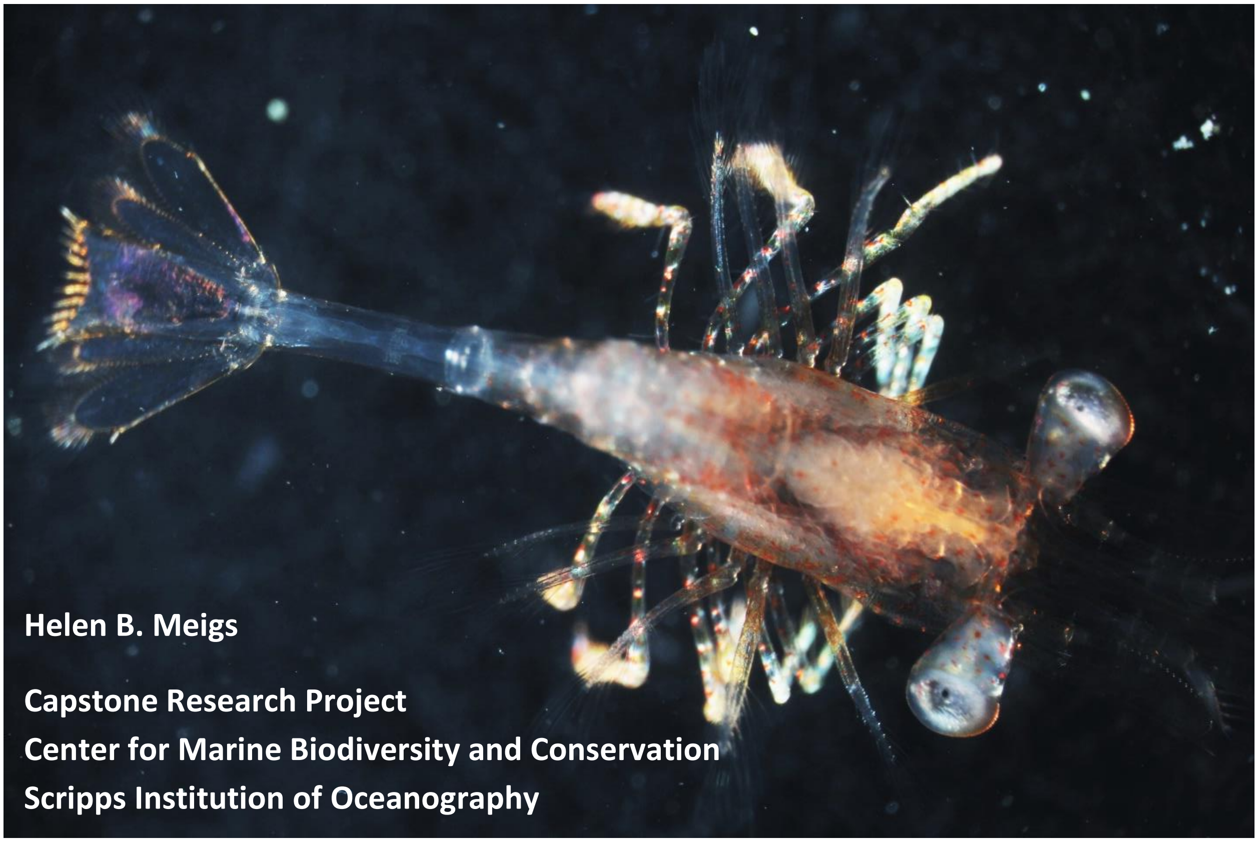
The biological and market potential of farming *Pandalus platyceros* along the Pacific coast



Committee:

Greg Rouse (Chair) Scripps Institution of Oceanography
James Hilger UCSD Department of Economics
Sarah Mesnick NOAA NMFS Southwest Fisheries Science Center
Dale Squires NOAA NMFS Fisheries Resource Division

June 2016

Capstone Advisory Committee Final Capstone Project Signature Form

The biological and market potential of farming *Pandalus platyceros*

Helen B. Meigs

MAS Marine Biodiversity and Conservation

Capstone Project

Capstone Advisory Committee

Signature ______________ Print Name ______________ Date ______________

Affiliation ______________ Email ______________ Phone ______________

Signature ______________ Print Name James R Hilger Date June 7, 2016

Affiliation NOAA SWFSC Email james.hilger@noaa.gov Phone 858-546-7140

Signature ______________ Print Name ______________ Date ______________

Affiliation ______________ Email ______________ Phone ______________

Signature ______________ Print Name ______________ Date ______________

Affiliation ______________ Email ______________ Phone ______________

Introduction: Global seafood production and aquaculture development

The premise of this study is that an increasing number of the world's fisheries are producing or exceeding their maximum yield, while the world demand for seafood increases. Global per capita seafood consumption has increased steadily from 9.9 kg in the 1960s to 19.2 kg per capita in 2012 (FAO, 2014). This skyrocketing demand in conjunction with population growth and increased fishing efficiency has led to overexploitation of many marine fish stocks. Technological advancements have made accessible areas that were once too remote or too deep to be exploited. Commercial fishing involves deploying hundreds of miles of nets and dragging various apparatus along bottom habitats. A side effect of this is environmental damage throughout ocean ecosystems, much of which is unobservable and immeasurable (Chuenpagdee et al., 2003). Fishery management authorities have started adopting ecosystem-based management approaches, understanding that fish populations depend upon habitat integrity (EPAP, 1999). Many fisheries stipulate gear restrictions and limited access, but enforcement, efficacy, and consideration of economic and social factors all vary on a case-by-case basis.

Despite increased efficiency, fleet size, and access, wild capture fisheries' annual production has stabilized to 1990 levels, varying up and down about three percent since 1998 (FAO, 2014). The relative consistency of wild catch over the past two decades, accompanied by the periodic dramatic stock collapse, such as the anchoveta crisis in 1998 (FAO, 2014) and today's California sardine fishery closure, suggests wild-capture marine food fish production may be at capacity.

Yet to date, seafood production has risen to meet demand, outpacing world population growth twofold in annual growth rates since the 2000s. This has been made possible by the aquaculture industry, which has been growing rapidly in the past few decades: aquaculture contributed to 5 percent of seafood production in 1962, and an impressive 49 percent in 2012 (FAO, 2014). From some perspectives, aquaculture is a means to contribute to global food security while alleviating pressure on wild stocks and preventing environmental damage from impactful fishing gear. But to others, farmed seafood comes with its own variety of health and environmental risks, and is neither an adequate nor sustainable substitute for its wild counterpart.

Area of Focus

In regards to U.S. seafood consumption, shrimp is the most consumed product, weighing in at 1.9 kg per year consumed by the average American (significantly above canned tuna, the runner up at 1.2 kg) (NOAA: Office of Aquaculture). Despite this popularity, we remain dependent upon foreign production for upwards of 90% of shrimp products. In 2015 the U.S. imported almost 1.3

billion pounds of shrimp, valued at over $5.4B (NMFS, 2015). The aquaculture industry continues expand, and import data prove shrimp is a top priority for the U.S.

However, ecosystem-based assessments of commercial fisheries particularly malign shrimp fisheries. The primary gear type for shrimp fisheries is trawl gear (Gillett, 2008). Certain types of trawls earn the highest rank among fishing gear in terms of physical and biological habitat damage (Chuenpagdee, 2003). Also, trawling for small species leads to massive amounts of bycatch: roughly five pounds of non-target species per pound of shrimp in the U.S. fisheries. Some bycatch is retained, but the global average discard rate for all shrimp trawl fisheries is more than 62 percent, over twice the rate of any other fishery (Gillett, 2008).

When shrimp farming first became profitable in the 1970s, it was lauded by some as a 'Blue Revolution', a way to avoid the environmental havoc described above. However, rapid, unregulated expansion of intensive level fish farms earned farmed seafood a reputation of being unhygienic and environmentally destructive in its own ways. Low survival rates, disease outbreaks, concentrated waste effluent, and undesirable feed ingredients soon disillusioned environmentalist support (Boyd & Clay, 1998). Over the decades though, aquaculture technology has evolved considerably, resulting in sustainable feed alternatives, the ability to reduce waste, and produce more efficient, cleaner products overall. At least in countries with effective regulation.

The majority of our current imports come from penaeid shrimp farms in India, Indonesia, and Ecuador (NOAA: Shrimp Report); countries with less stringent health and environmental standards than those of the U.S. One way to meet the growing domestic demand for shrimp, as well as ensure environmental integrity, is to produce our own. Marine shrimp aquaculture exists in the United States, but import statistics show that domestic products constitute a negligible amount of our annual consumption. Researchers in the 1970s looked into various shrimp species for farming along the Pacific coast, but studies were abandoned as it proved far cheaper at the time to get products from abroad and shrimp farming became dominated by warm water species (Price 1972).

Currently, people are becoming more cognizant of the origins and environmental impacts of their food. A locally-farmed shrimp could reduce the environmental footprint of long-distance imports; provide a fresher product to the consumer; and reduce ecosystem damage resulting from farming and fishing practices in unregulated regions. Major concerns and opposition regarding fish and shellfish farming include the risk of escape and subsequent introduction of an invasive species or pathogens. A solution to these factors for potential Pacific coast shrimp farming is to culture a local species. The spot prawn (*Pandalus platyceros*) is native to the North Pacific and to this point has never been utilized as a commercial aquaculture species.

Current Spot Prawn Fishery

There is an active wild capture fishery for spot prawn in California, Washington, Oregon, Alaska, and Canada. The California fishery is most active between Santa Cruz and San Diego, averaging 250,000 pounds per year. Only pots are used, as trawling for spot prawn is prohibited in all state waters. The fishery is regarded as relatively sustainable due to its small, limited access (28 permits), closure during peak spawning months, and the ban of trawling (Safina Center, 2012). However, California spot prawn earns only a "good alternative" (yellow) score from Monterey Bay Aquarium's Seafood Watch due to potential damage to seafloor habitats caused by the traps (Seafood Watch, 2016). Furthermore, no surveys are conducted to estimate or monitor population abundance, and the bycatch to target ratio was only monitored during the 2000-2001 season where it was found to be 1:1 in the south and 2:1 in the north (Safina Center, 2012).

Stable catch, limited access, and gear restrictions may indicate a well-managed fishery, but in reality, much of the spot prawn population health is unknown. Live spot prawns can reach $24 per pound ex-vessel price and $30 per pound at markets due to their large size – sometimes six shrimp to a pound. In Japanese restaurants the large, cold-water shrimp is known as amaebi (sweet shrimp), a high-end sushi item. Stateside Asian marketplaces are the primary consumers for California spot prawn, while the bigger fisheries in Alaska and British Columbia export a significant percentage of their landings to Japan or global sushi markets (Fisk, 2010). Farming *P. platyceros* is not a call to derail the wild-capture fishery, but a suggestion that supplementing this seasonal fishery with a farmed option may be a prudent way to support local industry and avoid increasing ecosystem stress or competition on the water.

Methodology

To address the feasibility of farming *P. platyceros*, the following study investigates two essential issues:

1. Whether the biology of *P. platyceros* is conducive to farm production;

2. Consumer demand for this species.

Chapter I examines the biological development of larval spot prawns to assess their survival in captive settings. The high fecundity of many marine fishes and invertebrates means high mortality rates are normal. The majority of this mortality occurs during the planktonic larval stages; this particularly vulnerable, early development period is referred to as the "critical period" (May, 1974). This study monitors the development of newly hatched *P. platyceros* larvae until they reach post-larval stage, beyond the critical period.

Chapter II consists of a discrete choice experiment based on surveying patrons of specialty seafood markets. Discrete choice experiments are a popular technique for documenting consumer preferences for different product characteristics. Through regression analysis one can estimate the part-worth utilities of each attribute level of a product, assigning a value to different characteristics (Aydin, 2014). Arranging these characteristics in new ways can predict the cumulative willingness to pay (WTP) for a previously un-marketed product (ie a locally farmed, native shrimp).

Through assessing the response of *P. platyceros* in culturing environments and determining a WTP for such a product, this study strives to determine if farming this species can be biologically and economically feasible. This methodology can be used as a framework for future research, including surveying broader market bases, exploring different product attributes, and investigating more detailed biological parameters for growing a new species for market.

CHAPTER I: Biological Analysis

1. Current Knowledge

Shrimp farming experienced a rapid increase in popularity (and profitability) in the 1970s (Boyd & Clay, 1998). At this time, researchers studied a range of species to assess their aquaculture potential. However, cold-water prospects were mostly abandoned as market forces drove shrimp production to tropical and subtropical regions. Thus knowledge about the development of *P. platyceros* is limited to observations of wild specimens (which are relatively low as this species spends much of its life in deep water) and few exploratory laboratory studies from the 1970s.

1.1 Habitat and Physical Characteristics

Pandalus platyceros live in rocky bottom habitats from San Diego to the Aleutian Islands of Alaska, though bycatch observations suggest their southern limit may extend into Baja California (National Marine Sanctuaries, 2011); they are also caught in the Sea of Japan (Safina Center, 2012). They have been found at depths ranging from intertidal to greater than 400 meters, migrating deeper with age. They are believed to spend the majority of their lives between 195 and 235 meters (National Marine Sanctuaries, 2011) and can tolerate temperature of 0 to 18° Celsius (Wickins, 1972).

Adults are red to pink in color with white stripes along the carapace and pereiopods, and four distinctive white spots along the body – two behind the head, two in front of the tail. They are the largest of the pandalid family, with a maximum recorded length 230 millimeters for males, 253 millimeters (9.9 inches) for females. They have a long rostrum, up to twice the length of the carapace (Bergström, 2000).

1.2 Reproduction

Spot prawns are protandric hermaphrodites – they begin life as males and then transition into females at age three or four. Females are ovigerous, carrying fertilized eggs for four to five months until hatching in spring (CDFW, 2008). Females carry 1400-5000 eggs during their first spawning, and approximately 1000 if they spawn the following year (National Marine Sanctuaries, 2011). A study analyzing growth rates of tagged wild spot prawns in Alaska suggests their lifespan may exceed 7 years (Kimker, 1996), but it is unclear how long females continue to spawn; all sources have observed a maximum of two spawnings with decreasing fecundity.

Newly hatched *P. platyceros* progress through several larval and post-larval stages before settling on the bottom (sancutaries.noaa.gov, 2011). From this point they develop through a two-year juvenile period in 4-55m depth, migrate to deeper waters, and reach sexual maturity as males around age three; they spawn at least once as males, transitioning to females thereafter (Kimker, 1996). Larvae and post-larvae can range from bright red and orange to light green and brown to translucent before adopting the red and white patterns of adults (Price & Chew, 1972).

2. Prior Studies

In 1970, Price and Chew of the University of Washington Fisheries Research Institute undertook the first laboratory rearing of *P. platyceros*. Until this study, the only descriptions of larval stages were drawn (literally) from plankton samples in the 1930s. The culmination of their study is the definitive morphological guide to spot prawn development through stage IX.

Price & Chew caught ovigerous females in Washington and reared larvae from the females and from loose eggs that had detached during transport. Loose eggs were kept suspended on a screen in a unique recirculating system with 10µ-filtered, aerated, UV-sterilized saltwater. In this setting, eggs could last up to sixty days with no fungus growth. There is no comment as to when the detached eggs hatched in relation to the eggs carried by females, but both hatched successfully. It took females 7-10 days to release all of their progeny once hatching began. Newly hatched larvae could survive two weeks on yolk reserves alone, but were capable of feeding immediately on *Artemia salina* if provided. Larvae were transferred to beakers of fresh, unfiltered seawater each day. All mortalities appeared due to a failure to completely shed their molt. Each stage, defined as the period between molting, lasted an average of 9 days, with specimens reaching the post-larval stage (stage V) at day 35 at 11°C. Both the morphological guide and the methods of egg incubation were utilized to guide the present experiment.

In the second study from this era, John Wickins (1972) investigated the influence of food density, salinity, temperature, and stocking density on the growth rate and survival of *P. platyceros*. Larvae hatching from females were reared in environments of 13-16°C and 30±1% salinity. Development to post-larva was achieved at 15-29 days, in contrast to the 35-day span for Price & Chew; this is likely due to the warmer culturing temperatures.

The stocking density yielding the highest survival rate was 5 larvae per liter at temperatures 13-15°C. Other key observations were that the size of *Artemia* fed to larvae did not influence larval growth rate or survival, and while larvae were raised successfully at a range of temperatures, there is a possible trend of fewer post-larvae survivors with increasing egg incubation temperature (Wickins, 1972).

The final major study addressing spot prawn rearing built off of those above to define the environmental extremes in which *P. platyceros* can thrive. Reiterating the others' findings, Kelly et al. (1977) observed the larval period to last 26 to 35 days at 9.5-12.0°C. They also concluded that spot prawns show a maximum thermal tolerance of 21.0°C and salinity tolerance down to 22%. Growth rate was increased in both larvae and post-larvae by supplementing *Artemia* nauplii with any of four unicellular algae species. Kelly et al. (1977) also includes extensive investigation of diets for enhancing post-larvae growth, which can be an important reference for further analysis of aquaculture potential, but the scope of this study is limited to larval development.

3. Proposed Study

The present study attempts to reaffirm that this species can develop in laboratory settings. Using an amalgamation of the environmental parameters and timelines defined above, spot prawn larvae were hatched from ovigerous females caught off the coast of San Diego, California and cultured to post-larvae (stage V). The current growth of the aquaculture industry in conjunction with the depletion of wild seafood stocks makes revisiting this prospective aquaculture species a timely endeavor. By culturing eggs to this critical developmental phase, this experiments aims to provide an updated assessment as to whether *P. platyceros* may be a viable native species for aquaculture along the Pacific coast.

4. Materials & Methods

4.1 Collection of Eggs

Adult prawns were collected opportunistically during several research trawls off the coast of San Diego, California, totaling six males and ten ovigerous females. Specimens were held in bins of iced seawater until transport to Scripps Institution of Oceanography (SIO) research aquarium. At the aquarium facility, males and females were kept together in a rectangular, aerated, flat-bottomed tank with seawater at 8°C, and fed a diet of fresh mussels. The SIO system provides flow-through seawater pumped from nearshore, through two sand filters to a settling tank, and gravity fed to the aquarium building. No further filtration or sterilization takes place.

4.2 Experimental Tank

Upon hatching from the females, a sample of fifty larvae were transferred to a kreisel tank constructed from acrylic siding and a large PVC pipe body. The purpose of kreisel tank design is to prevent larvae from settling on the bottom by providing a constant vertical circular flow. The tank was supplied with filtered, ambient temperature seawater for the duration of the trial; no aeration was provided as the system was flow-through and kreisel tanks are well-circulated. Temperature and salinity were measured daily by sensors near the intake pump for the SIO aquarium; these were periodically checked against measurements taken in the tanks to confirm accuracy.

The kreisel tank is just under 12 liters, thus a sample of fifty represents a density of approximately 4.2 larvae per liter. This density was chosen because the highest rate of survival achieved in prior studies was at 5 larvae per liter, and mortality increased with density (Wickins, 1972). This stocking density is comparable to that of "extensive" level aquaculture (Chen, 1991). The tank was cleaned approximately every ten days.[1]

4.3 Feeding Schedule

Larvae were fed live nauplii of *Artemia salina* supplemented with Zeigler® Larva Z Plus powder daily at a target concentration of about 10 *Artemia* per mL, or 120,000 *Artemia* per day. The daily diet was divided into 3 feedings per day during the week, 2 per day on weekends. *Artemia* were initially cultured for 18-24 hours; later for 36-48 hours to provide larger food.

4.4 Artemia Preparation

Artemia salina were cultured daily to provide a fresh supply of nauplii. Eggs were hatched in two 1.2L cones: cones were filled with 1L seawater and 1.2-1.5g *Artemia* eggs; water was oxygenated via airstone and heated with a 150-Watt heat lamp. Cones were on alternating schedules so while one was used for feeding, the other incubated for the next day.[2]

4.5 Eggs Incubated in Laboratory

On January 27, 2016 a sample of 68 eggs was removed from one of the females to monitor development in the laboratory. This sample was maintained in a cup with mesh over the top with a continuous seawater trickle. Photographs were taken about twice weekly to document development. On March 24, 2016 a large berried female died and 250-300 of her eggs were promptly removed to see if they were salvageable. These eggs were suspended on a mesh screen within a PVC cylinder. Water flowed into the top of the cylinder and exited the bottom, providing continuous flush of fresh seawater, a design guided by the hatching box of Price & Chew (1972). Eggs from the 1/27/16 sample were transferred to an identical setup on this day. All eggs were maintained at ambient seawater temperatures, ranging 14 to 19ºC throughout the months of incubation.

---

[1] See Appendix A.1 for tank cleaning protocol

[2] See Appendix A.2 for *Artemia* harvest protocol

5. Summary

Eggs from the captive females hatched during the timeframe of wild spot prawn hatching, indicating broodstock can be maintained in facilities with no compensation for the change in pressure.

Fifty larvae were collected from the adult tank at 16:00 PST on March 28, 2016, all between 0 and 2 days old. The larvae were transported in a plastic tub with 2" ambient seawater (16.5°C), and 5" water from the hatching tank (8°C). Larvae remained in the aerated transportation tub for 60 minutes for temperature acclimation: 1" ambient seawater was added to the container every 15 minutes. At 60 minutes, the larvae were transferred to the kreisel with an ambient seawater input (16.7°C at 17:00 PST). Upon transfer to the experimental tank, all larvae were actively swimming, some slowing to passive circulation shortly thereafter. All larvae were observed actively feeding upon the first introduction of food and were positively phototactic.

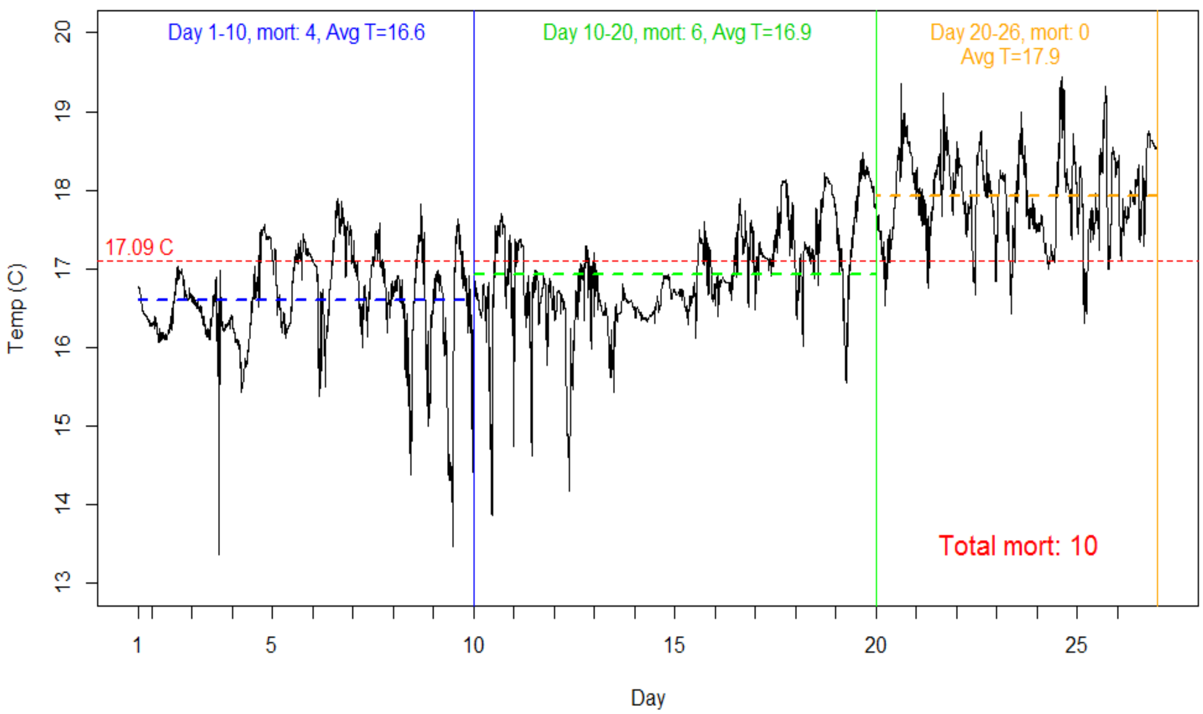
Forty of the fifty survived to post-larvae (PL) (Table 1).

Table 1. Survival and development of *P. platyceros* larvae.

No. of larvae	Larvae per L	Min Temp (°C)	Max Temp (°C)	Survivors to PL	Age of culture at PL
50	5	13.37	19.44	40	20 (50%) 26 (100%)

Eighty percent survival is relatively high compared to prior studies. Wickins (1972) indicated the first ten days of life were where to expect the most mortality, though mortalities were almost evenly distributed throughout the course of the trial. Four mortalities occurred in the first ten days, six in the following ten days. At day twenty, fifty percent of the tank had reached PL which would have marked the conclusion of Wickins' experiment; all remaining specimens reached PL by day twenty-six. No mortalities occurred during this time. The average temperature over the course of the trial was 17.093°C, higher than recommended temperature ranges. As seen in Figure 1, average temperatures rose throughout the trial so larvae were subjected to lower temperatures at the earlier developmental phases (SCCOOS, 2016).

Figure 1: Temperature throughout trial



Mortalities do not necessarily increase with temperature, as expected. The last six days of the trial have a higher average temperature (17.919°C) than the preceding days, well above the recommended 14-15°C, yet zero mortalities. But at this point most of the sample was near or beyond the critical period and presumably stronger in the face of environmental variation. However, the first ecdysis is historically considered the most vulnerable phase, so the fact that more mortalities occurred later in development (Day 10-20) may suggest the rising temperature did in fact impact early survival. Thus it is inconclusive if temperature changes in the trial are correlated with mortality.

Stage V development (PL) is identified by certain adult morphology and behavior (Figure 2). At PL, abdominal propulsion is evident, the telson (tail) has a distinct shape, and the characteristic spots for which spot prawns are named are first visible. At this time the shrimp begin to settle on the bottom instead of staying in constant circulation.

FIGURE 2 PHOTO PAGE

5.1 Eggs Incubated in Laboratory

Two eggs from the initial sample of 68 hatched successfully (Figure 3), on April 1 and April 7. Incubation below 15°C would have been preferable, but due to a broken chiller, eggs were incubated at ambient temperature. While the majority of the sample deteriorated by late March, the two survivors hatched in the same timeframe that eggs were hatching from the females, despite the significantly higher incubation temperature. Larva 1 survived six days, perishing during ecdysis. Larva 2 did feed immediately but otherwise exhibited signs of abnormal development: he was not phototactic, and had less vibrant coloration than successful larvae. Larva 2 perished in 36-48 hours.

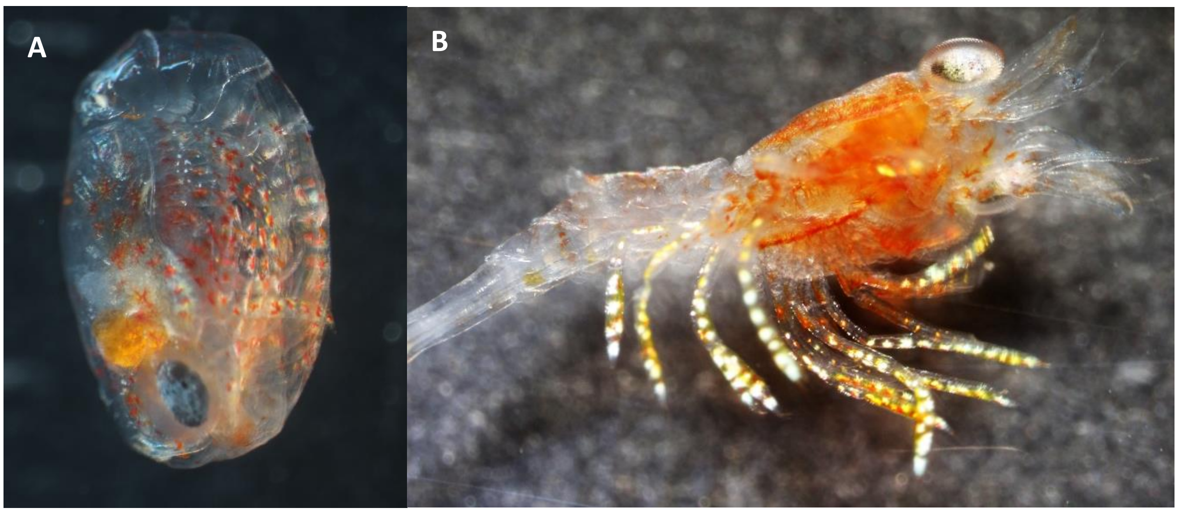


Figure 3: *only two lab eggs hatched, one pictured at day before hatching (A) and one at day 1 (B)*

With the exception of the two short-lived larvae, all other eggs decomposed. The initial sample declined gradually, while that from the deceased female decomposed rapidly. Figure 4 provides a visualization of the progression of egg incubation and deterioration.

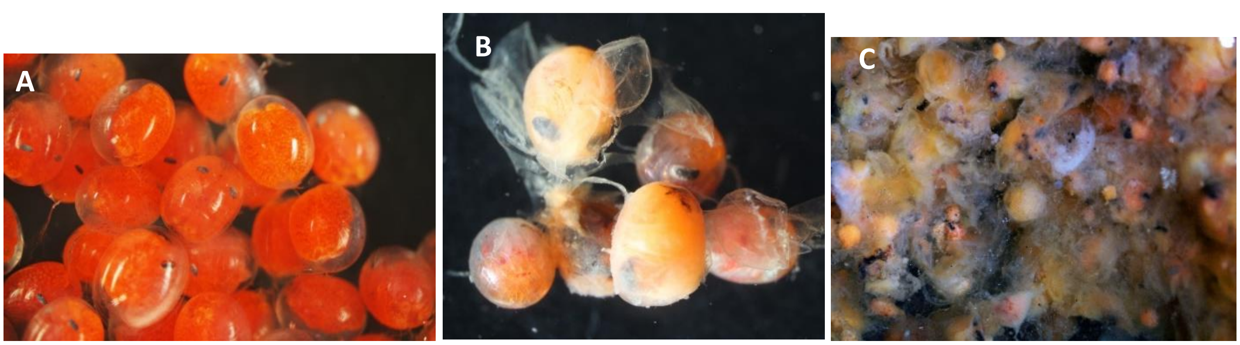


Figure 4: *a) healthy eggs; b) egg deterioration in late March; c) mass decomposition from dead female*

6. Discussion

6.1 Maintaining Broodstock

The success of the eggs from the captive females in contrast to the failure of the laboratory-cultivated samples implies it may be necessary to maintain ovigerous females to provide stock. Females required minimal maintenance, being fed once daily and held at constant temperature in a flow-through system. Two of the original lab-cultured eggs hatched successfully, though neither survived through the critical period. The entire sample from the deceased female decomposed rapidly despite immediate transfer to a constant-flow setup. Price & Chew (1972) were able to successfully hatch out eggs separated from females when maintained in highly sterilized environments. Furthermore, the eggs in the laboratory were subjected to temperatures up to 10ºC higher than those on the females, and Wickins (1972) noted a trend of decreased survival in larvae that were incubated at higher temperatures. Thus the survival of eggs removed from females may be improved by providing a colder, more sterile culturing environment, but in this study, successful hatching depended upon healthy females for incubation.

6.2 Critical Period Development

All of the surviving specimens achieved post-larval stage development (stage V or beyond) by day 26. Prior studies have defined larval life as the time at which fifty percent of the sample reach post-larval stage (Wickins, 1972); in this study, the sample achieved fifty percent development to post-larvae at approximately day 20. Larvae quickly acclimated to 16ºC seawater after being incubated in 8ºC, suggesting warmer temperatures can be used to speed up development.

80 percent survival is in the upper range observed in previous studies. Wickins (1972) achieved 80 percent or higher survival in about a quarter of his trials, and Kelly et al. (1977) observed a maximum survival of 70 percent. Achieving relatively high survival in an environment where temperature fluctuated with local weather patterns confirms this species is resilient to natural variation and can develop readily in environments with unsterilized seawater sources. Further trials can be run to see how survival compares in natural seawater versus the filtered seawater used here.

6.3 Other Notes

The filter screen of the kreisel was large enough to allow *Artemia* and powdered feed through to the outflow chamber. This made it impossible to conclude if water clear of food matter signified the larvae had consumed everything or if it had been flushed out. The water was typically clear before most feeds, regardless of the *Artemia* concentration in the prior feeding. Because of this, feed concentrations were increased to compensate for food lost through the filter and the 120k

Artemia per day became a minimum guideline. For future, the filtering screen of tanks should be of a finer mesh so as to allow longer retention of *Artemia.* This may require more frequent tank cleaning, perhaps stressing larvae, but the tradeoff would be observation of true feeding rates, which is required for maximizing efficiency of feeding schedules and densities.

Possible cannibalism was observed occasionally, potentially indicating insufficient feed levels. Victims were usually white or translucent in color, which made it hard to distinguish between a mortality or exuviate. Since many crustaceans ingest their exuviae, it is possible this was natural feeding behavior (Zanotto & Wheatly, 2002); it is also possible that larvae were cannibalizing each other due to lack of satiety. The uncertainty of this observation and that this occurred in the presence and absence of food renders this inconclusive. As Kelly (1977) and Price & Chew (1972) both observed that most mortalities occurred in ecdysis, it is likely that failure during the molting process caused mortality.

6.4 Future Research

In regards to investigating aquaculture potential, future research should include large scaler trials of laboratory rearing with a priority on higher stocking densities and food conversion ratios. Percent survival at higher densities is essential in determining farming feasibility. The developmental period observed here (20-26 days) is within the faster end of the range defined in previous studies and it would be useful to know if warmer temperatures could speed up the process further without significant increase in mortality. This trial experienced a maximum temperature of 19.4ºC, with sustained 19ºC temperatures for up to seven hours. Though not quite at the 21ºC thermal maximum, this culturing environment was very different than their natural habitat. Local waters did not reach higher temperatures until about halfway through the trial, so it would be interesting to see what impact consistently elevated temperature has during earlier larval stages. Furthermore, limitations in tank design prevented observations of feeding rates or food conversion ratios.

Another essential question for aquaculture is the source of new stock. It is unknown if female spot prawns spawn more than twice in a lifetime, which would result a high turnover of broodstock. Until farmed specimens reached female maturity at four to five years, broodstock would have to be supplied from the wild. It is prudent to learn more about the reproductive capacity of mature spot prawns in order to provide a consistent supply of hardy larvae. Can females spawn for more than two years? Can fecundity be increased or stabilized by environmental conditions or does it continue to decrease each consecutive spawning? Do specimens from San Diego have the same seven- to eight-year lifespan estimated in Alaskan prawns (Kimker, 1996)? Will they spawn in captivity? These questions are critical in establishing any level of commercial production and would also provide valuable information for future management of the wild fishery.

Finally, *Litopenaeus vannamei* is currently the marine species shrimp with the greatest global production by mass (FishStatJ, 2015). This results in a wealth of knowledge in regards to techniques for disease prevention, broodstock maintenance, and other marine species obstacles that will likely be applicable to spot prawns. Some of the procedures for the current study were directed by methods used with *L. vannamei*. *Macrobrachium rosenbergii*, known as giant river prawns, are a freshwater shrimp that is also farmed. Farming methods for freshwater species are very different, though of all shrimp species farmed at a commercial-scale, *M. rosenbergii* is genetically of closest relation to spot prawns. *M. rosenbergii* and *P. platyceros* are both of the infraorder *Caridae*, so this freshwater species may provide a stronger biological reference for production timelines and practices (New, 2002). It would be prudent to use both species in directing future research regarding *P. platyceros.*

7. Conclusion

This small-scale trial suggests *P. platyceros* has potential to be a viable aquaculture species. Its growth rate, large size, and adaptability to a range of temperatures are all desirable attributes. Furthermore, *P. platyceros* maintenance was guided by existing shrimp culturing protocols. This species is not currently farmed and there is still much to learn about its development and reproduction, but overall, it is possibly similar enough to penaeids or other carideans to be integrated into existing shrimp farming schemas.

The surface characteristics of a successful aquaculture species are present, but further research is needed to assess long-term and large-scale implementation.

Chapter II: Economic Analysis

1. Shrimp Market Evolution

In stores, shrimp can sell for $2.99 per pound, while some sell for over $30 per pound (Poindexter, 2016). They can be in the form of an ingredient for seafood salads with over 250 shrimp to the pound, or a delicacy the with a single shrimp being the size of an entrée. Given this variation, there are myriad methods of supplying shrimp that are economically feasible, and many that are not. In terms of establishing a farming operation for a new species, it is important to understand what attributes consumers are most interested in. The species in question is a cold-water shrimp prized for its size and sweetness.

In the face of ominous environmental forecasts, many consumers and producers have started prioritizing sustainably sourced seafood. "Green" products – those which in some way optimize environmental welfare – can demand a significant price premium because consumers are willing to pay more for them. Green product characteristics, such as organic sourcing, ecolabels, and supply-chain transparency have been researched extensively in regards to other goods (Durham et al, 2012); however, applying these attributes to seafood is comparatively unexplored. In general, green products are not only perceived to be environmentally friendly, but they are often associated with being healthier, of higher quality, or emblems of desirable social status (Delmas et al, 2012).

Whether consumer actions are derived from environmental, health, or social concerns, green goods are often niche products that demand more from consumers, and this leads to unique investment potential. A locally farmed species along the Pacific coast may not have been economically feasible at the genesis of commercial shrimp farming, but current market atmospheres are different. A locally farmed seafood product would be innately transparent in origin, travel shorter distances, and adhere to environmental and health regulations of familiar authorities. Shrimp grown or caught and processed overseas may continue to be the cheaper option, but a growing sector is willing to pay more for the aforementioned attributes. These attributes in conjunction with the unique culinary profile of spot prawns may make farming *P. platyceros* along the west coast an economically feasible endeavor.

However, given the complex environmental impacts of different seafood harvesting methods, defining sustainable seafood can be quite challenging. There are currently no 'organic' labels for seafood in the U.S., and the terms 'wild' and 'farmed' can garner contradictory reactions as both methods have potential to cause or mitigate environmental degradation. Environmental motives aside, determining what characteristics are most desirable to consumers is a necessary component in guiding new product development. This study investigates attributes known to be associated with greenness (ie local) and also characteristics specific to *P. platyceros* (ie large size) to determine how consumers structure preferences.

2. Discrete Choice Experiment

A discrete choice experiment (DCE) is a type of conjoint analysis, which defines a part-worth value for different characteristics of a product. As the name implies, this method relies upon respondents' choice amongst hypothetical alternatives. A 'no-choice' option can be utilized – as in this study – to further mimic real world purchasing decisions. A product profile is a combination of different attributes, with various levels within each attribute. An attribute is a descriptive category, and any descriptor is a level (Gesiot, 2012). For instance, the product 'sports drink' may have the attribute 'brand', consisting of three levels: Gatorade, Haterade, Powerade. Another attribute may be 'flavor' with levels Lemon, Lime, Mud. The possible product profiles are all the possible combinations of these attribute levels. If there are *A* attributes with *L* levels each, then there are L^A possible product profiles. The product considered in this study is shrimp.

In this design, each binary attribute has one level that is typically considered desirable and one that is less so. The purpose of this survey is to determine the relative weight of each attribute. This information can help producers prioritize investments as well as help direct marketing or education campaigns aiming to increase awareness of green products.

In this study, survey responses are analyzed via a conditional logit model to estimate choice probabilities. The probability of individual *i* choosing product *j* is defined as:

$$P_{ij} = \exp\left(\beta_j x_j + \gamma_j x_j z_i\right) / \sum_k \exp(\beta_j x_j + \gamma_j x_j z_i) \quad (1)$$

Where x_j is the vector of attributes of product *j*, z_i is the vector of characteristics of individual *i*, β_j is the marginal utility obtained through the attributes of product *j*, and γ_j is the change in marginal utility of attributes due to interactive effects of attributes and individual characteristics. The sign of the estimated coefficients is directly interpretable, though the magnitude is not. Thus the marginal value (WTP) for product attribute *j* is:

$$WTP_j = -(\beta_j / \beta_p) \quad (2)$$

Where β_p is the estimated marginal utility for price (Durham, 2012).

3. Methods

Six attributes are considered in this DCE; all have two levels with the exception of price, which has three: size (U12 or 16/20, head-on), method (wild-caught or farmed), country of origin (U.S. or foreign), locality (local or distant), processing (fresh or frozen), and price ($15, $20, or $25 per pound) (Table 2). Due to the restricted timeline and resources of this study, few attributes with primarily binary levels were used in order to limit the number of product profiles.

Table 2. Attributes and levels used in the choice experiment.

Product: Shrimp for human consumption, head-on	
Attribute	**Levels**
Size	U12 | 16/20
Method	Wild-caught | Farmed
Origin	U.S.A. | Foreign
Locality	Local | Distant
Processing	Fresh | Frozen
Price	$15 | $20 | $25

The survey consisted of two sections preceded by one page of instructions and key definitions for each level. Local was defined as products "harvested and processed approximately 200mi away or closer." Thus, for the survey locations throughout San Diego, 'U.S. Local' included shrimp harvested within Southern California, while 'Foreign Local' referred to products from facilities or waters in Northern Baja California, Mexico within 200 miles of San Diego.

The first section featured the discrete choice experiment, using a $(2^5 \cdot 3)$ fractional factorial design with 48 choice-sets. Choice-sets were divided into eight blocks of six; each respondent was given a randomly chosen block. Each of the six choice-sets presented to the respondent included two fictitious shrimp product profiles described as a semi-random combination of the attributes outlined above, and a "Neither" option (Figure 5).[3] Respondents were asked to select which of the two products they would buy if both were available at the market, or if they would make no purchase. The second section asked for demographics of gender, age bracket, race, annual household income, and education.

Without further parameters, the 48 choice sets would consist of entirely randomly selected combinations of levels. However, unrealistic product profiles – such that one answer is obviously superior or inferior to any other – do not provide useful information about trade-offs. Therefore, two prohibitions were included in the design, which prevented the 'best' profile from being paired with the lowest price, and the 'worst' profile from being paired with the highest price.

[3] See Appendix B.1 for full design.

Four interaction terms were also included to investigate if the level of one attribute had an impact on consumer perception of another attribute. Those interactions were Size*Method, Size*Locality, Method*Origin, and Origin*Locality.

	Option A	Option B	
Size	U12: Jumbo, Colossal	U12: Jumbo, Colossal	
Method	Wild-caught	Farmed	
Origin	Foreign	Foreign	
Locality	Local	Distant	
Processing	Frozen	Fresh	
Price	$20/lb.	$25/lb.	
Select one:	Option A ☐	Option B ☐	Neither ☐

Figure 5: *Example choice-set. Each respondent answered six choice-sets.*

The survey was administered in person at four sites chosen to target consumers who prioritize the freshness and origin of their seafood purchases. The three primary sites represented 'specialty markets' specializing in fresh seafood: Tuna Harbor Dockside Market, a Saturday weekly fishermen's market in downtown San Diego, California; Catalina Offshore Products (COP), a sustainably sourced seafood retail market in San Diego; and El Pescador, a combination restaurant and fish counter in La Jolla, California. The fourth site was the campus of Scripps Institution of Oceanography (SIO), UCSD. Survey distribution occurred in fourteen sessions averaging 2.25 hours each throughout April and May. Data utilized in this analysis is based upon 287 completed in-person paper surveys, the large majority from Tuna Harbor and COP.

4. Results

4.1 Demographics

The respondents were approximately 60% male. Catalina Offshore Products and Tuna Harbor yielded the most respondents at N=133 and N=103, respectively. 28 responses were obtained on SIO campus, and 23 at the El Pescador restaurant. The vast majority of respondents (~70%) identified as white, with Asian/Pacific Islander representing 16% and other races being minimally represented; this distribution was relatively consistent across locations. The number of respondents younger than 18 is minimal (<1%) because most grocery shoppers are adults. The middle age brackets were relatively evenly sampled, with a decrease in the youngest and oldest categories (Table 3).

Table 3. Demographics: Gender, Race, Age.

Variable	Sample (n)	% Total
Gender Male	171	59.6%
Gender Female	105	36.6%
Gender Did not answer	11	3.8%
Race Asian or Pacific Islander	47	16.4%
Race Black or African American	4	1.4%
Race Hispanic or Latino	14	4.9%
Race Native American	0	0.0%
Race White	200	69.7%
Race Other	8	2.8%
Race Did not answer	14	4.9%
Age <18	2	0.7%
Age 18-29	59	20.6%
Age 30-39	64	22.3%
Age 40-49	57	19.9%
Age 50-59	53	18.5%
Age 60+	38	13.2%
Age Did not answer	14	4.9%

Overall education was surprisingly high. Approximately 41% of total respondents had attained a graduate degree, dipping only slightly when excluding the university site. Table 4 groups education distribution by location, revealing that a strong majority of consumers at each locale has a bachelor degree or higher. Also of note is the annual household income distribution of respondents (Table 5). At each market location, the highest two income brackets encompassed 30-54% of respondents.

Table 4. Highest level of education.

Education	COP		Tuna Harbor		El Pescador		SIO	
Less than High School	1	0.8%	2	1.9%	0		0	
High School Graduate	4	3.0%	9	8.7%	2	8.7%	0	
Some College	14	10.5%	14	13.6%	3	13.0%	1	3.6%
Associate Degree	7	5.3%	6	5.8%	0		0	
Bachelor Degree	39	29.3%	26	25.2%	9	39.1%	9	32.1%
Graduate Degree	48	36.1%	35	34.0%	4	17.4%	14	50.0%
Did not answer	20	15.0%	11	10.7%	5	21.7%	4	14.3%
	N=133		N=103		N=23		N=28	

Table 5. Annual household income.

Income ($USD)	COP		TH		EP		SIO	
Less than 20,000	1	0.8%	6	5.8%	3	13.0%	3	10.7%
20,000-49,999	6	4.5%	22	21.4%	1	4.3%	11	39.3%
50,000-74,999	9	6.8%	14	13.6%	3	13.0%	7	25.0%
75,000-99,999	14	10.5%	12	11.7%	4	17.4%	1	3.6%
100,000-149,999	34	25.6%	16	15.5%	2	8.7%	2	7.1%
150,000 or more	39	29.3%	20	19.4%	5	21.7%	0	0.0%
Did not answer	30	22.6%	13	12.6%	5	21.7%	4	14.3%
	N=133		N=103		N=23		N=28	

4.2 Regression

Conditional logit model is used to estimate the choice probabilities. Effects coding was used for product attributes, except for the 'no-choice' variable. Price is the only main effect variable treated as continuous. All specifications use robust clustered standard errors with the cluster on the individual respondent. Table 6 contains the parameter estimates for the model with the main effects only (restricted) and the model with both main effects and interactive effects (unrestricted). Each coefficient represents the marginal utility for the attribute in question. A positive coefficient means that the attribute level denoted in the model increases the probability of purchase; a negative parameter means the probability of choice decreases. The magnitude of the coefficients is not directly interpretable, though the values are ordinal, so ranking the weight of attributes is possible.

All interactions were found to be insignificant. Based upon log likelihood test and a lower Akaike's Information Criterion (AIC) value, the main effects only model is statistically superior to that with interactions. Thus, the remainder of this discussion refers to the restricted model. The base product is defined as a large (U12) shrimp, farmed, in the U.S., local, and fresh.

With the exception of size, each of the main effects attributes is statistically significant at the 1% level. The sign of the coefficient for Price has the expected negative effect, indicating a higher price decreases the probability of purchase. Method has the largest negative effect indicating a strong consumer preference for wild-caught products; and all other base attribute levels increase the probability of selection.

The highest utility for a single attribute came from a restriction to only wild-caught shrimp, followed by U.S. country of origin, freshness, locality, and finally price.

When stratified by income, those with high annual household income (>$100k) rated the utility of each attribute higher than those at lower income levels and price was found to be insignificant.

Interestingly, when stratified by education the relative utility of the top two attributes switched: consumers with a graduate degree rate the utility of U.S. origin higher than that of Method.[4]

For the purpose of this report, education and income stratifications are the extent of consumer segmentation. However, results should be more fully explored for market development.

Table 6. Results of conditional logit regression. All calculations based on Restricted model.

	(1) Restricted	(2) Unrestricted
choice		
Size-Large	0.0496	0.0923
	(0.565)	(0.394)
Method-Farm	-1.157***	-1.113***
	(0.000)	(0.000)
Country-Domestic	1.030***	0.930***
	(0.000)	(0.000)
Local-Local	0.370***	0.264*
	(0.000)	(0.053)
Process-Fresh	0.515***	0.513***
	(0.000)	(0.000)
price	-0.0366***	-0.0376***
	(0.000)	(0.000)
outside	-1.476***	-1.533***
	(0.000)	(0.000)
I Large Farm		-0.138
		(0.282)
I Large Local		0.0207
		(0.856)
I Farm Domestic		0.0264
		(0.847)
I US Local		0.185
		(0.195)
Observations	4155	4155
AIC	2352.3	2357.2
BIC	2396.6	2426.8
ll	-1169.1	-1167.6
chi2	303.6	311.2

p-values in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

[4] See Appendix B.2 for complete regression with income and education stratifications.

4.3 Willingness to pay

As defined in Equation 2, WTP is the estimated marginal utility of product *j* over the estimated marginal utility for price. Using the coefficients from the base regression in Table 6:

$$WTP_{farmed} = -(-1.157/-.0366) = -31.61202$$

Farmed shrimp is valued at \$31.61 *less* than its wild-caught counterpart, all other attributes equal. In other words, a discount of \$31.61 per pound would be required for the consumer to achieve the same utility with a farmed product as with a wild one. By this same calculation, shrimp of domestic origin elicits a WTP of \$28.14 per pound over foreign alternatives. When assessed independently, these prices appear unrealistic; but attributes must be combined to form a complete product profile.

Calculating a basic welfare measurement allows us to determine the amount individuals are willing to pay for quality and quantity change. The utility a consumer receives from Product A is defined as:

$$U^0 = \beta_p(Price) + \beta_2(Product\ A) \qquad (3)$$

Product A is a generic quality factor resulting from a given combination of attribute levels. To monetize the welfare impact of change from Product A to Product B, the price changes by what is known as Compensating Variation (CV). CV equates the original utility with the subsequent utility level, solving the expression (Louviere et al, 2000):

$$U^0 = \beta_p(Price) + \beta_2(Product\ A) = \beta_p(Price + CV) + \beta_2(Product\ B) = U^1 \qquad (4)$$

Product A is modeled after common shrimp products found in Southern California markets: wild-caught, 16/20, frozen from a distant country sold at \$19.57 per pound – the average price for this kind of product at specialty markets. Product B is the profile of the proposed spot prawn product: farmed, U12, fresh from Southern California sold for \$25.07 per pound – the average price for similar but imported products (Poindexter, 2016). In this scenario, replacing Product A with Product B yields: [5]

$$CV = WTP = \$16.54$$

This means consumers are willing to pay \$16.54 more per pound to equate the utility of Product A to the utility of alternative Product B. Thus, while the wild-caught attribute level is highly valued, farmed products can elicit higher WTP if they embody other desirable characteristics.

---

[5] See Appendix B.3 for full CV equation.

5. Discussion

The demographic breakdown of this sample population is unique from the average citizen. That the survey sample was almost 60% male is already a contrast to typical grocery store distributions, where U.S. primary shoppers are 43% male (Food Marketing Institute, 2014). The three market venues all have unique formats with potential to attract a variety of customers, though the demographic data show that a majority of respondents are included in the highest two income brackets. Similarly, a bachelor degree or higher is common at all sites. All adult age categories are well represented. Overall, this sample population highly affluent, educated, predominantly white, and secondarily Asian or Pacific Islander. This is representative of the customer base of specialty fresh seafood markets in San Diego.

Method was rated as the attribute most influential in determining utility, with a negative association with farming. Despite recent media attention on the development of environmentally harmonious aquaculture (Smith, 2013), there remains a strong stigma against farmed shrimp. However, the monetized loss of utility due to farming may be compensated for by the other attributes of U.S. origin, freshness, and locality.

Among the base consumer, the attribute second to Method is Country of Origin, though the rank of these two attributes reverses amongst consumers with graduate degrees. The more educated consumer is more accepting of farmed products than of foreign products. However, the highest income consumers ranked attributes in the same order as the base consumer, but with a higher utility associated with each. Also price was found to be insignificant among this customer base.

Throughout survey dissemination, respondents asked for more information regarding farming methods, suggesting their purchasing decisions hinged on perceived effects of specific types of aquaculture. If a producer is considering farming *P. platyceros*, it could be beneficial to spread awareness of low-impact farming methods and provide information on their specific practices. A locally-based facility within Southern California would already achieve the positive utility associated with locality and country of origin, and the utility lost due to Method may be partially mitigated with well-advertised, sustainable farming practices. In similar niche eco-products, this transparency can be achieved via ecolabels, though success depends upon ecolabel clarity and perceived reliability. The impact of ecolabels on WTP has been explored in other studies (Delmas, 2012; Durham, 2012; Gesiot, 2012; Uchida, 2014), though there is room for further research, especially in applying this attribute to seafood.

The CV calculation described in Equations 3 and 4 addressed the WTP for a change in quality or quantity. However, it assumes the original Product A is definitively replaced with the alternative Product B. This calculation does not account for scenarios with many alternatives, such as the variety of existing shrimp products that may be present in a marketplace (Louviere, 2000). As such, the WTP provided above is limited in its application to determining a real world market price for Product B. In reality, a new shrimp product would be competing with several existing alternatives with varying product profiles. More comprehensive welfare measurements which consider multiple products are possible but are beyond the scope of the present study.

Overall, among the customer base of niche seafood markets, the method of harvest is the most influential in determining consumer utility, with a farmed product being detrimental, but the other significant attributes identified here can compensate for this loss of utility.

5.1 Production Cost Considerations

The primary operational costs of a shrimp farming facility are feed cost, electrical, insurance, maintenance, loans with interest, labor, and cost of PLs (Roll, 2008). In the case of spot prawns, there are no hatcheries to supply PLs, so a farm would have to culture their own or a separate large-scale hatchery facility would be required to jumpstart a farmed spot prawn industry. As determined above, the most important qualities to the sampled populace after Method are Country of Origin and then Processing. Thus directing farm development to within the U.S. will add value to the harvest; and the comparative ease with which farmed shrimp can be kept fresh in contrast to wild-caught products will also be a competitive advantage.

In farming the ubiquitous *Litopenaeus vannamei*, or Pacific white shrimp, sourcing of PLs can account for approximately a quarter of production costs (Quagrainie, 2015).

A target profit margin of 15% is considered a safe margin for an otherwise high-risk industry. With decreasing PL survival, one must sell at a higher price in order to reach this margin. Figure 6 is from Quagrainie's 2015 assessment on production costs of *Litopanaeus vannamei* indoor farming showing profits from various prices at various survival rates for shrimp. The indication that 21/25 count can produce a 46% profit at $18.00 per pound and 80% PL-survival is promising when applied to spot prawns. Larval development is the most vulnerable life phase, and this trial saw 80% survival to PL. Therefore, PL survival can reasonably be expected to be at or above this threshold.

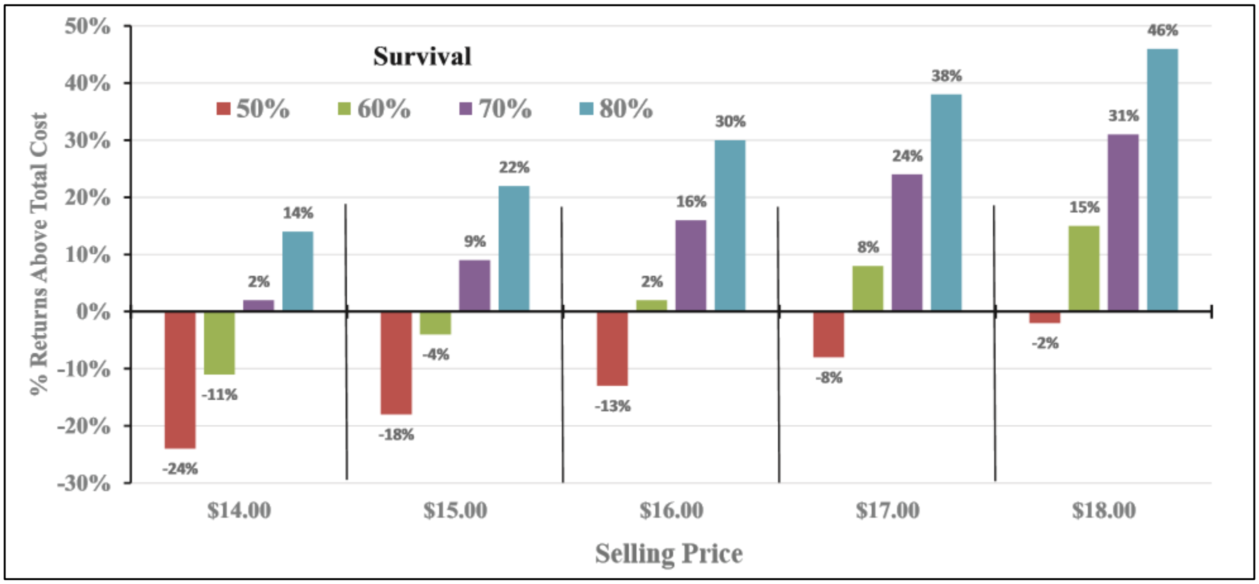


Figure 6: *Percentage Profit with Different Survival and Selling prices for 21/25 Count L. vannamei.*

In this same assessment, it is calculated to be economically beneficial for farmers to allow *L. vannamei* to grow bigger before harvesting even though it incurs higher operational costs (Quagrainie, 2015). Spot prawns would likely be farmed to at least 16/20 count and have potential to reach U7. If production costs for farming spot prawn were similar to those of whiteleg shrimp, the large size and high survival could yield a significant profit margin. A shortcoming is the longer time between initial investment and return because of the longer grow-out period of *P. platyceros*. *L. vannamei* is sold at smaller sizes and grows fast enough from PL to provide a harvest every six months. In areas with cheap operation costs this can turn a profit in year one (D. Anderson, personal communication, May 26, 2016). The complete grow-out time is as yet unknown for spot prawn, but one can assume with a larger-growing, cold-water species, this schedule would be delayed. By extrapolating Quagrainie's (2015) analysis that farmers do in fact benefit from postponing harvest until larger size is achieved, the delayed return on investment may be worth the wait.

As mentioned in Chapter 1, of commercially-farmed species, *M. rosenbergii* is genetically the closest relative to *P. platyceros* as they are both members of the *Caridae* infraorder. While *M. rosenbergii* is grown in freshwater and spot prawns are marine, this species can provide another reference for developmental timelines and production techniques. Combining operational information from *L. vannamei* and *M. rosenbergii* may be a better metric than referring to one species alone. The trial and error associated with commercial-scale development of these two popular species over the past several decades should be utilized to provide guidance for *P. platyceros* farming.

5.2 Further Research

The shrimp market within the United States is complex, with products varying from miniscule salad ingredients to lobster-sized delicacies. Willingness to pay for shrimp of different attributes may be very population specific and the demographic composition of this sample is limited in scope. This population represents patrons of specialty seafood markets in affluent, coastal locales. This is relevant to the question of establishing a Pacific coast shrimp farm, though in order to determine WTP of broader consumer bases, this survey should be administered on a larger scale at a greater variety of venues.

The attributes and levels that can comprise shrimp product profiles are many. There are myriad characteristics not addressed in this study, such as a range of processing techniques and sizes, seasonality, and ecolabels. In fact, spot prawn's unique culinary profile may add an additional price premium, but subjective attributes such as taste are challenging to address. Respondents provided their answers in regards to general 'shrimp', and amaebi is typically more desirable than ubiquitous whiteleg shrimp. Surveys addressing these characteristics could be used to supplement this design and determine a more refined WTP for a specific product.

Lastly, a more thorough understanding of production costs is needed to determine if the derived WTP does in fact indicate economic feasibility. The minimal information in this discussion is based on risk assessments for shrimp farming of different species in different environments. Researching the economic atmosphere along the Pacific coast and how existing shrimp farming protocols will need to be adjusted to facilitate *P. platyceros* are essential aspects in determining feasibility.

6. Conclusions

Respondents stated a strong preference for wild-caught and domestically produced shrimp products. Freshness and Locality significantly influenced purchasing decisions, but not to the same magnitude as Method and Country of Origin. Size did not significantly influence respondent choices. Incorporating these parameters into complete product profiles, a product with the attributes of a locally-farmed spot prawn can increase customer utility (and WTP) when substituted for the average shrimp products found at markets. These CV calculations are limited in application as they do not account for multiple alternative products.

Among the sampled population, aquacultured shrimp products will elicit a lower WTP than wild-caught. However, other positively perceived attributes may allow this product to be competitive.

Conclusion: Future aquaculture in Southern California

The results of this DCE survey are limited in scope to a small population, but the determined WTP for a large, locally-farmed shrimp indicates that farming spot prawn along the Pacific coast is potentially economically feasible. The survey population does perceive aquacultured seafood to be considerably less desirable than wild-caught options, though overall WTP for a product with desirable origin, locality, and processing is still high regardless of Method. The results of investigating spot prawn biology support pursuing research of this species for aquaculture. In order to definitively assess feasibility, more information is needed regarding the production costs and species-specific timeline associated with starting a hatchery or farming facility.

In terms of implementation, San Diego is primed for aquaculture development. The Port of San Diego is in the process of developing aquaculture facilities for lease (P. Sylvia, personal communication, January 13, 2016). Rose Canyon Fisheries, Inc. – the result of a partnership between Hubbs-Seaworld Research Institute and Cuna Del Mar – is moving forward with the first commercial-scale offshore aquaculture operation in U.S. federal waters for *Serioloa lalandi* off the coast of San Diego. This has garnered recent media attention and controversy, as the public grapples with historically negative implications of fish farming and the proposed "sustainable ocean farming" (HSWRI, 2015). Net Zero Enterprises is developing a closed-loop, indoor shrimp farming facility in Imperial, California, promising the first U.S. shrimp to fulfill the requirements of eco-conscious seafood purveyor, Whole Foods (Wietecha, 2016). This project raised $5 million in five months entirely via online crowdfunding (Yoshimura, 2015), which speaks to ample public interest.

The development of these projects in the face of farmed seafood stigmas has several implications. Firstly, wild stocks are not sufficiently meeting consumer demand; increasing seafood demand has necessitated farm development to increase global production capacity. Secondly, technological improvements and understanding of ecosystem-based management have improved vastly in recent years. All of these projects are confident they can produce sustainable seafood with minimal environmental impact and in accordance with U.S. regulations. Thirdly, these pioneer projects face more permitting and regulatory hurdles as they pave the way for future projects, yet investors still see potential. Not only is farmed seafood an essential component of food security, but it can be lucrative if done correctly. In the United States, much of that success relies upon public perception of quality food coming from trustworthy producers implementing sustainable methods. With these projects leading the way, the perception toward farmed seafood in Southern California may be about to change. Incorporating new native species into this development is yet another way to contribute to low-impact aquaculture.

This dual study supports the inclusion of *P. platyceros* into Southern California aquaculture. Biologically, the larval development observed here suggests viability. Economically, a fresh, locally farmed shrimp can elicit a promising WTP when compared to a commonplace wild-caught alternative. Based on this survey, negative perceptions of fish farming are still apparent in consumers but this does not negate investment opportunity. And these perceptions may be on the verge of transformation as sustainable aquaculture movements gain momentum. Exploitation of marine resources is a constant stressor on ocean ecosystems. Perfecting sustainable aquaculture is a practical and achievable way to attenuate this stress. Farming *P. platyceros* along the Pacific coast can prove to local communities that we can create our own high-quality products, support local industry, and avoid the environmental damage resulting from imported seafood.

References

Aydin, R., Kwong, C.K., Ji, P., and H.M.C. Law. (2014). Market demand estimation for new product development by using fuzzy modeling and discrete choice analysis. *Neurocomputing*, 142: 136-146.

Bergström, B.I. (2000). The Biology of *Pandalus*. *Advances in Marine Biology,* 38: 55-245.

Boyd, C.E., and J.W. Clay. (1998). Shrimp Aquaculture and the Environment. *Scientific American,* 278(6): 58-65.

California Department of Fish and Wildlife: Marine Region. (2008). Status of the fisheries report - an update through 2006. *Report to the Fish and Game Commission as directed by the Marine Life Management Act of 1998.*

Chen, S.N. (1991). Environmental problems of aquaculture in Asia and their solutions. *Scientific and Technical Review of the Office International des Epizooties*, 10(3): 609-627.

Chuenpagdee, R., Morgan, L.E., Maxwell, S.M., Norse, E.A., and D. Pauly. (2003). Shifting gears: assessing collateral impacts of fishing methods in US waters. *Frontiers in ecology and the Environment*, 1: 517-524.

Delmas, M.A., Nairn-Birch, N., and M. Balzarova. Lost in a sea of green: Navigating the eco-label labyrinth. *UCLA Institute of the Environment and Sustainability*, California. Draft 2012.

Durham, C.A., Roheim, C.A., and I. Pardoe. (2012). Picking Apples: Can Multi-Attribute Ecolabels Compete? *Journal of Agricultural & Food Industrial Organization,* 10(1): 1-23.

Ecosystem Principles Advisory Panel. (1999). Ecosystem-Based Fishery Management. NOAA National Marine Fisheries Service, Silver Spring, MD.

Food and Agriculture Organization of the United Nations. (2014). State of World Fisheries and Aquaculture: Opportunities and Challenges. Rome.

Fisk, G. (2010). Coldwater Shrimp Industry. *United States Department of Agriculture. Trade Adjustment Assistance Program. Alaska Sea Grant Marine Advisory Program.*

FishStatJ – software for fishery statistical time series. *Fisheries and aquaculture software.* Rome. Updated 23 June 2015. http://www.fao.org/fishery/

Gesiot, M. (2012) Explaining adoption and market success of “green products”: A Conjoint Analysis Experiment on German Students’ preferences on eco-labels.

Gillett, R. (2008). Global study of shrimp fisheries. *FAO Fisheries Technical Paper 475.*

Hubbs-SeaWorld Research Institute. (2015). Rose Canyon Fisheries Paves the Way for Sustainable Ocean Farming off San Diego. *HSWRI Aquaculture Program Research Report: October-November 2014.* Retrieved from www.hswri.org

Kelly, R.O., Haseltine, A.W., and E.E. Ebert. (1977). Mariculture potential of the spot prawn, *Pandalus platyceros* Brandt. *Aquaculture*, 10(1): 1-16.

Kimker, A., Donaldson, W., and W.R. Bechtol. (1996). Spot Shrimp Growth in Unakwik Inlet, Prince William Sound, Alaska. *Alaska Fishery Research Bulletin,* 3(1): 1-8.

Louviere, J.J., Hensher, D.A., and J.D. Swait. (2000). Stated choice methods: Analysis and application. Cambridge, United Kingdom: Cambridge University Press.

May, R.C. (1974). Larval mortality in marine fishes and the critical period concept. *The Early Life History of Fish,* 3-19.

National Marine Fisheries Service: Fisheries Statistics and Economics Division. (2015). *Cumulative Trade Data by Product*. Retrieved from https://www.st.nmfs.noaa.gov/

National Marine Sanctuaries. NOAA. (2011). *Fishery Basics - California Fishers: Spot Prawn.* Voices of the Bay. Retrieved from http://www.sanctuaries.noaa.gov

National Oceanic and Atmospheric Association: Office of Aquaculture. *Seafood & Human Health.* Retrieved from http://www.nmfs.noaa.gov/aquaculture/faqs/faq_seafood_health.html

National Oceanic and Atmospheric Association: Office of Science and Technology. *Shrimp Report.* Retrieved from https://www.st.nmfs.noaa.gov/apex/f?p=169:2:0::NO:::

New, M. B. (2002). Farming freshwater prawns: A manual for the culture of the giant river prawn (*Macrobrachium rosenbergii*). *FAO Fisheries Technical Paper 428.*

Poindexter, O. (2016). Blue market incentives for bycatch reduction. NOAA Southwest Fisheries Science Center, United States Marine Mammal Commission, Ocean Associates, Inc. Unpublished dataset, cited with permission.

Price, V.A., and K.K. Chew. (1972). Laboratory rearing of spot shrimp larvae (*Pandalus platyceros*) and description of stages. *Journal of the Fisheries Research Board of Canada*, 29: 413-422.

Quagraine, K. (2015). Profitability of Indoor Production of Pacific White Shrimp (*Litopenaeus vannamei*): a case study of the Indiana Industry. *Purdue University Extension*. Funding provided by Indiana State Department of Agriculture, Illinois-Indiana Sea Grant, and Indiana Soybean Alliance.

Roll, R., Bergheim, A., and A. Gravdal. (2008). Profitability analysis of the NIRI technology for land-based salmon farming. *International Research Institute of Stavanger*.

Safina Center: Sustainable Seafood Program. (2012). *Spot Shrimp - U.S. Pacific Coast, Washington-California.* Species Report.

Seafood Watch - Official Site of the Monterey Bay Aquarium's Sustainable Seafood Program. (2016). Retrieved from http://seafoodwatch.org

Smith, B. (2013). *Bren Smith: 3D farming the ocean for sustainability* [Video file]. Retrieved from http://tedxtalks.ted.com/video/3D-farming-the-ocean-for-sustai

Southern California Coastal Ocean Observing System (SCCOOS). Temperature and Salinity Data: Scripps Pier. Retrieved May 2016. Download provided by SCCOOS. http://sccoos.org/query/

Uchida, H., Onozaka, Y., Morita, T., and S. Managi. (2014). Demand for ecolabeled seafood in the Japanese market: A conjoint analysis of the impact of information and interaction with other labels. *Food Policy*, 44: 68-76.

Wickins, J.F. (1972). Experiments on the culture of the spot prawn *Pandalus platyceros* Brandt and the giant freshwater prawn *Macrobrachium rosenbergii* (de Man). *Ministry of Agriculture, Fisheries, and Food: Fishery Investigations*, 2(27.5): 1-22.

Wietecha, O. (2016). Net Zero Enterprises to 'revolutionize' US shrimp farming. *Undercurrent News: Seafood Business News from Beneath the Surface.* Retrieved from https://www.undercurrentnews.com

Yoshimura, M. (2015). Net Zero Aqualife, Producer of Organic, Non-GMO Shrimp, Nearing End of Crowdfunding Campaign. *Crowdfund Insider.* Retrieved from www.crowdfunderinsider.com

Zanotto, F.P., and M.G. Wheatly. (2002). Calcium balance in crustaceans: nutritional aspects of physiological regulation. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology,* 133(3): 645-660.

APPENDIX

Appendix A

1. *Tank Cleaning*

   Tank cleaning occurred at or before the time the bottom third of the kreisel acquired a thin, continuous film of coverage or showed other significant accumulation of waste; approximately once every ten days. Larvae were transferred to a plastic holding tub with aeration and provided some *Artemia* to prevent cannibalism. The holding tub did not provide the same circulation as the kreisel and larvae usually settled on the bottom. Larvae were caught for transfer by using a light to attract them and scooping them into a cup. This would not be practical for a larger scale trial. For larger scale, a better approach would be siphoning the tank with a screen or vessel to retain larvae that may get sucked up. The vacant kreisel was drained and power-washed with tap water until no debris or film remained. The tank was re-filled at least halfway before transferring the larvae back to circulation.

   Siphoning out the tank proved challenging given the small size of the tank and its position among other ongoing experiments. In a different configuration, it would be better to clean the bottom of the tank more regularly with a siphon; however, the described method of less frequent but more thorough cleaning sufficed.

   It was not apparent if the transfer between tanks or brief settlement had adverse effects on the larvae. No mortalities were directly associated with tank cleaning.

2. *Artemia Harvest*

   To harvest the nauplii, the airstone was removed from the hatching cone and unhatched cysts on the bottom of the cone were drained. A light was held to the bottom of the cone to attract the *Artemia* toward the spigot and away from floating egg capsules, and then 300-500mL was drained into a beaker. 0.5mL was then pipetted to a plastic disc where the *Artemia* could be counted; if *Artemia* were too numerous to count this would be repeated with 0.25mL. This count provided how many milliliters were required for the subsequent feeding, depending what fraction of the total daily diet was the target. About 0.05 Zeigler powder was stirred into the nauplii (cumulative 0.15g daily), and the solution was slowly poured into the kreisel. If the ambient seawater temperature was particularly low, nauplii would be mixed with seawater prior to feeding to mitigate temperature difference.

Appendix B

1. *Complete Discrete Choice Experiment Design*

Block	choice_set	alt	x1	x2	x3	x4	x5	x6	x7
1	4	1	1	1	2	1	1	2	1
1	4	2	2	1	1	1	2	1	2
1	9	1	2	1	1	2	1	1	1
1	9	2	1	1	2	2	2	1	2
1	11	1	1	2	1	2	1	2	1
1	11	2	2	2	2	2	2	1	2
1	21	1	1	2	2	1	1	2	1
1	21	2	2	2	1	1	2	1	1
1	29	1	1	1	1	2	1	1	2
1	29	2	1	2	1	1	2	1	1
1	40	1	2	1	1	2	2	2	1
1	40	2	2	2	1	1	1	1	2
2	3	1	1	1	1	1	2	1	1
2	3	2	1	2	1	2	1	1	2
2	15	1	2	2	1	2	2	1	2
2	15	2	2	1	1	1	1	2	1
2	24	1	1	2	1	1	2	1	2
2	24	2	2	2	2	1	1	1	1
2	33	1	2	2	2	2	1	2	1
2	33	2	2	1	2	1	2	1	1
2	43	1	1	1	2	1	2	1	2
2	43	2	1	2	2	2	1	2	1
2	44	1	2	2	1	1	2	2	1
2	44	2	1	2	2	1	1	1	1
3	8	1	1	2	2	2	2	2	1
3	8	2	2	2	1	2	1	1	2
3	20	1	1	2	1	2	1	1	1
3	20	2	1	1	1	1	2	2	1
3	22	1	1	1	2	2	2	2	1
3	22	2	1	2	2	1	1	1	1
3	32	1	2	1	1	1	1	2	1
3	32	2	1	1	2	1	2	1	2
3	34	1	2	1	1	2	1	1	2
3	34	2	2	2	1	1	2	1	1
3	38	1	2	2	1	2	2	2	1
3	38	2	2	1	1	1	1	1	2
4	12	1	2	1	2	1	1	2	1
4	12	2	1	1	1	1	2	1	1
4	19	1	1	1	2	2	1	1	2
4	19	2	1	2	1	1	2	1	1
4	30	1	2	2	2	1	2	1	1
4	30	2	1	2	1	1	1	2	1
4	36	1	2	1	2	2	2	2	1
4	36	2	2	2	2	1	1	1	2

4	46	1	2	1	2	2	2	1	2
4	46	2	1	2	2	1	1	2	1
4	47	1	2	1	1	2	1	1	2
4	47	2	2	2	1	1	2	2	1
5	2	1	2	1	2	1	1	2	1
5	2	2	1	1	1	1	2	1	1
5	6	1	2	2	1	2	1	1	1
5	6	2	2	1	1	1	2	1	2
5	23	1	1	2	2	2	2	2	1
5	23	2	2	2	1	2	1	1	2
5	26	1	1	2	1	2	2	1	1
5	26	2	1	1	1	1	1	2	1
5	37	1	1	1	1	2	1	1	1
5	37	2	1	2	2	1	2	1	2
5	41	1	1	2	2	1	2	1	1
5	41	2	2	2	1	1	1	2	1
6	5	1	2	1	1	2	2	2	1
6	5	2	1	1	2	2	1	1	2
6	7	1	2	1	2	2	1	1	1
6	7	2	1	1	1	2	2	2	1
6	14	1	2	2	2	1	2	2	1
6	14	2	1	2	1	1	1	1	2
6	16	1	1	2	1	2	1	1	1
6	16	2	2	2	2	2	2	1	2
6	17	1	1	1	2	1	1	1	1
6	17	2	1	2	2	2	2	1	2
6	25	1	1	2	2	1	2	1	2
6	25	2	2	2	1	1	1	1	1
7	1	1	1	2	2	2	1	1	2
7	1	2	1	1	2	1	2	2	1
7	27	1	1	1	1	2	2	1	1
7	27	2	2	1	2	2	1	2	1
7	31	1	2	2	2	2	1	1	1
7	31	2	2	1	2	1	2	1	2
7	35	1	2	1	1	2	2	1	2
7	35	2	1	1	2	2	1	1	1
7	45	1	1	2	1	1	1	1	2
7	45	2	1	1	1	2	2	1	1
7	48	1	2	1	1	1	1	1	1
7	48	2	2	2	1	2	2	2	1
8	10	1	1	1	1	2	2	1	2
8	10	2	2	1	2	2	1	1	1
8	13	1	2	1	2	1	2	1	1
8	13	2	1	1	1	1	1	2	1
8	18	1	2	2	2	1	1	1	2
8	18	2	2	1	2	2	2	1	1
8	28	1	2	2	2	2	1	1	1
8	28	2	1	2	1	2	2	2	1
8	39	1	1	1	2	1	1	2	1
8	39	2	1	2	2	2	2	1	1

8	42	1	1	1	2	2	1	1	1
8	42	2	2	2	2	1	2	2	1

2. Regression results for income and education stratifications.

Regression with Income Stratification

	(1) Low Income, R	(2) Low Income, UR	(3) High Income, R	(4) High Income, UR
choice				
Size-Large	0.188*	0.0948	-0.129	-0.00164
	(0.100)	(0.539)	(0.307)	(0.991)
Method-Farm	-1.140***	-1.188***	-1.201***	-1.112***
	(0.000)	(0.000)	(0.000)	(0.000)
Country-Domestic	0.983***	0.850***	1.118***	1.024***
	(0.000)	(0.000)	(0.000)	(0.000)
Local-Local	0.372***	0.195	0.383***	0.321*
	(0.005)	(0.315)	(0.001)	(0.094)
Process-Fresh	0.469***	0.476***	0.584***	0.574***
	(0.000)	(0.000)	(0.000)	(0.000)
price	-0.0551***	-0.0567***	-0.0163	-0.0190
	(0.000)	(0.000)	(0.271)	(0.220)
outside	-1.642***	-1.790***	-1.290***	-1.338***
	(0.000)	(0.000)	(0.000)	(0.000)
I Large Farm		-0.0545		-0.151
		(0.765)		(0.409)
I Large Local		0.205		-0.132
		(0.176)		(0.428)
I Farm Domestic		0.110		-0.0375
		(0.575)		(0.846)
I US Local		0.151		0.241
		(0.460)		(0.228)
Observations	2076	2076	2079	2079
AIC	1208.5	1214.5	1143.4	1148.7
BIC	1248.0	1276.5	1182.9	1210.8
ll	-597.3	-596.3	-564.7	-563.4
chi2	159.5	178.7	175.0	179.4

p-values in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Regression with Graduate Education Stratification

	(1) Lower Edu (R)	(2) Lower Edu (UR)	(3) Grad degree (R)	(4) Grad degree (UR)
Choice				
Size-Large	0.00981	-0.0434	0.0968	0.269
	(0.932)	(0.758)	(0.464)	(0.111)
Method-Farm	-1.191***	-1.175***	-1.086***	-1.037***
	(0.000)	(0.000)	(0.000)	(0.000)
Country-Domestic	0.978***	0.870***	1.107***	1.012***
	(0.000)	(0.000)	(0.000)	(0.000)
Local-Local	0.375***	0.189	0.360**	0.390*
	(0.000)	(0.259)	(0.018)	(0.094)
Process-Fresh	0.470***	0.468***	0.576***	0.569***
	(0.000)	(0.000)	(0.000)	(0.000)
price	-0.0306**	-0.0315**	-0.0451***	-0.0475***
	(0.021)	(0.020)	(0.004)	(0.003)
outside	-1.517***	-1.634***	-1.450***	-1.455***
	(0.000)	(0.000)	(0.001)	(0.001)
I Large Farm		0.0387		-0.367*
		(0.812)		(0.082)
I Large Local		0.0534		-0.0294
		(0.717)		(0.874)
I Farm Domestic		-0.0954		0.216
		(0.599)		(0.311)
I US Local		0.303*		0.00311
		(0.095)		(0.989)
Observations	2427	2427	1710	1710
AIC	1364.8	1369.5	986.3	990.2
BIC	1405.4	1433.3	1024.4	1050.1
ll	-675.4	-673.8	-486.1	-484.1
chi2	187.9	184.4	119.2	149.1

p-values in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$