively.
Two fishermen explained that they start the season in deeper waters and then move in closer to the beach as the season progresses because winter storms will destroy pots set in shallow waters. Another crabber asserted that crabs move in towards the beach in the spring and summer, and that he accordingly fished in closer in the spring. Competition with other fishermen also influenced depth preferences. One respondent indicated that he fishes deeper than other boats (around 50 fathoms on average) to avoid competition, even though he catches fewer crabs at depth.

The minimum, maximum, and mean distances traveled from home port were 0.25NM, 500NM, and 37.65NM, respectively. 29.2% of respondents said that the distance they traveled from port did not change significantly over the course of the season, while 58.3% said that it did.

Among those who traveled varying distances, weather and perceived concentration of crabs were the two most frequently cited motivators for shifting location. The minimum, maximum, and average soak times (or length of time the crab pots were left in the water before being pulled, were 12 hours, 14 days, and 3.29 days. All respondents reported that they turned over pots rapidly at the beginning of the season and more slowly as the season progressed due to the declining abundance of crabs and decreased rivalry.

When asked to rank effectiveness, availability, and cost in terms of strongest to weakest determinants...
influencing bait choice, 83% placed effectiveness as the most influential factor. They indicated that despite the high price of bait, the expense of preferred bait is worthwhile if it leads to higher catch. Availability and cost were evenly split as the second strongest motivators, while cost was the most frequent third choice. 54.17% of participants indicated that they always get their bait from the same company that buys their catch, 33.33% said that they sometimes do, and 12.5% said that they always get bait from a different outfit than the one that buys their crabs. The most frequently mentioned bait suppliers were Pacific Seafoods (33.33%), Hallmark Fisheries (8.33%), Tri Marine Fish Company (8.33%), Dayang Seafood (8.33%), and Pacific Coast Seafood (8.33%). The California Shellfish Company, Bornstein Seafood, and Port Orford Sustainable Seafood were also mentioned less frequently. Crabbers also reported getting bait from recreational charter boats, mink farms, local clam diggers, and their own terrestrial hunting (especially deer) and marine fishing efforts.

![Bait Use by Hierarchical Cluster](image)

**Figure 7:** Percent of respondents in each cluster who use each bait type discussed.
Although a variety of combinations of bait are used by commercial Dungeness crab fishermen on the Oregon coast, this analysis did not show any clear regional trends in bait use strategy. The clustering algorithm using Ward’s distance produced six groupings of fishermen according to the type of bait they used. Fishermen from the North region were assigned to four groups, those from the central region were assigned to 5 groups, and those from the south region were split among all six groups, demonstrating there is no clear regional variation in the types of baits used in the commercial Dungeness crab fishery (Figure 6). The types of bait used within each cluster group are broken down in Figure 7. Groups 1 & 2 are characterized by the greatest variety of baits used. At least one fisherman in each of those groups used eleven out of the 13 bait categories. The percentage of participants in the groups that use mink is one noticeable feature that differentiates the two groups: none of the fishermen in group 2 use mink. Groups 3 & 4 used a lower diversity of baits than groups 1 & 2 but a greater diversity than groups 5 & 6. None of the fishermen in either of those two groups used clams other than razor clams. Groups 5 & 6 used the lowest diversity of baits, but all the members of group 5 use clams while none of the members of group 6 do.

A bait use correlation network also indicated that there is no clear regional variation in the types of baits used (Figure 8). However, the Newport fishermen appear more tightly clustered in the Network than fishermen from other ports. The Newport fishermen are at the center of the network and geographically in the center of the coast. Crabbers from the North and south occupy the fringes of the network, suggesting that they tend to have more unique bait combinations than Newport fishermen. Respondent 18 stood out from the group because he only
uses squid bait, while respondent 20 did not use any clams and preferred instead to use squid, bonito, other pelagic fishes, and rockfish.

5. Discussion

The broad scale goals behind this analysis were to (1) determine which bait types would be most important to include in $\delta^{13}C$ and $\delta^{15}N$ stable isotope mixing models, (2) explore whether regional variability in bait use could explain spatial variability in stable isotope values, and (3) add resolution to currently available information on bait use in the commercial Dungeness crab fishery to better understand the ecological impacts of those activities. The interviews helped to answer these questions, but also inspired a slew of additional questions. According to the
breakdown of bait types used by participants in this study, squid, rockfish, razor clams, sardines, cockle clams, chicken, and mink were selected for stable isotope analysis based either on frequency of use or, as with chicken and mink, putative alien isotopic composition compared to naturally occurring species in the coastal marine environment.

Bait types reported by participants largely mirrored ODFW logbook data, except for rockfish. ODFW reported only minimal utilization of rockfish (in terms of total pounds per season; Bostrom et al. 2018), while in this study it ranked as the second most frequently used bait type. One possible explanation for this discrepancy is that although rockfish are available for purchase from seafood distributors (including Pacific Seafoods in Newport, OR), crabbers also source rockfish carcasses at low or no cost from recreational charter boats through informal channels. This casual and opportunistic acquisition could translate to fewer overall pounds of rockfish used as well as a lower likelihood that crabbers would record those sporadic windfalls in their logbooks. Another explanation could be the combination of a relatively small interview sample size (n=24) and the “snowball” sampling method. Most of the participants in the study were included based on personal references from other participants. This raises the question: are crabbers connected through social or professional ties more likely to use similar bait strategies (i.e., including rockfish in their bait cocktail) than unconnected crabbers?

The results did not show any clear regional variations in the types of bait used that could help explain regional variation in stable isotope values. This finding suggests that naturally occurring environmental and ecological factors are more likely to contribute to spatial variability in δ¹³C and δ¹⁵N stable isotope ratios than fishery discards. On the other hand, the correlation network analysis did indicate that participants from Newport had more similar bait recipes to each other than crabbers from the North and South study areas. This trend could be explained in
part by one variable that was not initially considered in this study: port size. The Newport harbor is relatively large (both in terms of the number of slips and the size of vessels it can accommodate) compared to several of the home ports of respondents in the North and South region, including Garibaldi, OR, and Port Orford, OR. Skippers on small, independently operated vessels could be more likely to acquire baits from different sources than larger vessels that contract with major seafood wholesalers. Seafood processors and distributors do appear to influence bait choices based on the finding in this study that over half of fishermen interviewed always purchased their bait from the same entity that buys their catch.

Regardless of its source, commercial Dungeness crab fishermen discard millions of pounds of bait into Oregon’s coastal ocean each year. Participants in this study approximated that they each added an average of 35,000 ± 12,431.63 lbs of bait per season. Numerous authors have shown that organic matter subsidies can alter benthic ecosystem functioning (Groenewold and Fonds 2000; Ramsay et al. 1997; Furness et al. 1988; Berghahn 1990; Wassenberg and Hill 1990), especially if those subsidies are frequent, predictable, and sufficiently large in magnitude (Polis et al. 1996). Of course, these interviews did not measure ecological impacts, but rather informed the development of hypotheses regarding ecological impacts. One noteworthy process that could alter carbon isotope distribution and the trophic positioning of organisms on Oregon’s coastal shelf is the transport of pelagic species into near-coastal areas and estuarine or near-coastal species into deeper waters. Reported fishing depths ranged between 2 fathoms and 125 fathoms, and fishermen indicated using a wide variety of baits throughout those depths. The transport of carrion from pelagic species like sardines, mackerel, herring, tuna, and bonito into shallow waters could decrease δ13C ratios and increase δ15N ratios in the coastal benthos.

Grabowski et al. (2009) found that pelagic herring dietary supplements increased growth rate and
decreased molt increment and time to maturity of American lobsters (*Homarus americanus*) in the Gulf of Maine. Inputs of the pelagic species listed above could have a similar impact on *Cancer magister* or other benthic scavengers.

Unlike in the Grabowski et al. (2009) study, the commercial Dungeness crab fishery also transports nearshore or estuarine species like razor clams (*Siliqua patula*), cockle clams (*Clinocardium nuttallii*), and butter clams (*Saxidomus giganteus*) offshore. Based on the interview responses, this transport peaks at the beginning of the crabbing season, which generally opens in December or January. Several crabbers mentioned that they start the season setting their pots in deeper waters to avoid winter swells and then move in closer to shore as the seas calm in early spring. They also reported a trend of using more and a greater variety of bait at the season opener to make their pots more attractive than those of competitors, followed by a decreased proportion of fish and an increased proportion of clams as the season progressed. The combination of setting shallower pots and using more clams could make Dungeness crab consumption of discarded bait more difficult to identify through stable isotope analysis, as bivalves constitute a major wild food source for the crabs (Stevens et al. 1982, Gotshall 1977, Butler 1954). In a general sense, the difficulty of differentiating bait from wild prey provides a major challenge in investigating the contribution of that bait to Dungeness crab diets. $\delta^{13}$C and $\delta^{15}$N isotopic analysis of reported bait types, prey identified through gut content analysis and literature, as well as Dungeness crabs could offer a first step in parsing out shifts in relative food source utilization.

6. Conclusion

Interviews with commercial Dungeness crab fishermen indicated no clear regional variation in the types of bait they use, however, crabbers based in Newport, OR, appeared to
have more similar bait “recipes” to each other than the fishermen from other ports. This study also provides useful information about depth and distance from port where crabbers set their pots, which sheds light on the spatial distribution of bait in Oregon’s coastal waters. The bait strategies employed by the interviewed crabbers clearly shift over the course of a given season, influenced by factors including competition with other fishermen, weather, perceptions of crab population concentrations, and the cost, availability, and effectiveness of bait. In the context of the larger project, these results lead to the conclusion that if Dungeness crab isotope values are influenced by the consumption of discarded fishery bait, that consumption will create a stronger seasonal rather than regional signature.

7. References


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https://oregonshores.org/marine-reserves/


CHAPTER 3: ASSESSING SPATIOTEMPORAL VARIATION IN DUNGENESS CRAB (CANCER MAGISTER) FEEDING ECOLOGY DUE TO FISHERY BAIT INPUT USING $\delta^{13}C$ AND $\delta^{15}N$ STABLE ISOTOPE AND GUT CONTENT ANALYSIS

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Abstract

The commercial Dungeness crab (Cancer magister) fishery is Oregon’s largest trap-based fishery, deploying an average of 115,180 pots and landing an average of 17.42 million pounds of crab between the 2010-2011 and 2019-2020 seasons. Each year, crab vessels discard millions of pounds of bait, including squid, razor clams, and sardines, into the near-coastal ocean. Although the fishery season typically runs from December 1st through August 14th, most landings occur within the first six weeks of the open season. Regional and seasonal variation in Dungeness crabs’ δ^{13}C and δ^{15}N stable isotope (SI) composition and gut contents across multiple sex and size classes were assessed to investigate the potential consumption of discarded bait by the crabs. Stable isotope mixing models were employed to approximate possible spatiotemporal variability in bait contribution to Dungeness crab diets. The δ^{13}C and δ^{15}N signature of crabs collected during four seasons (December 2019, March-April 2020, June-July 2020, and October 2020) across three regional study areas showed highly significant regional and seasonal variation. Tissues of female crabs sampled in the springtime across multiple sites contained increased δ^{15}N ratios compared to all other seasons, which could be indicative of trophic enrichment through bait consumption. Overall, the results demonstrated the complex and dynamic nature of coastal food webs and the importance of considering multiple habitats over time when evaluating trophic relationships.

1. Introduction

The commercial Dungeness crab fishery is Oregon’s largest and typically most profitable fishery. During the 2019-2020 season, 320 active permit holders harvested 19.98 million pounds of Dungeness crab, generating 72.7 million dollars in total revenue. 86% of total harvest was landed within the first two months of the open season (ODFW 2020). The Oregon Department of
Fish and Wildlife (ODFW) manages the fishery through vessel and pot limits. Historically, Dungeness crab landings have fluctuated in loosely decadal cycles, although that cyclical trend has broken down over the last several decades (Botsford et al. 1982; Botsford and Lawrence 2002), when catch has increased despite similar levels of effort (a limited-entry system of 465 permits started in the 1995-96 season, which has now been reduced to 424 permits; ODFW 2021). Between 1998 and 2018, landings averaged 17.3 million pounds per year compared to a previous two-decade average of 9.6 million pounds (ODFW 2021).

Commercial catch generally serves as a sufficient proxy for legal sized male abundance (Richerson et al. 2020), suggesting that Dungeness crab abundance could be increasing. Fishery discards could be a mechanism contributing to this increase. On a global scale, fisheries discards increase the availability of organic material to benthic communities (Britton and Morton 1994). These food subsidies impact ecosystem functioning in numerous ways, including increasing secondary productivity (Groenewold and Fonds 2000; Ramsay et al 1997), reducing consumption of natural prey species (Waddington and Meeuwig 2009), and transporting biomass from pelagic to coastal systems (Grabowski et al. 2009).

Numerous authors have hypothesized that fisheries discards increase the abundance of benthic scavengers (Furness et al. 1988; Berghahn 1990; Wassenberg and Hill 1990; Kaiser & Spencer 1996; Ramsay et al. 1997). Research on trap-based commercial lobster fisheries in Maine and Western Australia found that bait subsidies have altered the trophodynamics of lobsters in those regions (Grabowski et al. 2009; Saila et al. 2002; Waddington and Meeuwig 2009). Grabowski et al. (2009) asserted that herring bait “augmented lobster populations” at a heavily fished site in the Gulf of Maine.
The current study uses δ¹³C and δ¹⁵N stable isotope and gut content analysis to investigate possible seasonal variation in Dungeness crab diets related to the consumption of discarded fishery bait. Gut content analysis can provide information about an organism’s feeding preferences hours to days prior to capture, although crustaceans heavily masticate their prey, making it difficult to identify (Waterman 1960; Stevens et al. 1982). Stable isotope analysis approximates longer-term diet composition over weeks to months. Numerous studies indicate that isotope ratios of consumers reflect those of their prey. Although fractionation values and tissue turnover rates vary widely across organisms, δ¹³C in animals usually remains within ~1‰ of their diet and δ¹⁵N increases by ~3.4‰ per trophic level (Deniro and Epstein 1978; Michener and Schell 1994; Post 2002).

The aims of this study are to (1) contribute to the current understanding of Dungeness crab diets, including feeding on wild prey (2) to assess seasonal variability in Dungeness crab isotopic composition that could indicate consumption of fishery bait discards and (3) to compare seasonal variation across regions as well as size and sex classes. This is the first study to investigate potential impacts of organic matter subsidies from the commercial Dungeness crab fishery on that target species.

The hypothesized results vary seasonally according to fluctuations in expected feeding behaviors, Dungeness crab fishery effort, and available food sources previously described in literature. Given that fishing effort generally peaks between December and February (Harbison Chapter 2), stable isotope values and gut contents were hypothesized to reflect peak bait consumption during that period, characterized by relatively high δ¹⁵N and δ¹³C from the consumption of pelagic higher trophic level bait species and few hard structures in the guts. In the spring, juveniles Dungeness crab recruit into estuaries (Gunderson et al. 1990) and many
authors report cannibalism between (MacKay 1942; Butler 1954; Gotshall 1977) and within age class (Jacoby 1983; Karpov 1983; Fernandez et al. 1993a, b, 1994). Accordingly, guts collected in the spring and summer were hypothesized to contain *Cancer magister* fragments. Both juvenile recruitment and commercial Dungeness crab harvest cease almost entirely by early fall, therefore, we hypothesized that crabs collected in October and December would reflect peak consumption of benthic invertebrate food sources such as bivalves, gastropods, polychaetes, and small teleost flatfish (see Bernard 1979; Feder & Paul 1980; Stevens et al. 1982) characterized by the lowest relative $\delta^{15}$N ratios.

2. Methods

2.1 Study Area

Dungeness crabs of sizes 108-198 mm carapace width (CW) were collected across three geographic regions of the Oregon coast (North, Central, and South) during four seasons (December 2019, March/April 2020, June/July 2020, and October 2020) at 20-50m depth. Regions were determined by splitting the Oregon coastline into three latitudinal sections; the Oregon/California border (41.99°N) to Reedsport, OR (43.72°N) was considered “South,” Reedsport to Lincoln City, OR (44.96°N) was considered “Central,” and Lincoln City to the Oregon/Washington (46.26°N) border was considered “North.”

2.2 Sample Collection

Whenever possible, 10 legal-sized males (CW>159mm), 10 sub-legal males (CW<159mm), and 10 female crabs were collected during each sampling session, except in December 2019 when samples were obtained with ODFW’s meat fill sampling and only legal males were collected. Samples were collected by commercial fishermen at the Garibaldi (North)
and Pacific City (North) sites in Spring 2020 using unknown baiting methods. All other samples were collected using closed bait pitchers that prevent crabs from consuming bait inside the pot.

Dungeness crab food sources identified from literature, including macroalgae, bivalves, and eelgrass were collected from the Yaquina Bay mudflats near Newport, OR. All other putative prey, including *Olivella* sp., *Crangon* sp., juvenile *Cancer magister*, cumaceans, *Citharichthys sordidus*, and small bivalves were sorted from beam trawl samples conducted by Henkel between 2011-2016. Fishery bait species were selected based on ODFW fishery logbook data. Squid, mackerel, and sardines were acquired from Pacific Seafood, Inc., in Newport, OR. Cockle clams were collected from the Yaquina Bay mudflats. Rockfish carcasses were sourced from a recreational charter vessel in Garibaldi, OR.

### 2.3 Gut Content Analysis

Complete digestive tracts were removed from collected crabs after they were euthanized according to IACUC regulations (except in December 2019 when samples had been frozen prior to acquisition) and stored in 70% ethanol. Stomachs were then dissected using a straightedge blade and tweezers and inspected under a dissecting microscope. Similar items were sorted into piles and photographed with a Leica camera for taxonomic identification. Gut contents were identified to the lowest taxa possible. The presence or absence of each taxonomic group, as well as soft tissue and sand were recorded for each stomach. The frequency of occurrence (FO) of each item was calculated as the percentage of stomachs that contained that item within each sample site, region, and season. FO across sex and size classes across and within sites and seasons were also compared.
2.4 Stable Isotope Analysis

Dungeness crab leg muscle tissue, whole prey items, and fishery bait were frozen at 20°C prior to analysis. All samples were dried at 60°C for ≥ 48 hours and then manually ground to a fine powder using a mortar and pestle. The mortar and pestle were cleaned with acetone under a laboratory hood between each sample. The powdered samples were stored in airtight 1.5-2mL Eppendorf tubes. 1.0mg (±0.1 mg) of each powdered sample was weighed, transferred into tin capsules (EA Consumables–Part #D1002), and placed in 96 well plates (VWR–Part #10062-902). Samples were analyzed at the NOAA Alaska Marine Fisheries Science Center in Auke Bay, Alaska, or at the Stable Isotope Lab at Oregon State University (OSU) in Corvallis, OR. V-PDB and atmospheric N₂ were used as standards for carbon and nitrogen, respectively. Stable isotope ratios were expressed in δ notation according to the following equation:

\[ \delta X = \left[ \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right] \times 1000 \]

where X represents \(^{13}\)C or \(^{15}\)N and R is \(^{13}\)C/\(^{12}\)C or \(^{15}\)N/\(^{14}\)N ratio, respectively.

2.5 Data Analysis

Initially, the SIBER (Stable Isotope Bayesian Ellipses in R; Jackson et al. 2011) package was used to assess relative variation in δ\(^{13}\)C and δ\(^{15}\)N ratios and isotopic niche area across sex and size classes (sub-legal males (<159mm), legal males (>159mm), small females (<159mm), and large females (>159mm)) within three seasons (spring, summer, and fall). Winter samples were excluded because no female samples were collected during the winter. Isotopic niche was estimated by calculating SEAc (Standard Ellipse Area, corrected for sample size) for each of the classes, a metric that reports the area of an ellipse drawn around the centroid, containing 40% of the sample points. The directionality and magnitude of the differences between each class were approximated by calculating the pairwise polar vectors among all groups. These vectors were
visualized using polar histograms. Next, the polar coordinates were converted into cartesian space using the following function:

\[ f(r, \theta) = (r \cos \theta, r \sin \theta) \]

The median angle and median length of each class-wise comparison in cartesian space were then reported following Jackson (2021). Based on the results of the class-wise comparisons, the same procedure was repeated comparing all male crabs across four seasons and all female crabs across three seasons. Sexes were not subdivided into size classes due to limited sample size when considering individual seasons.

The stable isotope signature for each sample area in each region was summarized according to mean $\delta^{13}$C and $\delta^{15}$N ratios ± 1 standard deviation. The mean ± 1 standard deviation was then calculated for each sex within each region. Regional means ± 1 standard deviation were calculated for all samples within each region (Table 1).

Nested analyses of variance (ANOVAs) for $\delta^{13}$C and $\delta^{15}$N ratios of all samples (n=345) were performed considering region, sex, class, season within region, site within region, and seasonal variation within in region by sex. Normality was tested by plotting model residuals and equal variance was tested using Levene’s Test for Homogeneity of Variance. A post hoc Tukey test was performed on the ANOVA output. The significance level, \( \alpha \), was set at 0.05 for all analyses. All statistical tests were performed in the coding language R.

SI data for legal-sized males from Newport, OR, females from Newport, OR, females from Pacific City, OR, and all males from the southern region were analyzed with the Bayesian isotope mixing model ‘simmr’ (A Stable Isotope Mixing Model) in R (Parnell 2021). These subsets were selected as case studies for seasonal variation in feeding strategies within each region. The Pacific City females and southern males were additionally selected because their
\[ \delta^{15}N \text{ values showed significant variation} \ (p > 0.05) \text{ from crabs of their sex sampled at other sites.} \]

Fractionation values were not available for Dungeness crab, so estimates of 1\% \delta^{13}C and 3\% \delta^{15}N were used for all mixing models.

Dietary sources were grouped into five categories to approximate the relative contribution of fishery bait and wild food sources to the diets of Dungeness crabs: Invertebrate Prey, Teleost Prey, Teleost Bait, Eelgrass, Squid Bait. The Invertebrate Prey group was made up of small bivalves \((n=10)\), shrimp \((Crangon \text{ sp.}; \ n=17)\), Cumacea \((n=15)\), juvenile Dungeness crab \((Cancer \text{ magister}; \ n=15)\), hermit crabs \((Paguroidea; \ n=10)\), and dwarf olive snails \((Olivella \text{ biplicata}; \ n=16)\). The Teleost Prey group was made up of Pacific sanddab \((Citharichthys \text{ sordidus}; \ n=5)\) <5cm in length. The Squid Bait group was made up of shortfin squid \((Illex \text{ sp.}; \ n=11)\). The Eelgrass group was made up of \(Zostera \text{ marina}\). These groupings were determined based on species that were relatively clustered in bivariate delta space and those that occupy similar ecological niches.

Although Dungeness crab tissue turnover rates are unknown, one experimental study of the blue swimmer crab, \(Portunus \text{ pelagicus}\), suggested that the tissues of that species required >9 weeks to turnover \((Kangas \ 2000)\). In the present study, Dungeness crab samples were collects ~8 to 14 weeks apart. Therefore, we approximate tissue samples collected in any given season to be representative of feeding habits in the previous season.

3. Results

3.1 Gut Content Analysis

The most frequently occurring food sources across all samples were Teleost \((FO=27.74\%)\), Bivalvia \((24.84\%)\), soft tissue \((20.97\%)\), Decapoda \((20.00\%)\), and Gastropoda \((17.74\%)\). Overall, teleost parts had the most consistent frequency of occurrence across seasons; however, this prey
item also had the greatest variability among sites within a season (Figure 9). Soft tissue was the second most consistent diet item across seasons. Teleost parts (scale, bones, and fin rays) were especially abundant at site in the North in spring (Pacific City = 43%) and summer (Garibaldi = 67%) and the South (Port Orford = 77%) in the fall (Table 2). In contrast to the seasonal consistency of teleost parts, bivalves increased from 16% in spring to 26% in summer and 31% in fall (Table 2). Summer had the highest proportion of soft tissue and decapods relative to other seasons with guts from Newport collected in June containing the highest frequency of soft tissue (37%) and summer Garibaldi guts containing the highest frequency of decapods (63%).

Table 2: Frequency of occurrence of: Tel. (teleost), Biv. (bivalve), ST (soft tissue), Dec. (decapod), Gas. (gastropod), Mac. (macroalgae), Sand (sand), Bry. (bryozoa), Ech. (echinoderms), wood, Sea. (seagrass), and empty guts.

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</table>
While macroalgae, sand, seagrass and wood debris were found in smaller proportions of the guts overall, they were most prevalent in the south coast sites. Macroalgae was four times more frequent at Reedsport than any other site in July, at 28%; wood debris and seagrass also occurred most frequently at the Reedsport site (Table 2). Fall Port Orford samples contained sand most frequently, at 33%, over four times greater than any other site. Bryozoans were found infrequently (≤5% on average) but in all seasons. Echinoderms were also found infrequently (≤4% on average) but only in summer and fall. By far the greatest proportion of empty stomachs were sampled in the spring (35% on average) (Figure 9).

*Figure 9: Frequency of occurrence of diet categories in all sampled Dungeness crab guts by season.*
3.2 Stable Isotope Analysis

3.2.1 Ellipse Analysis

The isotopic niches of each Dungeness crab sex and size class varied from each other, with the greatest degree of differentiation occurring between large females and legal-sized males. Additionally, the ellipses surrounding sample points for each season varied, although the magnitude and directionality of those variations differed between the two sexes. Across sizes and sexes the tissue of legal males contained the highest mean $\delta^{13}C$ values (-15.69 ± 0.49) and the lowest mean $\delta^{15}N$ values (13.22 ± 0.52) (Figure 10a; red). The Standard Ellipse encompassing 40% of the samples around the centroid of the legal male ellipse showed to greatest degree of overlap with the sub-legal male ellipse, followed by the small females and the least overlap with the large females (Figure 10a). The mean $\delta^{13}C$ value of sub-legal males (-16.01 ± 0.58) was lower than legal males, while $\delta^{15}N$ was similar at 13.32 ± 0.48. The small female group showed still lower $\delta^{13}C$ (-16.35 ± 0.59) and similar $\delta^{15}N$ (13.34 ± 0.50) compared to sub-legal males. Large females had the highest relative mean $\delta^{15}N$ values, at 13.75 ± 0.60. The mean $\delta^{13}C$ of large females, -16.35 ± 0.60, was similar to that of small females. The Standard Ellipse Areas corrected by sample size (SEAc) were slightly larger for females (LF = 0.94; SF = 0.94) than males (LM = 0.83; SM = 0.89).

The vector analysis (Figure 10b) indicates that the degree of variation between groups was greatest when comparing LF vs. LM, characterized by a median vector distance of 0.924 with a median vector angle of 2.20. In descending order by median vector distance followed by
median vector angle, the remaining pair-wise outputs were LM vs. SF (0.76; -1.41), LF vs. SM (0.57; 2.47), LF vs. SF (0.46; 1.21), LF vs. SM (0.45; -1.36), and lastly SF vs. SM (0.35; 1.64).

The ellipses comparing $\delta_{15}^N$ and $\delta_{13}^C$ ratios of all females across three seasons suggest that $\delta_{15}^N$ decreases from spring through fall, while $\delta_{13}^C$ remained similar (Figure 11a). Mean $\delta_{15}^N$ values declined from a high of 13.98 ± 0.58 in the spring to 13.47 ± 0.31 in the summer and 13.07 ± 0.53 in the fall. Mean $\delta_{13}^C$ values were -16.24 ± 0.45, -16.44 ± 0.51, and -16.34 ± 0.69, respectively, across seasons. Median pairwise vector distances were greatest between spring and summer.

Figure 10: (Above) Standard Ellipses indicating trophic niche variation by sex and size. (Below) Polar histogram indicating the direction of paired difference vectors between all points in each group.
(0.96), followed by spring and summer (0.61), and summer and fall (0.49). SEAc, which approximates the relative size of a consumer’s trophic niche, was largest in the fall (1.19), followed by the spring (0.67) and the summer (0.51) (Table 3).

Trophic variation of all male samples across four seasons showed the highest relative mean δ¹³C ratios (-15.40 ± 0.41) in the springtime and the lowest relative mean δ¹⁵N ratios in the fall (13.06 ± 0.65) (Figure 11b). δ¹⁵N was similar between spring (13.34 ± 0.38), summer (13.34 ± 0.48), and winter (13.23 ± 0.46). SEAc was greatest for fall (1.06), followed by summer (0.74), winter (0.68), and spring (0.48) (Figure 11b). Median pairwise vector distance was greatest between spring and fall (0.67), followed by spring vs. summer (0.56), spring vs. winter (0.51), summer vs. fall (0.34), fall vs. winter (0.29), and summer vs. winter (0.24). All mean stable isotope and SEAc values are reported for males and females at each sample site in Table 3.

Figure 11: Seasonal Standard Ellipses drawn around female (above) and male (below) Dungeness crab samples across seasons.
3.2.2 Analysis of Variance

The nested analyses of variance (ANOVAs) conducted on the $\delta^{15}$N values of all samples showed substantial variation between regions ($p < 0.001$), sexes ($p < 0.001$), classes ($p < 0.001$), seasons within each region ($p < 0.001$), and seasons within each region, separated by sex ($p < 0.001$). Sites within each region, on the other hand, did not vary substantially ($p = 0.46$). When considering $\delta^{13}$C, all samples showed substantial variation between regions ($p < 0.001$), sexes ($p < 0.001$), classes ($p < 0.001$), seasons within each region ($p < 0.001$), seasons within each region, separated by sex ($p = 0.035$), and site within regions ($p = 0.002$).

The post hoc Tukey HSD (honestly significant difference) indicated that overall, both $\delta^{13}$C and $\delta^{15}$N varied for all pairwise regional comparisons ($p < 0.001$); however, regional differences were not consistent across seasons. All these comparisons are visualized in Figure 12. In the spring, no significant regional differences were detected in $\delta^{13}$C, but $\delta^{15}$N did vary between the North and Central regions ($p = 0.036$). Samples were not collected in the South region during spring 2020. In the summer, $\delta^{13}$C values in the South and Central regions were different from each other ($p < 0.001$), but neither varied significantly from the North. No significant regional variation in $\delta^{15}$N was detected during the summer season. In the fall, $\delta^{13}$C and $\delta^{15}$N values in the South varied from the Central and North ($p < 0.001$). When comparing the North and Central regions in the fall, $\delta^{13}$C was marginally different ($p = 0.059$), but $\delta^{15}$N did not vary. In the winter, $\delta^{13}$C values varied between the South and Central regions ($p = 0.005$). During that season, $\delta^{15}$N in the North varied significantly from the South ($p = 0.003$) and marginally from the Central ($p = 0.056$).
Table 3: Mean and sample standard deviation of all samples and Standard Ellipse Area corrected by sample size.

<table>
<thead>
<tr>
<th>Date</th>
<th>Region</th>
<th>Area</th>
<th>n</th>
<th>$\delta^{13}$C v. V-PDB</th>
<th>$\delta^{15}$N v. Air</th>
<th>SEAc</th>
</tr>
</thead>
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<td></td>
<td></td>
<td></td>
<td>M</td>
<td>F</td>
<td>M</td>
<td>F</td>
</tr>
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<td></td>
<td>North</td>
<td></td>
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<td></td>
</tr>
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<td>-16.17 ± 0.40</td>
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<td>3/25/2020</td>
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<td>20</td>
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<td>13.48 ± 0.52</td>
<td>1.16</td>
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<tr>
<td>10/15/2020</td>
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<td>Garibaldi</td>
<td>20</td>
<td>-1.60 ± 0.88</td>
<td>13.69 ± 0.46</td>
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<td>-16.03 ± 0.88</td>
<td>13.55 ± 0.41</td>
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<td>All</td>
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<td>-16.40 ± 0.50</td>
<td>12.96 ± 0.57</td>
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Within regions, the North region varied considerably in $\delta^{13}\text{C}$ in the spring versus summer ($p = 0.007$). $\delta^{13}\text{C}$ in the winter versus spring varied to a lesser extent ($p = 0.075$). $\delta^{15}\text{N}$ only varied between fall and winter ($p = 0.056$). Considering specific sites, $\delta^{13}\text{C}$ varied in Garibaldi between spring and summer. No seasonal variation in either isotope was detected in the Central region. In the South, no seasonal differences were detected for $\delta^{13}\text{C}$, and $\delta^{15}\text{N}$ only varied between fall and winter ($p < 0.001$). Spring samples were not collected in the South, and therefore possible variation between that season and others in the South is undefined. Overall, the analysis showed no substantial variation between sites within each region for $\delta^{13}\text{C}$ ($p>0.05$), but a high degree of variation in $\delta^{15}\text{N}$ between Reedsport (summer) and Port Orford (winter and fall) ($p < 0.001$).
The ANOVA indicated strong variation in both $\delta^{13}C$ and $\delta^{15}N$ within the leg tissue of all male vs. female crabs ($p \leq 0.001$). Broken down by size class, the $\delta^{13}C$ values varied significantly between legal males (LM) and sub-legal males (SM) as well as SM versus small females (SF) ($p \leq 0.05$). $\delta^{15}N$ varied between large females (LF) and SF, LF vs. LM, and SF vs. SM ($p \leq 0.05$). Regarding variation in $\delta^{13}C$ between the sexes in specific regions across seasons, males and females varied substantially in the springtime in both the North and Central regions, and in the summer in both South and Central regions ($p \leq 0.027$). $\delta^{15}N$ values did not vary significantly between the sexes in specific regions across seasons ($p > 0.05$).

3.2.3 Mixing Models

Table 4: $\delta^{13}C$ and $\delta^{15}N$ of mixing model sources, listed individually and then by group.

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<td>.invertabrate prey</td>
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<tr>
<td>Teleost Bait</td>
<td>30</td>
<td>-19.30</td>
<td>1.97</td>
<td>14.32</td>
<td>0.86</td>
</tr>
</tbody>
</table>

3.2.3 Mixing Models

Table 4: $\delta^{13}C$ and $\delta^{15}N$ of mixing model sources, listed individually and then by group.

<table>
<thead>
<tr>
<th>Source</th>
<th>n</th>
<th>$\delta^{13}C$</th>
<th>$\sigma$</th>
<th>$\delta^{15}N$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bait</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>.invertabrate prey</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bivalve (~20mm)</td>
<td>10</td>
<td>-17.00</td>
<td>0.83</td>
<td>9.71</td>
<td>0.16</td>
</tr>
<tr>
<td>Crangon sp.</td>
<td>17</td>
<td>-16.58</td>
<td>1.33</td>
<td>11.66</td>
<td>0.65</td>
</tr>
<tr>
<td>Cumacean</td>
<td>15</td>
<td>-16.91</td>
<td>0.74</td>
<td>8.07</td>
<td>0.67</td>
</tr>
<tr>
<td>Eelgrass</td>
<td>1</td>
<td>-10.95</td>
<td>--</td>
<td>7.53</td>
<td>--</td>
</tr>
<tr>
<td>Hermit Crabs</td>
<td>10</td>
<td>-16.54</td>
<td>1.31</td>
<td>9.42</td>
<td>0.50</td>
</tr>
<tr>
<td>C. magister (CW&lt;25mm)</td>
<td>15</td>
<td>-15.74</td>
<td>1.13</td>
<td>10.22</td>
<td>0.71</td>
</tr>
<tr>
<td>Olivella sp.</td>
<td>16</td>
<td>-17.80</td>
<td>0.33</td>
<td>9.86</td>
<td>0.59</td>
</tr>
<tr>
<td>Citharichthys sordidus</td>
<td>5</td>
<td>-22.25</td>
<td>0.52</td>
<td>11.43</td>
<td>0.35</td>
</tr>
<tr>
<td><strong>Grouped</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Invertabrate Prey</td>
<td>92</td>
<td>16.59</td>
<td>1.37</td>
<td>10.09</td>
<td>1.32</td>
</tr>
<tr>
<td>Teleost Prey</td>
<td>5</td>
<td>-22.25</td>
<td>0.52</td>
<td>11.43</td>
<td>0.35</td>
</tr>
<tr>
<td>Eelgrass</td>
<td>1</td>
<td>-10.95</td>
<td>--</td>
<td>7.53</td>
<td>--</td>
</tr>
<tr>
<td>Squid Bait</td>
<td>11</td>
<td>-19.82</td>
<td>1.53</td>
<td>10.60</td>
<td>0.78</td>
</tr>
<tr>
<td>Teleost Bait</td>
<td>30</td>
<td>-19.30</td>
<td>1.97</td>
<td>14.32</td>
<td>0.86</td>
</tr>
</tbody>
</table>

3.2.3 Mixing Models

Table 4: $\delta^{13}C$ and $\delta^{15}N$ of mixing model sources, listed individually and then by group.

Bait and Prey

Source inputs into the stable isotope mixing models were clustered into five groups: invertabrate prey, eelgrass, squid bait, teleost bait, and teleost prey, based on the bivariate SI delta space (Figure 13) as well as similar habitat distributions as described in the methods. The individual $\delta^{13}C$ and $\delta^{15}N$ values for each diet item along with the grouped means are listed in Table 4.
Consumers

The Bayesian mixing model results suggest complex and dynamic dietary sources for Dungeness crabs across seasons, regions, and sexes. A comparison between all large female samples and all legal male samples suggested that LFs consume more teleost bait overall compared to LMs (7% difference), while LMs consume more eelgrass overall than LFs (8% difference). Off Garibaldi, which was located in the North region, estimated female dietary proportions tended to vary more than those of males across seasons (Figure 14, left panel). The model attributed a greater proportion of female diet to invertebrate prey and squid bait in the fall compared to any other season. Additionally, values of female teleost prey consumption in the summertime were nearly twice those of the spring and fall. Overall, estimates of male consumption of eelgrass was higher than females, except in the fall, when the estimates were approximately the same between the sexes. The proportion of male diets attributes to invertebrate prey, squid bait, teleost bait, and teleost prey changed less between seasons than for females.

Figure 13: Mixing model source tracer biplot by δ13C and δ15N. Bars indicate sample standard deviation.
The model showed minimal seasonal variation in dietary proportion of both males and females in Newport, OR (Figure 14, center panel). However, among males, the reported values for invertebrate prey and squid bait consumption were higher in the spring and winter than any other seasons. Also, approximated teleost prey consumption by males increased between spring and summer, but decreased between summer, fall, and winter. Diet proportion of invertebrate prey and squid bait for females in Newport, on the other hand, were highest in the summer. Values for eelgrass consumption by females were lowers than for males (~3.4% to 17.8% difference).

In the South region, which was made up of samples from Reedsport, OR, in the summer, Port Orford, OR, in the fall, and Port Orford, Cape Arago, and Langlois, OR in the winter, a greater proportion of both male and female diets were attributed to teleost prey than in any other regions, especially in the fall (Figure 14, right panel). In fact, the highest single proportional estimate out of all the mixing model results was for male consumption of teleost prey in the fall.

Figure 14: Seasonal estimated % diet proportion by grouped source type from the Garibaldi, OR, Newport, OR, and the South study region (Port Orford, OR, Reedsport, OR, and Langlois, OR) separated by sex.
Conversely, values for teleost bait consumption were the lowest for both males and females in the South region. The single lowest proportional estimate for teleost bait consumption, was for southern male crabs in the fall, almost 10% lower than estimated teleost bait proportion for all males. A comparison between male diet proportions in the South region vs. all male crabs shows that the model inferred an almost 20% difference in teleost prey consumption for South males versus all males combined (Figure 15).

4. Discussion

The primary aim of this project was to characterize seasonal variability in Dungeness crab feeding ecology using stable isotopes and gut contents to assess the extent to which a commercial Dungeness crab fishery bait signature could be identified. To parse out seasonal variation in dietary sources from other possible sources of variation, we first assessed differences in the isotopic niches of male and female crabs, divided into two size classes (<159mm and
≥159mm) based on the size limit of harvestable crabs within the commercial fishery. Next, we explored the extent to which isotopic values and gut contents varied across regions of the Oregon coast. The results of these initial analyses indicated highly significant differences in stable isotope signatures by sex and region, which was an unexpected finding, providing a novel contribution to the understanding of Dungeness crab ecology. These findings guided our analysis of seasonal variation, which was also found to be statistically significant for some regions and sexes.

Sex-dependent differences in site fidelity, reproductive role, and fishery harvest practices could explain the highly statistically significant ($p < 0.001$) difference in both $\delta^{13}$C and $\delta^{15}$N values between male and female crabs. Although a tagging study conducted by Collier (1983) did not show any specific pattern of movement within adult Dungeness crab populations in the ocean, some evidence suggests that female crabs inhabit smaller depth ranges than males. Stone and O’Clair (2001) found that female Dungeness crabs in Fritz Cove, Southeast Alaska typically only ranged ~1.5 km outside the cove while their male counterparts ranged ~7.2 km. Cerdal and Wolff (1993) hypothesized that observed heterogeneous diets of male and female Cancer polyodon, a closely related species to Cancer magister, were the result of relatively mobile male crabs protecting a “harem” of sedentary female crabs (Orensanz and Galucci 1988; Wolff and Soto 1992). The mobile males would be more likely to graze on readily available epibenthic sources, while the females would be more likely to exhibit predatory behavior within a reduced range. Although mate guarding has not been observed in Cancer magister, some authors hypothesize that behavior it likely occurs (Christy 1987; Smith et al. 1994). Furthermore, females form dense brooding aggregations across their range (Diamond and Hankin 1985; Armstrong et al. 1987; O’Clair et al. 1996; Scheding et al. 2001), burying themselves in
sediment and reducing feeding and foraging. Stone and O’Clair (2002) documented female Dungeness in Southeast Alaska entering a period of relative inactivity during the winter and early spring at around 16m depth, especially if they were carrying eggs. δ^{13}C values calculated in this study are consistent with higher levels of offshore foraging in males and inshore or estuarine feeding in females, with an average enrichment of 0.56‰ in males compared to females.

Dungeness crab harvest methods could be a mechanism behind relatively high δ^{15}N ratios in spring females. The Oregon Department of Fish and Wildlife (ODFW) only permits harvest of male crabs over 6 ¼ inches (or ~159mm), however, sublegal males and females also enter the pots. Fishermen return captured females and sublegal males to the ocean; those unharvested crabs have the opportunity to eat discarded bait and could reenter pots and consume more bait. If repeated capture and bait consumption increases δ^{15}N ratios, this would likely be evident in both sublegal males and females, however, spring sublegal males (n = 9) were only sampled at the Newport site (Central), which showed the lowest overall seasonal variation of any site in the study (no sublegal males were obtained from the Pacific City (North) spring sampling, and Covid-19 restrictions precluded a South spring sampling trip). Therefore, further study would be required to discern possible nitrogen enrichment of sublegal males in the spring.

Evidence for fishery bait consumption is inconsistent across the sexes. For sampled females, δ^{15}N values peaked in the spring and decreased into the summer and fall, which is consistent with the hypothesis of higher trophic level bait consumption during the fishery season, decreasing as fishing effort decreases. However, δ^{13}C values varied little across seasons for females, suggesting either consistent food source provenance or sifting sources creating a similar cumulative signature over time. In males, δ^{13}C values were higher than the mean in spring and δ^{15}N values were slightly lower than the mean in fall, which could reflect consumption of pelagic
bait in the winter, shifting towards lower trophic level benthic prey after the fishery season. The SEAc values approximating trophic niche were the greatest among crabs of both sexes collected in the fall, which is consistent with broad foraging due to bait scarcity in the summer. Additionally, by far the greatest proportion of empty crab guts were sampled in the spring, while none of the fall guts were empty. This difference could be the result of feeding on soft baits (like squid, fish, and razor clam flesh) during the fishery season, which can be digested and extruded relatively quickly and food sources with hard parts (like small invertebrate prey) in the fall.

The high proportion of empty guts in the spring was surprising given our hypothesis that cannibalism would contribute heavily to crab diets during that season. In fact, we did not find any evidence of cannibalism within the guts. This result could be explained by the observation that cannibalism occurs most frequently among small crabs with CW < 60mm (Stevens et al. 1982). Additionally, given our hypothesis that winter crabs would have the lowest relative $\delta^{15}N$ values due to the lack of bait in the system, another surprising finding was that males had relatively high $\delta^{15}N$ values during that season. This suggests that there are wintertime drivers of $\delta^{15}N$ enrichment that are unrelated to bait consumption.

According to Bostrom et al. (2018), the three most used bait types in the commercial Dungeness crab fishery are squid, clams, and sardines. These differing estimates of the most common baits along with the varying isotopic signatures of this wide variety of species based on their ecological niches and trophic positions makes discerning a single “bait signature” impossible. Theoretically, a female Dungeness crab consuming only razor clams from commercial crab pots would be difficult to differentiate from a female Dungeness crab consuming only small, naturally occurring bivalve species in shallow waters given the similarity in source signatures. Information on the types, amounts, and spatiotemporal distribution of
commercial bait presented previously in this thesis will help to develop a more dynamic and accurate representation of variable bait inputs.

Several patterns of regional variation were similar for males and females. \( \delta^{13}\text{C} \) and \( \delta^{15}\text{N} \) did not show significant seasonal variation in the Central region, mean \( \delta^{13}\text{C} \) and \( \delta^{15}\text{N} \) values were consistently the lowest in the South, and there was statistically significant seasonal variation in the North. The lower \( \delta^{13}\text{C} \) and \( \delta^{15}\text{N} \) values in the southern region could indicate consumption of lower trophic level, estuarine or terrestrial based food sources, especially when read in combination with the gut content results.

The summer Reedsport (South) samples stood out from all other sample sites across regions and seasons in that the highest mean proportion of their guts contained macroalgae (28%), seagrass (Zostera marina) (17%), and wood (7%) with 8% containing sand. This result suggests feeding on near-coastal and/or estuarine rather offshore food sources. Numerous authors have suggested that lower trophic level food sources, such as benthic microalgae, are often underrepresented in Dungeness crab feeding studies due to the difficulty of identifying food sources that lack hard structures. Jensen & Asplen (1998) hypothesized that filamentous diatoms, eelgrass epiphytes, and algae could provide food during periods of prey scarcity or intense competition between densely recruited juveniles. They observed early instar crabs feeding on eelgrass epiphytes in Puget Sound. In British Columbia, MacKay (1942) reported algae as the fourth most important food source for Dungeness crabs behind crustaceans, bivalves, and polychaetes. Cerdal & Wolff (1993) observed at least five macroalgae species in Cancer polyodon guts in a Chilean bay, including Gracilaria sp., Polysiphonia sp., Ulva sp, an unidentified Phaeophyta, and an unidentified Rhodophyta. According to Antonio et al. (2012), coastal benthic macroinvertebrates, including crabs, utilized microalgae, terrestrial leaf litter, and
riverine particulate organic matter as food sources in shallow waters of the Tango Sea off Japan. Additionally, several researchers have cautioned against ignoring sand in gut contents, suggesting that crabs could eat it on purpose to capture calories from epibenthic microalgae (Jensen & Asplen 1998; Haefner 1990).

The stable isotope mixing models provided another tool to investigate regional, seasonal, and sex-dependent variations in stable isotope values, although their outputs should be considered cautiously given the uncertainty of fractionation values and tissue turnover rates for Dungeness crabs. In broad terms, the mixing model results agreed with the stable isotope and gut content analyses. For instance, the mixing model attributed a relatively high proportion (~37%) of spring Pacific City female diets to teleost bait, and 43% of those crabs’ guts contained teleost parts, with an above average frequency of occurrence of soft tissue and empty guts. Given that these samples were collected in late March when 80% of crabbers were still active (Harbison, Chapter 2), both the isotope values and gut contents could reflect feeding on fishery bait. In contrast, all the mixing models attributed relatively high diet proportions to eelgrass. Given the relative scarcity of eelgrass in the gut contents, this high proportion probably does not reflect actual levels of foraging on eelgrass, but rather foraging on other, lower trophic level sources not included as potential inputs in the model. This aligns with the hypothesis that lower trophic level sources have likely been underestimated in previous Dungeness crab diet studies.

The high degree of isotopic variability within Dungeness crabs and their food sources observed in this study agrees well with previous studies of macroinvertebrate scavengers at the land-sea interface. Physical mixing in estuaries and primary production in coastal waters drives fluctuations in the sources of organic materials (Hughes et al. 2000; Antonio et al. 2012) available for benthic organisms to eat. An analysis of seasonal variation in the trophic niches of
three decapod species, *Upogebia africana*, *Callichirus kraussi*, and *Palaeomon peringueyi*, in the Kowie River Estuary of South Africa indicated that their diets shifted temporally according to changes in food availability. Kennish (1997) found that seasonal variation in food availability impacted the reproductive output and body condition of an herbivorous crab, *Grapsus albolineatus*, off Hong Kong. Cannicci et al. (2007) found that in the Mediterranean, the intertidal crab *Pachygrapsus marmoratus* shifts seasonally between carnivory and herbivory, taking advantage of shifting marine and terrestrial inputs as food sources. All these examples relate to species that spend most of their lives within estuaries and/or the intertidal zone. Researchers have focused less research on seasonal variation in the feeding behaviors of species, like *Cancer magister*, that primarily inhabit estuaries as juveniles but then travel back and forth into the ocean as adults.

This analysis highlights the inherent complexity of coastal marine and estuarine ecosystems, which create dynamic contexts in which to interpret evidence for seasonal fluctuations in the consumption of commercial fishery bait by Dungeness crabs. Despite and perhaps because of this complexity, the results contributed to the pre-existing body of knowledge about Dungeness crab feeding ecology, especially by characterizing differences between the isotopic niches of sampled male and female crabs, demonstrating strong regional variations in isotopic tissue composition, and indicating that previous Dungeness crab feeding studies may have underestimated the importance of vascular plant and/or lower trophic level food sources.

5. Conclusion

Despite the economic and ecological importance of *Cancer magister* off the Oregon coast and on the west coast of the United States in general, this was the first study to look for evidence of an impact of commercial Dungeness crab fishery bait on the feeding ecology of that species. It
was also the first study to investigate variation in the isotopic niches of male and female Dungeness crabs. The results demonstrated the ecological complexity of feeding pathways across the estuarine-coastal zone, with substantial variation in isotopic composition in crab tissues and gut contents across regions, seasons, sexes, and size classes. Female crabs in the North region showed the strongest evidence for trophic enrichment through bait consumption in the spring. The gut contents added support to a growing body of literature suggesting that lower trophic level sources must be included in future Dungeness crab diet studies to gain a more complete understanding of their feeding strategies. Laboratory studies to determine stable isotope fractionation values and tissue turnover rates would help to further advance such dietary analyses. More specific information about spatiotemporal variation in commercial fishery bait inputs as well as the relative caloric values of wild prey and bait would advance our understanding of the role of bait in Dungeness crab diets.

6. Literature Cited


https://www.dfw.state.or.us/mrp/shellfish/commercial/crab/
CHAPTER 4: CONCLUSION

1. Summary of Findings

The overarching purpose of this work was to better understand the impact of commercial Dungeness crab fishery bait on the feeding ecology of that species using stable isotope analysis, gut content analysis, and fishermen interviews. I hypothesized that bait inputs contribute to seasonally and regionally variable $\delta^{13}C$ and $\delta^{15}N$ stable isotope ratios in the tissues of Dungeness crabs, characterized by peak $\delta^{13}C$ and $\delta^{15}N$ in the spring after the height of the commercial season, with declining nitrogen values as the summer, fall, and winter progressed. I interviewed twenty-four commercial crabbers with home ports ranging the entire Oregon coast. The primary interview objectives were to (1) record bait species to inform our stable isotope mixing models, (2) assess seasonal variation in bait types used, and (3) to assess regional variation in bait types used. I found that squid, rockfish, and razor clams were the most widely used baits and that the use of these (and other) baits vary seasonally but not regionally. Based on these results, I determined that bait inputs would be more likely to generate seasonal rather than regional isotope signatures.

The stable isotope and gut content analysis showed substantial variation in $\delta^{13}C$ and $\delta^{15}N$ across regions, seasons, sexes, and size classes, reflecting the complexity of coastal and estuarine trophic systems. Females in the north region (especially in Garibaldi, OR and Pacific City, OR) showed the strongest evidence of $\delta^{15}N$ enrichment through the consumption of higher trophic level bait species. As hypothesized, $\delta^{15}N$ values did decline overall by fall, the seasonal decrease in mean $\delta^{15}N$ was driven by strikingly low $\delta^{15}N$ within crabs sampled in Port Orford, OR. The high relative proportion of those guts that contained sand, which could indicate benthic microalgae consumption, as well as the high proportion of summer Reedsport guts that contained seagrass, macroalgae, and woody debris, could explain those low values. These findings add
credence to the growing body of literature suggesting that low trophic level sources should be carefully considered in Dungeness crab diet studies. In order to assess seasonal variation in isotope values, we also assessed variation by sex and within region, which yielded significant results. Of particular note, the analysis indicated that large females (>159mm) tend to occupy an isotopic niche characterized by relatively high $\delta^{15}N$ and low $\delta^{13}C$, while legal-sized males (>159mm) tend to occupy a niche characterized by relatively low $\delta^{15}N$ and high $\delta^{13}C$.

Additionally, we found that seasonal isotopic ratios varied much more substantially in the North and South regions than in the Central region.

2. Future Research

At the culmination of this project, I feel like I have only seen the very tip of the iceberg when it comes to understanding the impacts of commercial fishery bait on coastal benthic feeding ecology off the Oregon coast. I gained a wealth of valuable information from talking to commercial crabbers that didn’t fit well into the scope of this analysis, including information about price negotiations and the economics of operating an independent fishing vessel, firsthand knowledge about the distribution and behaviors of Dungeness crabs, and a better understanding of the social networks that shape the commercial crabbing industry. Pertaining to the question of how fishery bait impacts crab diets, further interviews could help gain a better understanding of the spatial distribution of fishing effort as well as the temporal variation in bait use throughout Oregon’s coastal waters.

On the stable isotope side, I think the first steps moving forward with this research would be to (1) conduct laboratory experiments to determine tissue turnover rates and fractionation values in Dungeness crabs (2) to use ODFW logbook data combined with fishermen interviews to attain a more accurate and precise quantification of the number of pounds of bait that is used
by the fishery each year and (3) to calculate the caloric needs of Dungeness crabs and the caloric value of benthic food sources and prey. These steps would allow for more specific quantifications of source consumption and potentially the impacts of varying diets on growth and fecundity.


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VI: APPENDIX
Appendix I: Dungeness Crab Bait Use Survey 2020  
Written by Toby Harbison  
May 2020

1. Which types of bait do you use in commercial Dungeness crab pots?  
   Select all that apply.  
   □ Razor clams  
   □ Clams (other)  
   □ Squid  
   □ Sardines  
   □ Herring  
   □ Tuna  
   □ Mackerel  
   □ Rockfish  
   □ Hake  
   □ Chicken  
   □ Mink  
   □ Fish (other)  
   □ Other

2. Please list the three baits you use most frequently from most used to least used.  
   1\textsuperscript{st} choice:  
   2\textsuperscript{nd} choice:  
   3\textsuperscript{rd} choice:  
   If you selected “Other” or “Fish (other)” above, please provide details.

3. What motivates you to use certain types of bait?  
   Please rank these choices in order from strongest motivator to weakest motivator: Cost, Availability, Effectiveness  
   1\textsuperscript{st} choice:  
   2\textsuperscript{nd} choice:  
   3\textsuperscript{rd} choice:  

4. Does the type of bait you use change over the course of the season?  
   Please answer yes or no and explain briefly.

5. During which months do you usually harvest Dungies?  
   □ December  
   □ January  
   □ February  
   □ March  
   □ April  
   □ May  
   □ June  
   □ July  
   □ August
6. Approximately how many pounds of bait do you use per pot?

7. Approximately how many pounds of bait do you use per season?

8. Approximately how much money do you or the vessel you work on spend per season?

9. After pulling a pot, how often do you reuse bait?
   - Always
   - More than half the time
   - About half the time
   - Less than half the time
   - Never

10. Do you toss used bait overboard?

11. Do you use closed bait boxes, hanging bait that the crabs can access, or both?
   - Closed bait boxes
   - Hanging bait
   - Both

12. Why do you prefer the method of baiting you use?

13. What method of baiting do you think most commercial crabbers use in Oregon?
   - Closed bait boxes
   - Hanging bait
   - Both

14. What is your home port?

15. What are the minimum, maximum, and average distances you travel from your home port to set your pots? Please answer in nautical miles.

16. Does the distance you travel from your home port change over the course of the season?

17. Where do you offload your catch? Do you offload in different ports over the course of the season? If so, why?

18. Where do you get your bait? Do you always get your bait from the same place or does it depend on price and/or availability?

19. Do you get your bait from the same place you offload your catch?
   - Yes
   - No
   - Sometimes
20. What are the minimum, maximum, and average depths at which you set your pots?

21. On average, how many pots do you bait or rebait per trip?

22. How many trips do you typically make per season?

23. What are the minimum, maximum, and average soak times you use?

24. Is there any other information you would like to add about bait use in the commercial Dungeness crab fishery?

25. May I contact you if I have follow-up questions?
   □ Yes, email preferred
   □ Yes, phone preferred
   □ No

26. What is your name?
   *Optional*

27. What is your phone number?
   *Optional*

28. What is your email address?
   *Optional*