Mapping microhabitats defined by water flow velocity in the Giant Kelp, *Macrocystis pyrifera*

A Capstone Project

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by

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Abstract

The Giant Kelp, *Macrocystis pyrifera* is widely harvested in California by removing the uppermost four feet of the canopy. The canopy may be a microhabitat that experiences a water flow regime unique to that portion of the kelp. Plaster of Paris clod balls, which dissolve at different rates under different flow conditions, were used in this study to determine if there was a significant difference in water flow in four microhabitats in Giant Kelp: the holdfast, the stipe, the curve of the stipe immediately below the canopy, and the canopy. Diffusion factors (the ratio of weight loss of plaster in the field to the weight loss of plaster in controlled still water conditions) were calculated for each microhabitat. Paired t-tests were conducted to determine if the diffusion factor at the different microhabitats was significantly different. The statistical tests showed that the diffusion factor of the holdfast is significantly different from the diffusion factors at the other three microhabitats, and since the diffusion factor is directly related to water flow velocity, the holdfast experiences a unique water flow regime. The canopy was found to be significantly different from the holdfast and not from the other microhabitats on the kelp. More research needs to be focused on determining whether or not the microhabitats have a significant difference in other environmental characteristics, such as light availability and nutrient delivery. Additionally, research needs to be conducted on the effects of kelp harvesting on the holdfasts.

Introduction

The focus of this study is the brown algae *Macrocystis pyrifera*, the Giant Kelp. The purpose of this capstone report is to determine flow microhabitats (smaller, specialized habitats within a larger habitat) along a stipe (or stem) of Giant Kelp to assess habitat loss caused by kelp harvesting in Monterey Bay, California. Water flow is an important habitat parameter because it influences the distribution and abundance of marine organisms (Mathieson et al., 1977). By measuring the flow on different points on the kelp, a determination can be made as to whether these microhabitats have significantly different water flow velocities. If the canopy is found to be significantly different from the rest of the kelp, then the canopy microhabitat is unique in terms of water flow. Therefore, unique microhabitat may be lost when the canopy of the kelp is removed during harvesting and, therefore, it may be important to evaluate ecosystem...
impact more carefully to determine if policies concerning kelp harvesting should be modified.

Kelp forests occur in temperate to subpolar regions. Their southern boundary is set by the 20°C water isotherm of the warmest month because the gametophytes do not form any reproductive bodies in temperatures higher than 18-20°C (Chapman and Chapman, 1980). In the Monterey Bay, nearshore temperatures range from 8°C in the winter and early spring to 17°C in the autumn months (MBNMS, 2000).

The ability of kelp forests to thrive depends on an array of environmental variables. Kelp beds are tolerant of freshwater runoff and grow well nearshore where surface salinities are reduced by runoff from larger rivers (Molles, 1999). In the Monterey Bay, nearshore surface salinities vary from 34.0 psu (practical salinity units) when a strong upwelling is present to 33.2 psu otherwise (MBNMS, 2000), which is low compared to the salinities of warmer, tropical waters. There must also be sufficient light present to support photosynthesis. Light penetration varies with local conditions from a few meters to nearly 100 meters (Molles 1999). Additionally, oceanic currents must continuously wash kelp beds. These currents deliver oxygen and nutrients and remove waste products (Molles, 1999). Wind-driven upwelling facilitates the delivery of nutrients in the Monterey Bay. There is a seasonal difference in nutrients due to the seasonal variations in upwelling (MBNMS, 2000). During upwelling, an offshore transport of surface water occurs when wind blows south along the coast. These waters are replaced by cold nutrient rich waters from 25-300 meters deep (Breaker and Broenkow 1982).

Kelp forests grow in areas that have rocky seafloor substrates. The rocky coastline of Central California is ideal for kelp attachment. This nearshore environment
is characterized by hard granitic substrates with a limited number of sandy beaches, which usually are found in small coves (NOAA, 1992). The stretch of coastline between Seaside and Santa Cruz does not allow for kelp attachment due to the sandy beaches and the lack of rocky seafloor substrate.

The kelp holdfast is anchored to solid seafloor at depths sometimes greater than 25 meters. The stipes are buoyant due to gas-filled bladders along the stipe, and grow upward toward the surface. The stipes extend along the surface of the water producing a canopy. They may grow up to 150 meters long (Chapman and Chapman, 1980), and since individual stipes have an average life span of only about six months (North 1961), the growth rate is very high. Sargent and Lantrip (1952) measured the average elongation of stipe apices at 7.1 cm ± 4.5 cm per day.

Giant Kelp provides microhabitats for an abundant and diverse array of species. Foster et al. (1983) classifies the microhabitats associated with a typical Central California kelp forest as: (A) canopy assemblages, (B) planktonic assemblages, (C) holdfast assemblages, (D) horizontal substrate assemblages, and (E) vertical wall assemblages (see Figure 1). Andrews (1945) surveyed five Giant Kelp holdfasts in Monterey and Carmel Bays and found approximately 23,000 individuals from nine invertebrate phyla. Sponges, anemones, cup corals, and tunicates are the most commonly occurring sessile organisms in a kelp forest (Foster and Schiel, 1985). Jellyfish, crustaceans, and fish larvae inhabit the water column and the canopy is home to a large number of invertebrates, such as the kelp isopod *Idotea resecata* (MBNMS, 2000).
Giant Kelp is not only the home to thousands of species of marine organisms, it is also an economic commodity to humans. *Macrocystis pyrifera* is harvested for its algin. In *Macrocystis*, algin is present in 13 to 24 percent of the dry weight of the kelp (Chapman and Chapman, 1980). Algin is used for many purposes. It is used as an emulsifier in processed foods (Frey, 1971) and in other products where a smooth texture is required, such as paints, cosmetics, and pharmaceuticals (MBNMS, 2000). About half of the total output from the U.S. is applied to these purposes (Chapman and Chapman, 1980). Other uses of harvested kelp are as food for abalone raised in aquaculture facilities, and as substrate for the herring-roe-on-kelp fishery, (MBNMS 2000).

The California Department of Fish and Game/Fish and Game Commission (CDFG/FGC) has regulatory authority over California’s kelp resources. Current
management strategies include the use of kelp harvesting permits, closure of certain areas to harvesting, leasing of kelp beds, and determining allowable harvesting methods (mechanical and hand harvesting). Under the National Marine Sanctuaries Act, the National Oceanic and Atmospheric Administration (NOAA) has authority to disseminate policies regulating kelp harvesting in the Monterey Bay National Marine Sanctuary (MBNMS). The City of Monterey claims that under the Treaty of Guadalupe-Hildago, the city has land rights to the 60-foot depth contour and can regulate kelp harvesting within that area. But when the city’s permit restricted harvesting was challenged in court, the Superior Court declared that this regulation is preempted by state law and is therefore invalid.

Currently, harvesting policies (CA Code of Regulations) include the limitation that only the top four feet of the canopy can be harvested, that the harvester must obtain a permit from CDFG, and when harvesting is complete, the harvester must declare how much kelp (in wet tons) was removed. Permits are valid from January 1 to December 1 of the specified year and allows harvesting in open beds only. Mechanical harvesting is not allowed in open beds. Leased beds are reserved for contracted harvesting between CDFG and the larger harvesting corporations.

In 1999, 142 wet tons of kelp was harvested from California Department of Fish and Game (CDFG) Kelp Bed #220, which stretches from Asilomar Beach to the Coast Guard Breakwater in Monterey Harbor. This is a decline from the mean annual harvest of 592 wet tons from 1987 to 1999. The study site for this project lies within CDFG Kelp Bed #220. The decline in harvesting in this bed has been attributed to social pressure to
harvest elsewhere, collectivization of harvesting efforts, oceanographic conditions, and abalone facility failures (MBNMS, 2000).

The ecological effects of kelp harvesting are still being analyzed. Kelp harvesters argue that the limited removal of the canopy allows more light to penetrate the bottom, leading to the increase in kelp growth and the resulting amount of kelp availability. Kimura and Foster (1984) conducted a study in which the results supported this concept. Conversely, of all the groups of species that rely on kelp forests as their habitat, invertebrates may be most affected by kelp harvesting. Species of turban snails exhibited significant reductions in harvested areas when compared to non-harvested areas (Hunt, 1977). Studies have estimated that 1/4 to 1/3 of motile invertebrates in the kelp canopy are removed during large-scale harvesting (Quast, 1968). The effect of harvesting on
species attached to kelp fronds is poorly understood, and the Monterey Bay National Marine Sanctuary has begun research in collaboration with University of California scientists to gain a better understanding of these relationships (MBNMS, 2000).

Another factor that is still being analyzed by the Monterey Bay National Marine Sanctuary office is the socioeconomic implications of kelp management policies. They recognize such studies are lacking, and that these studies can determine what the different user groups are (harvesters, divers, etc.), as well as the nature and extent of their activities, perceptions, attitudes and opinions regarding the kelp resource, its use and the conflict (MBNMS, 2000). User conflicts arise between two groups, the harvesters and the recreational users, who use the same areas for similar reasons. Such reasons include easy access, relatively safer conditions than in the open ocean, and kelp availability in winter months when most other areas have had kelp removed by winter storms. Some of the most pronounced user conflicts arise in CDFG Kelp Bed # 220, since the area (and the kelp that grows there) is more protected from winter waves and other sea conditions (MBNMS, 2000).

This capsionte project is to assess the loss of microhabitat defined by water flow velocity as a result of kelp harvesting. The goals of this project are to determine if four microhabitats on kelp are significantly different in terms of water flow. If this is the case, then a unique flow microhabitat at the canopy is being removed due to harvesting. The loss of a unique flow microhabitat may have significant ecological effects and these ecological effects must be carefully analyzed to determine if it is necessary to place stricter regulations on harvesting. While this would have a negative impact on the harvesting industry, it would be beneficial to the ecotourism industry, as well as the
tourism industry, and the ecosystem itself. If no unique flow microhabitat is lost when kelp is harvested, this project serves as evidence to the harvesting industry that they are not distressing the ecosystem and therefore the current restrictions on kelp could be lessened. This would boost their business but would have a negative effect on the ecotourism industry, especially in the winter months when kelp availability is already low due to storms and low growth rates.

A microhabitat is characterized by its difference in environmental variables compared to other parts of the kelp. Such environmental variables include water flow velocity, light availability, nutrient/food delivery, temperature, pressure, salinity, and space. The canopy of kelp may have a high ambient flow, but since it is very flexible, it can "go with the flow" and have a very low flow relative to the surrounding water. Conversely, the holdfast may have a very low ambient flow, but since it is stationary and inflexible, it may have a higher relative flow than found at the canopy. Similarly, the canopy is fully exposed to light, whereas the light may not penetrate through the canopy to reach other kelp microhabitats, and therefore, the light is less intense at depths. Also, organisms that reside in the canopy or along the stipe may have more space, whereas in a holdfast, the same organisms would be competing for limited space. Temperature decreases and pressure increases as depth increases. Microhabitats are defined by integration of these variables. Organisms that reside in a microhabitat must be able to deal with all of the variables in that microhabitat. If just one variable at one position on the kelp is different than at another position, then the two positions are different microhabitats and the difference is defined by that variable. Because these variables may change in different locations on kelp, they each need to be analyzed independently to
determine how the microhabitats might vary. Although, microhabitats are defined by the integration of many different environmental variables, this project focuses specifically on the variable of water flow. Little is known about how environmental variables differ in each of the microhabitats. This project will look at the variable of water flow and determine if it is a defining variable that differentiates the microhabitats from each other. This will lead to a better understanding of kelp and the differences in its microhabitats.

Water motion is a major factor that determines the distribution and abundance of marine organisms (Mathieson et al., 1977). Forces imposed by moving water considerably affect the morphologies, behaviors, life cycles and ecology of marine organisms (Vogel, 1981; Denny, 1993). Kelps exist in habitats that are distinguished by continuous, time varying water motion (Gaylord and Denny, 1997). The advantage that Giant Kelp has in a wave-swept environment is its size and flexibility. Since it is large and flexible, it can “go with the flow” as waves roll through the kelp, reducing the relative velocity and acceleration between the kelp and the surrounding water (Koehl and Wainwright, 1977; Koehl 1984, 1986; Denny, 1988). Some organisms reside in the microhabitats that are protected from incoming waves (Emson and Faller-Fritsch, 1976; Koehl, 1977; Menge, 1978). Others thrive in areas that are fully exposed and receive the full brunt of waves (Ricketts et al, 1985), such as barnacles and mussels, which produce shells and strong adhesives. In this case, the distribution of species is based on the water flow velocity.

Organisms, such as bryozoans, living within the kelp also depend on water flow for filter-feeding and nutrient delivery. Whereas mobile suspension feeders can swim through the water to collect food particles, bryozoans rely on water movement to carry
food resources to their feeding surfaces. If there is not enough water flow, the food or
nutrients the bryozoan needs to survive may not be delivered. All other factors being
equal, increased water flow increases the amount of food available to the bryozoan
(Okamura and Partridge, 1999). An increase in water flow will also result in an increase
in the turbulent mixing of the water, and therefore a reduction in of depletion in food
particles in the water surrounding the feeding surface (Frenchette et al, 1989). However,
too much water flow may cause a decline in feeding rates (Okamura and Partridge, 1999).
This decline is due to a deformation in filtering structures, which reduce surface area for
particle capture, drag effects that reduce efficiency of handling or processing particles,
and adverse pressure gradients that inhibit effective processing of water in feeding
(Eckman and Duggins, 1993). There are many species of bryozoans, as well as
barnacles, gastropods, sponges and anemones (all filter-feeders) that are found in the kelp
forests in Monterey Bay. The distribution of these species would again be based on water
flow velocity.

Water motion produced by storms is also significant. Often times, storms create a
strong surge that will uproot and dislodge an entire kelp plant. Rosenthal et al. (1984)
suggested that when one kelp plant is ripped out from waves, it might become entangled
in other kelp plants. This increases the drag of the group of kelp plants, and causes the
uprooting of more kelp plants. In a study conducted by Harris et al. (1984), the effects of
two severe storms were observed. The first storm started unspecified degenerative
changes that led to the *Macrocystis pyrifera* in the area becoming overgrazed by sea
urchins. The second storm, three years later, decimated the urchin population since the
urchins were grazing on new plant growth and no kelp litter was present for the urchins to
survive on when the storm arrived. This decrease in the urchin population, along with new space opened up by the storm, allowed the kelp in the area to regenerate.

Without water flow, kelp would not receive the nutrients or gases needed to photosynthesize and grow; it would not be able to disperse gametes to other locations (all the kelp would be in one dense area); and the holdfast would be covered in sediment that has settled. Organisms living on the kelp would not receive essential nutrients or dissolved oxygen; non-motile filter-feeding organisms would not receive food; and gametes released by these organisms would settle on the ocean floor, as would waste products. There would be distinct temperature and salinity gradients with depth due to the absence of turbulent mixing. The presence of water flow delivers nutrients, food, and dissolved gases to the kelp and its inhabitants. It facilitates in the successful gamete and larval dispersal and recruitment by mixing the gametes and transporting the larvae to other locations. Water flow removes waste products and sediments that would otherwise settle and bury benthic organisms, as well as kelp holdfasts.

In this study, clod balls (blocks of plaster of Paris which dissolve in flow) will be used to measure water flow velocity. Clod balls are an inexpensive and widely used method of measuring time averaged water flow velocity. Introduced independently by Doty (1971) and Muus (1968), plaster mass loss was shown to be linearly related to mean water velocity (Muus, 1968; Komatsu and Kawai, 1992; Thompson and Glenn, 1994). Results are expressed as a diffusion factor (DF), which is defined as the ratio of weight loss of the clod balls placed in the field to the weight of clod balls from the same batch held under controlled still-water conditions in the laboratory. DF is meant to express the
multiplication factor of diffusion of clod ball exposed to water flow relative to the
diffusion in the absence of moving water (Doty, 1971; Thompson and Glenn).

Methods

Construction of clod balls

The clod balls were constructed according to the methods described by Thompson
and Glenn (1994), with a few minor modifications to fit the purposes of this project. Two
batches of clods were made by mixing commercial plaster of paris (gypsum and
limestone mixture, Custom Building Products) with tap water at a ratio of 2:1, and
stirring with a wooden spoon. The mixture was poured into ice cube trays to get a
uniform shape throughout the clods. The trays were tapped vigorously on a bench top
while the mixture was still liquid in order to dislodge air bubbles. Most of the air bubbles
surfaced after approximately one minute of tapping. After roughly two minutes, an
eyebolt was inserted through a washer and into the plaster. The mixture was then
allowed to harden for thirty minutes. Each individual clod had an eyebolt (Figures 5 and
6).

Figure 3: Clod balls curing in ice cube trays.

Figure 4: Clod balls curing in ice cube trays.
After thirty minutes, the trays were twisted to loosen the clods and then the clods were removed from their molds. The clods were sanded to remove any jagged edges or corners. Two coats of resin (West Systems Fiberglass Resin 105 with a 105 hardener) were mixed according to the instructions on the packaging and applied to the base of the clod. The resin prevented any dissolution from the base of the clod (Leichter and Whitman, 1997; Guichard and Bourget 1998). A serial number was printed on two separate small squares of paper and the squares were sealed into the resin on the base of the clod using second coat of resin. The clods were put into an oven set at 65°C for 24 hours (Porter et al, 2000) to completely dry. When the clods were dry, they were removed, weighed and placed into a sealed bag to ensure that the plaster would not absorb any moisture from the atmosphere.

The clod balls were initially tested to determine approximately how long the clod balls could remain in each of the environments before dissolving completely. This study was conducted in the tide pools in Pacific Grove, California, close to the northernmost tip of the Monterey Peninsula. The study site is on the coastal side of Ocean View Road about 0.2 miles northwest of Lover’s Point Park. The study site is in the middle to high intertidal zone. The experiment consisted of anchoring four clod balls during low tide in the intertidal area: two in a protected area that were protected by rocks from waves, and two in an exposed area that saw a greater amount of water flow. These clods were left in the intertidal area for 24 hours.

A subtidal test was also conducted to determine potential design flaws or possible problems that may be encountered during deployment and retrieval of the clod balls. This test also gave an idea of approximately how much time and air is needed to attach
and retrieve the clods, since the use of SCUBA is required to complete the study. In this
test, four clods were attached directly to the stipe using 4-inch cable ties. Attachment of
the clods using these smaller cable ties was successful, but they were too small to
continue to be used effectively underwater and therefore the modification was made so
that 8-inch cable ties were used. The clods were attached to four locations along the
kelp: one at the holdfast (A), one on the stipe about 2.5 meters from the bottom (B), one
at the curve of the stipe near the surface, just before the canopy (C), and one at the
canopy (D) (see Figure 5). The clods were supposed to be left out for the 24-hour interval
that we had originally projected in the first of the preliminary experiments, but a storm
forced the clods to stay out for 48-hours. The clods were retrieved and examined for
design flaws and possible modifications for the main experiment.

![Diagram of clod placement on Macrocystis pyrifera.]

Figure 5: Diagram of clod placement on Macrocystis pyrifera.

The site for the study (as well as the test of the experimental design) was
MacAbee Beach (see Figure 2), just off of Cannery Row in Monterey, California. The
beach sits on Monterey Bay facing north. The seafloor substrate is rocky with some large
patches of sand. There are also large steel pipes that run along the seafloor perpendicular
to the shore. These pipes, which are remnants of the old canneries, facilitate the growth
of kelp at the site because they provide a hard substrate to which the holdfast can attach. The specific site was marked by a permanent white buoy and the pipe that the buoy-line intersects at the bottom. The two kelp plants studied (Kelp A and Kelp B) were in the vicinity of this intersection. The depth at that area was about 8 meters (24 feet).

Using SCUBA, the clods were fastened to the kelp with 8-inch cable ties in four places (see Figure 5). The location of each clod along the kelp was recorded on a dive slate as the clods were being attached. The clods were deployed midday, without regards to tidal height. Therefore, the clod at the curve may be completely submerged during high tide and part of the canopy at low tide. This discrepancy, however, is representative of what organisms which reside in this microhabitat may experience in terms of large variations in flow over different parts of the tidal cycle. The clods at all other positions were less affected by the variations in tidal height during deployment. The clods were left in the field for a 48-hour time interval, after which the clods were removed, rinsed with distilled water for about 5 seconds, dried in an oven as done previously, and reweighed. Weights (both prior and after) were recorded in the lab. All data was collected and maintained by referencing the serial numbers of the clods, and was entered into an Excel spreadsheet.

The pH of the water at each microhabitat was also tested to determine if there were any variations in pH that could cause variations in dissolution of the plaster. A water sample was collected at each microhabitat on each kelp, and was brought back to the lab and tested with pH Paper.
Obtaining the diffusion factor

One clod from each of the batches was put in a still water bath as a control. The bath was created by putting 40 liters of seawater into a plastic tub. Jokiel and Morrissey (1993) found that weight loss increased with a calibration volume increasing up to 20 liters (per 50-gram clod) after which there was little variation in weight loss with increasing water volume. This is most likely because the dissolving solid saturates the calibration water, which will prevent further dissolution. The water for the still bath was fresh water mixed with Instant Ocean so that the salinity (measured with a hand-held CTD) was 33.2 psu, which is the salinity of nearshore waters under normal conditions in Monterey Bay (MBNMS, 2000). Jokiel and Morrissey (1994) calibrated the effects of salinity over increments of 5 psu and found a small decrease in the amount of weigh loss between 30 and 35 psu. The salinity in Monterey Bay has a range of approximately 0.9 psu (between 33.1 and 34.0 psu), and therefore, any variations in salinity between the still bath and the field experiments are considered to be negligible. The bath was set inside a large aquarium full of water, and the temperature of the bath was controlled at 11°C by a temperature regulator on the aquarium. The two clods were placed in the bath for 48 hours, after which time they were removed, rinsed with fresh water for about 5 seconds, dried in the oven at 65°C, and reweighed. The ratio of plaster weight loss in the field to plaster weight loss in the still water bath (DF) was calculated for each data point collected from the field, and recorded onto a spreadsheet.

Calibration using a flow tank

A flow tank was used to get dissolution rates for the clod balls in steady unidirectional flow. This gave a crude estimate as to the velocity of the flow regime in
the field. The estimate is rough because in the field there is a multidirectional flow, whereas the flow in the tank is unidirectional.

The tank was constructed from acrylic Plexiglas that was 48 inches long by 6.5 inches wide by 10 inches high on three sides with a 6-inch high spillway on one end. The tank was braced on the top by four 2 inch long sections of acrylic that stretched across the width of the tank (refer to Figure 6).

![Diagram of flow tank](image)

Figure 6. Diagram of flow tank.

The acrylic was bonded together by acrylic cement and was made watertight using a silicone sealant. Layers of plastic drinking straws were placed in the middle of the tank using the silicone sealant. The purpose of the straws were to create laminar flow. The water used was fresh water mixed with Instant Ocean in the same manner as the still water bath. The water was circulated using a Rio 3100 Powerhead pump (with adjustable pump speeds) and was allowed to pass over the spillway into a temperature-regulated aquarium (with a constant temperature of 11°C), from which the water was pumped back into the tank. The flow velocity was determined by how long it takes a particle suspended in the water to travel 0.5 meters. One clod from each batch was placed in the same area where the velocity was measured for 48 hours, after which time
they were removed, rinsed with fresh water for approximately 5 seconds, dried in the oven at 65°C, and reweighed. This calibration was done at three different velocities.

Data Analysis

The diffusion coefficients at different locations along the stipe were compared using a paired T-test to determine if the microhabitats were significantly different. Approximate flow speeds were extrapolated for the field measurements from the relationship of the rates of dissolution between these three flow speeds.

Results

Figures 7 and 8 show the diffusion factors on each kelp over five separate 48-hour increments. The holdfast is the position with the highest diffusion factor in all cases. The other positions fluctuate and no distinct pattern can be determined. The first four points on each figure were taken from the tank experiment to compare with the field flows.

Figure 7: Diffusion factor at each position on kelp A for each test period.
Individual paired t-tests were conducted to compare each of the four microhabitats to determine whether there was a significant difference in the diffusion factors (Table 1). The results of those tests show that the canopy has a significantly different diffusion factor from the holdfast, but not from the rest of the kelp. The holdfast has a significantly different diffusion factor from the other microhabitats.

<table>
<thead>
<tr>
<th>Comparison</th>
<th>t</th>
<th>p-value (t&lt;sub&gt;0.05&lt;/sub&gt;)</th>
<th>Result</th>
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</thead>
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<tr>
<td>Holdfast vs. Canopy</td>
<td>4.48</td>
<td>3.250</td>
<td>Reject H&lt;sub&gt;0&lt;/sub&gt;</td>
</tr>
<tr>
<td>Holdfast vs. Curve</td>
<td>4.93</td>
<td>3.250</td>
<td>Reject H&lt;sub&gt;0&lt;/sub&gt;</td>
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<tr>
<td>Holdfast vs. Stipe</td>
<td>6.80</td>
<td>3.250</td>
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<tr>
<td>Stipe vs. Canopy</td>
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<td>3.250</td>
<td>Do not reject H&lt;sub&gt;0&lt;/sub&gt;</td>
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<tr>
<td>Stipe vs. Curve</td>
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<td>3.250</td>
<td>Do not reject H&lt;sub&gt;0&lt;/sub&gt;</td>
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<tr>
<td>Curve vs. Canopy</td>
<td>0.06</td>
<td>3.250</td>
<td>Do not reject H&lt;sub&gt;0&lt;/sub&gt;</td>
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</table>
Figure 9 shows the relationship between water velocity and the diffusion factor. This relationship was determined by placing clods in known velocities in the flow tank. By conducting a linear regression on this relationship, an equation was obtained to quantify the relationship between flow velocity and weight loss. The data from the tank show a 91.1% ($r^2=0.8291$, $r=0.911$) correlation for this linear relationship between tank velocities and DF obtained from clods submerged in the tank.

From this linear relationship, the time averaged flow velocities in the field can be estimated based on their diffusion factors, since the relationship is linear until about 30% of the initial weight is lost (Jokiel and Morrissey, 1993). Table 2 shows the estimated average flow velocity for each microhabitat based on the average diffusion factor for that microhabitat.
Table 2: Approximate average flow velocities extrapolated from equation in from linear regression of tank DF values ($y=46.482x+1.134$; where $y$=DF and $x$=velocity).

<table>
<thead>
<tr>
<th>Canopy (surface)</th>
<th>Curve (~0.5 m deep)</th>
<th>Stipe (~5.5 m deep)</th>
<th>Holdfast (~8 m deep)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. DF</td>
<td>Avg. Velocity (m/s)</td>
<td>Avg. DF</td>
<td>Avg. Velocity (m/s)</td>
</tr>
<tr>
<td>9.56</td>
<td>0.181</td>
<td>9.54</td>
<td>0.180</td>
</tr>
</tbody>
</table>

Figure 10: Correlation between initial weight (relative to surface area) and amount of weight loss.

Figure 10 shows the correlation between initial weight and the amount of weight lost in the field. This correlation was performed to determine if the initial surface area (which is proportional to the (initial weight)$^{3/2}$) had a substantial effect on the amount of plaster dissolved. Figure 10 shows a very poor correlation ($r^2=0.057$; $r=0.239$) between surface area and weight loss. Therefore, the difference in surface area did not have a noticeable effect on the amount of plaster lost.

From the water sample collected at each microhabitat, there were no differences in pH between the different microhabitats. Every water sample had a pH of 7. Therefore, pH had no effect on the amount of weight loss.
Discussion

Many parameters are important when determining evaluating a microhabitat. Due to its physical/biological/ecological importance to the kelp forest ecosystem, this study focuses on parameter of water flow. The results of the statistical tests show that there is a significant difference between some of the four microhabitats in Giant Kelp, but not others. The results of this study have shown that the diffusion factor at the holdfast was significantly different from the other microhabitats. Since the diffusion factor is directly related to the water flow velocity, the water flow at the holdfast was significantly different from the stipe of the kelp, the curve of the kelp directly under the canopy, and the canopy. However, the canopy is not one of the flow microhabitats that are significantly different, and therefore unique flow microhabitat is not directly lost because of kelp harvesting. There are likely to be individuals from the same species residing in the canopy as in the curve or the stipe of the kelp for flow reasons and therefore harvesting won’t remove all of the individuals in this species or leave the surviving individuals without suitable habitat. However, these organisms may not be able to inhabit other microhabitats due to a significant difference in variables other than water flow, such as light or nutrient availability, yet that exceeds the scope of this project. More research needs to be conducted to determine if there are significant differences between the four microhabitats in other defining environmental variables. One example of such research is to set light sensors with dataloggers at each of the microhabitats and determine if there is a significant difference in the light availability at each microhabitat. Also, although unique habitat is not directly lost due to harvesting, organisms that inhabit
the canopy at the time of harvesting are completely removed from the ocean with the kelp.

Estimated average flow velocities supported the results from the statistical tests by showing that the holdfast had a much higher average flow velocity than the other three microhabitats. This is a rough estimation, however, because it is an estimation of a multidirectional flow based on a unidirectional flow calibration.

Weakness in the data collected also exists in the variation in initial clod weight. The weight of the clod is proportional to the volume, which is proportional to the surface area, since the densities of the clods were uniform. Since some clods had a greater weight than others did, those clods also had a greater volume and surface area. This may lead to a greater amount of weight loss in the larger clods due the greater amount of surface area exposed to water flow. There are two ways that this error can be corrected.

The first is through mathematical analysis. The initial weight is proportional to the initial volume, since clod densities are uniform.

\[ \text{Volume} \propto \text{Weight} \]

The ratios of length to area to volume are:

\[ \text{Length} = \text{Length}^1; \text{Area} = \text{Length}^2; \text{Volume} = \text{Length}^3. \]

Therefore, these ratios can be used to calculate a percent difference in surface areas.

\[ ((\text{Volume})^{1/3})^2 \propto \text{Area} \Rightarrow (\text{Weight})^{2/3} \propto \text{Area}. \]

To determine the ratio of the surface areas between two clods:

\[ (\text{Weight clod}_1/\text{Weight clod}_2)^{2/3} = (\text{Area clod}_1/\text{Area clod}_2). \]

The second method to correct the data is to sand the clods until they are all about the same weight (within 1.5 grams of each other). This method has been used in some
studies, such as Thompson and Glynn (1994). This practical method, although tedious, can result in less error in the data when factoring in the eyebolt, washer, and resin in and on the clod. This alters the shape and density and would be difficult to correct using a mathematical method. With all components considered, sanding would be the easiest method in correcting for variations in surface area.

In this study, however, the physical correction was not conducted because this issue was not considered until after the data was collected and the mathematical correction was not done because of the addition of the resin, eyebolts and washers to the clods. A linear regression was performed (Figure 12) to determine the correlation between the initial volume and the amount of weight lost. The correlation was poor (23.9%), so difference in surface area did not have a noticeable effect on the amount of plaster lost. However, the variation in surface areas of the clods in an issue that should be accounted for in future studies so that errors in the data are minimized.

The data from many other studies using clod balls is quite different because in some studies electronic flow meters have been used side by side with the clods and the data collected from the flow meters was used to calibrate the clods (Mathieson et al, 1977; Leichter and Whitman, 1997; Guichard and Bourget, 1998). In other studies, experiments have been conducted in the labs under a controlled setting with known flow velocities (Gerard, 1982; Thompson and Glynn, 1994). Gerard (1982) used plaster buttons to determine a correlation between water flow and nutrient uptake by *Macroystis pyrifera* and the diffusion factors in that study were much lower than in this project because the buttons weighed two grams whereas the clods weighed between forty to fifty five grams, which is a massive difference in terms of surface area available for
dissolution. Jokiel and Morrissey (1993) calibrated the control clods in different temperatures, salinities, volumes of water, and over different amounts of time. Their field studies measured water flow over coral reefs and had similar resulting data from the clods, however they extrapolated the diffusion factor over a continuous depth using a regression of the diffusion factor and depth. The diffusion factors were also lower than were in this capstone project but the study was conducted in a protected lagoon where flow was not as strong. They also obtained diffusion factors in the breaker zone of an ocean reef, which are very similar to the diffusion factors obtained in this capstone project. No other studies of water flow at different parts of Macrocystis pyrifera could be found to compare the results of this study to, although one study by Wheeler North, where similar work using clods to measure water flow in kelp forests, was suggested but could not be found.

This project was created by an integration of many previous studies. Although water flow with the kelp forest is often studied, as well as the effects of water flow on kelp (and vice versa), the variations between kelp microhabitats had not been previously looked at. We now know that water flow velocities at the holdfast are significantly different and the stipe, curve, and canopy of kelp are similar. Past studies were modified and combined to create a design that would accurately determine if there were significant flow differences in kelp flow microhabitats. Such modifications included creating clods large enough to be left in the field for more than 24 hours, as well as creating a design for the construction and attachment of the clods so effective, that none of the clods were lost while in the field.
Based on the time averaged data collected in this study, the holdfast is the only microhabitat that has a unique water flow regime, and it is unknown whether it is directly or indirectly affected when the canopy is removed during harvesting. An observation made by Miller and Geibel (1973) suggested that harvesting might weaken the holdfast, making it vulnerable to being uprooted by storms. The Monterey Bay National Marine Sanctuary (2000) is unable to locate any studies that analyze the effect of kelp harvesting on kelp forest benthic invertebrates. MBNMS expresses the need for further research on the effects of kelp harvesting and harvesting alternatives on kelp forest ecology, specifically the effects of harvesting on the holdfast microhabitat, as well as an examination of characteristics of that unique flow microhabitat other than water flow velocity.

The results of this study do not suggest an immediate change in policy because based on flow, the canopy is not a significantly different microhabitat. However, differences in the other environmental variables should be determined before any recommendations are made. This is because if the canopy is significantly different than the other microhabitats in terms of just on of these variables, then it can be regarded as a unique microhabitat, because there exists a unique combination of environmental variables that does not exist anywhere else on the kelp and organisms may require that combination of variables to survive. For example, if studies conducted found that there are significant differences in light availability in the different microhabitats, but all other variables were the same, then policies should be modified to limit the amount of the canopy harvested from four feet to two feet, to ensure that some of canopy still remains after harvesting. If future studies reveal that harvesting does in fact weaken the holdfast
of the kelp, the greater restrictions should be implemented to ensure that the holdfast is not weakened to the point where it could be removed in the event of a storm. The results of my study alone are not adequate to recommended changes in policy, but I feel that my work can be effectively combined with the future work of others to make informed policy decisions that will benefit all stakeholders involved and preserve the ecosystem at the same time.

A cost-benefit analysis of kelp harvesting and kelp management alternatives should also be conducted to get a better understanding of the socio-economic aspects of this issue. By combining the understanding of ecological effects gained by scientific research with the socio-economic aspects of this environmental issue, policymakers (CDFG and NOAA/MBNMS) can make the most informed decision of how to best manage kelp resources.

One kelp management alternative that the Monterey Bay National Marine Sanctuary (2000) has recommended to the California Department of Fish and Game is a proposed no-take zone, similar to Hopkins Marine Reserve, be designated in part of CDFG kelp bed #220. This area could be used as a scientific comparison to harvested areas. This capstone project can be duplicated in this no-take zone to compare the harvested and non-harvested sites to determine if harvesting has a significant effect on water flow in the different microhabitats. It could also be used as a recreational area, so that SCUBA divers and kayakers would have an untouched recreational site, which could sustain business at dive and kayak shops year round. Harvesting outside of the designated area could still occur, which would sustain businesses relying on harvesting. This would somewhat ease tensions created by the user conflict issue discussed earlier. If
harvesting outside of this area begins to have a significant impact on the availability of habitat to those organisms that live outside this area, then this area could serve as a refuge to those organisms.

Other alternatives to kelp management should be explored. The development of an alternative food source for aquaculture facilities would lessen their dependence on the harvested kelp, which would benefit the ecotourism industry and ease the user conflict present in the kelp beds. For the aquaculture facilities, there may be a substantial development cost, but a cost-benefit analysis could be conducted to determine if it would be worth it in the future to invoke these costs now. All the facilities in the area could also split the development costs because the outcome would be beneficial to all corporations involved. Also, MBNMS (2000) has recommended that CDFG put a cap on the total annual amount of kelp harvested from a bed to 50% of that bed’s total maximum canopy cover. This would require harvesters to continue to declare the amount of kelp taken per harvesting trip, and for either MBNMS or CDFG to keep a database to closely monitor how much of the canopy in each of the kelp beds has been harvested. This would allow for the continuation of harvesting but would prevent the depletion of the resource. Another alternative is to minimize the length of a canopy that can be harvested to five or six feet, since harvesters are only allowed to harvest the top four feet of the canopy. This would leave one or two feet of visible canopy. The purpose of this would be twofold. The first would be to ensure habitat for canopy dwelling organisms. The second would be to maintain a visible canopy to attract tourists and to help the dive and kayak shops in the area, especially during winter months when the availability of kelp is limited due to storms and lower growth rates.
The next step in this study would be to set out electronic flow meters in the different microhabitats to obtain high-resolution data in order to analyze the fluctuations in water flow velocities over time. This methodology would be superior to using the clod balls because it allows for deployment over a longer period of time, thus decreasing travel costs and conserving valuable time because the number of visits that must be made to the site have decreased. Moreover, the data collected will be high-resolution data that would measure peak flow velocities, which may be significantly different in the four flow microhabitats, and these peak velocities may be the factor that limits some of the presence of certain organisms, as opposed to the time-averaged data collected by the clod balls. Thermistor flow meters (Appendix 1) would be an inexpensive way of collecting this high-resolution data. A thermistor flow meter was partially constructed for this study, but due to time restrictions, the circuit was never fully debugged and calibrated. Using this technology to gather high-resolution data would be an optimal way to continue and expand this study.

In any case more research is essential in order to correctly determine the effects of kelp harvesting on a kelp forest ecosystem and make policy decisions that are well informed and are beneficial to all stakeholders in the issue. This project has been a step in that direction.

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**Literature Cited**


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Miller, D J. and J. J. Geibel. 1973. Summary of blue rockfish and lingcod life histories; a reef ecology study; and Giant Kelp, *Macrocystis pyrifera*, experiments in
Monterey Bay, California. *California Department of Fish and Game Fish Bulletin* 158:1-138.


Appendix 1: Circuit diagram of thermistor flow meter at the completion of this project. The circuit is still under construction.

Appendix 2: Flyer printed by The Friends of the Edward F. Ricketts Marine Park regarding a public meeting of the Department of Fish and Game concerning kelp harvesting on April 6, 2001.
Appendix 1: Circuit diagram of thermistor flow meter at the completion of this project.

Component | Value
---|---
R₁ | 240 Ω Resistor
R₂ | 10k Ω Trimpot
R₃ | 5k Ω Trimpot
R₄ | 4.7k Ω Resistor
Tₛ | 250 Ω Thermistor
Tₖ | 5k Ω Thermistor
Dear ESSP Faculty,

This capstone project is designed to identify different water flow microhabitats in the kelp forests off the coast of Monterey, California, and assess the potential loss of the canopy microhabitat due to kelp harvesting.

This project is significant because there are many groups that value the kelp forests. Kelp is harvested for its chemical components as well as for food for abalone farms. Outdoor recreation shops in the Monterey Peninsula depend on the intrinsic value that divers, kayakers, and other ecotourists place on the kelp forests to maintain a successful business. Many different species depend on the kelp forest as their habitat. Agencies such as the Monterey Bay National Marine Sanctuary and the California Department of Fish and Game are trying to balance the economic and ecological importance of kelp by recommending and developing policies, such as the Monterey Bay National Marine Sanctuary Final Kelp Management Plan. This project is for anyone who values the kelp forests and for the agencies that are trying to regulate activities in the kelp forests (see Appendix 2).

This project serves as another factor to be weighed when considering policies regarding kelp harvesting. If this project shows that a unique flow microhabitat is lost when kelp is harvested, then policymakers should take a more critical look at what the effects of the loss of that flow microhabitat have on the rest of the ecosystem. They might subsequently place more restrictions on kelp harvesting if its effects are found to be detrimental to the ecosystem. Such restrictions will lead to sustained business for the local dive and other outdoor recreation shops, as well as the tourism industry, which is largely based on the health of the kelp ecosystem and its most charming resident, the sea otter. Such policies will be beneficial to the tourism and ecotourism industries (and the ecosystem itself) but it will be detrimental to the kelp harvesting and abalone aquaculture industries, which rely on harvested kelp for their livelihoods. However, if no unique microhabitat is lost when kelp is harvested, then harvesters will have evidence to lessen restrictions on harvesting, which would be beneficial to the harvesters and abalone farms. This would be damaging for tourist/ecotourist industries because it would appear that there is no kelp left in the area, when in fact there is kelp right below the surface.

During the course of this project, I have had to work with many members of the surrounding community. I discussed my construction design with sales associates at local hardware stores, requested a large amount of information from the Monterey Bay National Marine Sanctuary regarding kelp harvesting in the sanctuary, and consulted with local dive shops about daily dive conditions. However, majority of collaboration that I did was with students and staff in ESSP.

I believe that sustainable use of a natural resource is ethical. However, as a SCUBA diver, I hold an intrinsic value to the kelp forests, and therefore, I believe that the amount of kelp removed from the forests should be limited to an absolute minimum. I chose this project because of the value that I place on the kelp forest and my desire to see that this is a resource that is conserved not just for future monetary value, but also for its beauty and biodiversity. This project has reaffirmed these values and beliefs, but it
has also forced me to acknowledge that I use products that contain the chemicals found in kelp, and therefore realize that kelp harvesting is essential.

This capstone project should be assessed in the Application of Knowledge in the Physical and/or Life Sciences (MLO #3) Area of Depth because it integrates concepts that exhibit physical-biological-ecological interactions within the kelp forest. It should also be assessed in the Acquisition, Display, and Analysis of Quantitative Data (MLO #5) Area of Depth because it implements the scientific method to collect, analyze, and synthesize quantitative data, and the data collected are applied to the further analysis of an environmental problem.

Respectfully,

Mary A. Wackerman