Optimizing Pickleweed Habitat In Degraded Estuarine Marshlands: Should Estrada Marsh be Opened to Natural Tidal Conditions?

A Capstone Project
Presented to the Faculty of Earth Systems Science and Policy in the College of Science Media Arts and Technology at California State University, Monterey Bay in Partial Fulfillment of the Requirements for the Degree of Bachelor of Science

by
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Preface

Over the last hundred years, the number of coastal estuaries has declined to only 10% of their former numbers. As a result of this, coastal marshland restoration is rapidly becoming a forefront issue. However, there has yet to be a consensus on the best method for restoring estuarine salt marshes.

Coastal estuaries provide important functions within coastal ecosystems. They are one of the gateways to our nation’s oceans, allow for bird rookeries, cycle nutrients and are home to endangered and endemic species, such as Salicornia virginica. Which is a perennial halophyte whose growth function has been reported to be optimized at .13 m for its lower elevation limits above mean high water (MHW) and .42 m for its upper elevation limits above MHW. Locally, the Elkhorn Slough is home to one of the nation’s last and largest populations of the endangered pickleweed, and an effort has begun to restore Estrada Marsh to its once former state.

To date, the Elkhorn Slough is managed by the Elkhorn Slough National Estuarine Research Reserve (ESNERR), owned and partially funded by the California Department of Fish and Game (CDGF) and funded primarily by the National Oceanic and Atmospheric Administration (NOAA). Because of the complex levels of oversight, ESNERR has to comply with various state and federal regulations that dictate how their management options are implemented and maintained, such as the McAteer-Petris and the Endangered Species acts.

This study is an analysis to determine the present vertical elevation of Estrada Marsh with respect to mean high water (MHW), and provide stakeholders with several management scenarios in which to maximize habitat for Salicornia virginica. The results
of this study will be the foundation for the Elkhorn Slough National Estuarine Research Reserve so they can best implement management options to restore the Estrada Marsh.

I initially began this study as a continuation of a previous project in which I began a health survey of *S. virginica* in Estrada Marsh. My assessment of Estrada Marsh led me to the conclusion that the pickleweed that inhabited the marsh was stressed, and on the verge of collapsing. This was an initial bias that I had. However, that work blossomed into an opportunity to stay on with ESNERR as a research volunteer to help collect baseline data needed for the restoration of Estrada Marsh, and to hopefully one day see this particular piece of marshland be restored.

I highly value the coastal ecosystems that are only sparsely populating the coast of California. It is not only based on the reasoning that these ecosystems are valuable, but also because these unique ecosystems provide an intrinsic, aesthetic value that is important to the vitality of this region.
Abstract:

California coastal estuaries are among the most valuable ecosystems in the world. They provide faunal nurseries, pollution control and are home to endemic, endangered species, such as *Salicornia virginica*. Recently, the Elkhorn Slough National Estuarine Research Reserve initiated a restoration project for Estrada Marsh with a management goal of optimizing pickleweed habitat. In order to establish restoration protocols, baseline data had to be collected in the form of: LIDAR obtained from the National Oceanographic and Atmospheric Administration, RTK GPS, total station and rotating laser surveys. And, in turn, Arc GIS and Fledermaus software was used for analysis. The data show that Estrada Marsh is significantly lower than mean high water given several scenarios. There is no difference in the upper and lower elevations of pickleweed in either North or Estrada Marsh (upper: p = 0.542, n = 40) (lower: p = 0.262, n = 40). It was found that the upper and lower colonizing limits in Estrada are 0.807 m and 0.607 m respectively, and 0.783 m and 0.573 m for North Marsh above mean sea level. It was also found that North Marsh had a higher water height than Estrada Marsh on October 9th and 10th of 2004 $\mu = 0.627$ m ($p = 0.000$, n = 30).

Based upon these new data, pickleweed habitat will be optimized by removing the elevated berm separating Estrada and North Marsh.
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1 Background

1.1 General Ecological Problem

Human evolution has led to a species that has had a significant impact its landscape. In doing so, humans have directly, and indirectly, displaced countless numbers of floral and faunal species. More specifically, throughout history humankind has always migrated to the coasts in great numbers because of itsbeckoning seaports that support trade and life, the abundance of food sources and temperate living conditions (Haviland, 1999). However, if one species enters an ecosystem en mass, then the net result is to displace other species (Molles, 2002).

Due to human encroachment, the United States has seen a significant decline in the number of coastline ecosystems. As humans began to migrate towards the coasts for better life opportunities or to establish trade routes with other countries, the coastal ecosystems fell victim to advancements in human progression, such as altering the landscape for agricultural or industrial usage. To date, the area of coastal estuaries has fallen to a mere ten-percent of their once former numbers one hundred years ago (Marcus, 2000). At one point, the State of California had thriving salt marshes that were located along its beautiful coastline, but most of these habitats were converted from prolific salt marshes to human related environments, such as houses, farmland or cattle grazing (VanDyke, 2003).

Salt marshes are a unique coastal ecosystem. They are found in estuaries; an estuary is an environment that is exposed to inundation by both saline and fresh water
(Cearreta et al., 2001; Williams et al., 2002). The fresh water is typically generated from an incoming stream or river, and the salt water is generated from the ebb and flow of tidal cycles from the ocean. These unique ecosystems are home to species that have to be able to survive in an environment that can cycle through saline and fresh water conditions, for example, *Salicornia virginica* (pickleweed) (Fig. 1).

Pickleweed is a succulent, perennial halophyte that is bright red from August to November and greenish-grey during the rest of the year. It is a shrub that can reach heights up to 40 cm (Davy 1958) with a root system that generally does not penetrate less than 20 cm below the surface (Seliskar 1985), and it is found throughout much of the mid to upper intertidal zone in a natural marsh system (Page 1997). Seliskar (1985) found pickleweed elevation range to be a narrow elevation band between 0.13 m and 0.42 m above mean high water in a salt marsh fringing Netarts Bay in the Pacific Northwest. Instead of excreting salt once it is consumed, pickleweed stores the salt uptake in its upper segments; pickleweed gets its name from the many green segments that resemble small pickles. And, once a segment has taken up enough salt, the segment falls to the ground providing possible material to the detrital carbon and nitrogen pool (Page 1997).
The coastal marshlands located in the Elkhorn Slough were once rich, fruitful habitats for native coastal species. The same soil composition that made these marshlands so productive, also made them prime real estate for industrial and commercial development (VanDyke, 2003). The soil structure of these marshlands is such that they are plentiful with nutrients and favorable to sustaining plant life (Marcus, 2000). And, because of this richness, the marshlands were easily converted to agricultural use by simply diking and draining the land (VanDyke, 2000). It was an ideal situation for allowing the future expansion of human integration into a coastal ecosystem. These actions would lead to the inevitable reduction of once vital habitat to almost critically
levels. However, the process of reducing the landscape is not permanent. It can be re-altered to reflect a managed or natural vital habitat.

Coastal marshlands lying close to sea level can be very sensitive to vertical elevation changes. It has been hypothesized that some species of vegetation will suffer detrimental consequences if the vertical elevation changes as little as two to three centimeters (VanDyke, 2003). Given that a viscous under layer of mud primarily supports these areas, marshlands are susceptible to subsidence once they are diked and drained (Marcus, 2000). An analogous situation would be the swelling and shrinking of a sponge as it soaks and dries. Remove access to water by the sponge, and it will begin to desiccate and deflate. If water is no longer available to expand the marshland substrate, it will begin to dry out, compact under its own weight, and the marsh surface will subside to a lower elevation (Marcus, 2000). The motivating factor in current salt marsh restoration on the California Coast is the McAteer-Petris act of 1960. This piece of legislation states, “There would be no more net loss of tidal wetlands.” This simple piece of legislation has fostered the regeneration of coastal ecosystems.

1.2 Governmental Influence

Within the last century, efforts in conservation, rehabilitation and restoration have had a significant impact on the environment and the rules and regulations that govern it, such as the endangered species act and the McAteer-Petris act (Williams et al., 2002). State and national parks, sanctuaries and reserves were set up to counter the effects of habitat encroachment by humans and pollution. These agencies have been responsible for efforts like reintroducing the wolf back into Yellowstone National Park (Watson, 2004), maintaining a small population of Giant Sequoias (Molles, 2002), leaving areas
undisturbed to progress and reclaiming and restoring once converted land to an approximation of its once former state.

The basic concept of restoration is to re-establish an object, area or space to its original configuration. The idea of restoring land is the same. However, it can be very difficult in some cases to restore converted land, because there may not be any records of the area in antiquity, the landscape may have been forever altered (rock quarries), the area may be contaminated (the coast of Alaska where the EXXON Valdez spilled millions of barrels of oil) or the techniques may not have been fully developed (salt marsh restoration) (Williams et al., 2002; Marcus, 2000; VanDyke, 2003).

1.3 **Local Problem**

The oversight of Elkhorn Slough (Fig. 2) can have complex levels (Fig. 3). For instance, the Elkhorn Slough National Estuarine Research Reserve (ESNERR) maintains and performs research on the property, the California Department of Fish and Game (CDFG) manages the reserve and is primarily funded (approximately 70% ) through the National Oceanic and Atmospheric Administration (NOAA) (Fig.3). The many levels of input that support and maintain this property is an interesting intertwining of both state and federal governments attempting to influence the goals of the Elkhorn Slough, itself. The California Department of Fish and Game oversees all of the local issues as it pertains to the state of California. However, since certain species that reside in the Elkhorn Slough are on the federal endangered species list (*Salicornia virginica*), NOAA oversees the federal aspects of the Reserve. Also, NOAA manages the Reserve’s footprint. Despite a complex managing system for the Reserve, the overall collaborative goal is restoring and maintaining the Elkhorn Slough.
Fig. 2: A map depicting where the Elkhorn Slough is in California. North is toward top of map.
Figure 3: Conceptual systems diagram showing relationships amongst stakeholders and their influence.

Key:
Present = _______
Future = ________ or options

Taxpayers

California Dept. of Fish and Game (Providing roughly 30% of funding)

NOAA (Providing roughly 70% of funding)

Donations provided by visitors

Elkhorn Slough National Estuarine Research Reserve (ESNERR)

Managing and research capabilities

ESNERR’s influence over Elkhorn Slough and salt marshes (North and South Marsh)

ESNERR’s influence over Estrada Marsh

Research carried out to maintain and restore the slough (this study 2004)

Estrada is under ESNERR’s influence

Healthy and productive coastal ecosystem

Restoration of Estrada Marsh

Attempting to incorporate Estrada Marsh into ESNERR’s footprint

Estrada Marsh (currently outside of ESNERR’s managing capabilities)
In the late eighteenth century, the marshes at Elkhorn slough were diked and drained by a railroad company allowed train tracks to be laid for intrastate commerce and travel (VanDyke, 2003; Fig. 4). In order for this to happen, the railroad company built a semi-permanent elevated railway bisecting the slough and the marshes, effectively cutting the marshlands off from tidal access and removing vital habitat from the marsh’s species (VanDyke, 2003). However, the Estrada marsh was somewhat protected by a single owner for many years. The land was used primarily as The Elkhorn Country Club (Fig. 4 and Fig. 5). It was then used agricultural use, possibly strawberries or lettuce. And, lastly, it was used for cattle grazing. In the mid-1990’s, the northernmost tip of the slough, the Estrada Marsh (Fig. 4 and Fig. 6), was acquired by the State of California from the Estrada family for possible rehabilitation (VanDyke, 2003).
Figure 4: Schematic timeline of past and possible future events affecting Estrada Marsh.

- **Present**
  - Southern Pacific Rail Road Company installs railroad through Elkhorn Slough (1870)
  - Coastal salt marshes sold to private owners
  - Salt marshes segmented as private property

- **Future**
  - North Marsh is separated from Estrada via a transecting berm
  - Estrada Marsh is diked and drained to be used as commercial property
  - Estrada Marsh is converted to agricultural fields and pastureland

**Management options**
- Leave Estrada alone, i.e. no human restoration attempts
- Managed tide gates
- Insert two channels to Estrada (leaving berm intact)
- Remove berm, allowing managed flow from North to Estrada Marsh to be controlled by road elevation
- Reconnect to full tidal cycles of Elkhorn Slough
- Estrada is independent of North Marsh

**Options**
- North Marsh is restored to a managed marshland
- A channel with a tide gate from Elkhorn Slough is connected to North Marsh (1950)

**This study (2004)**
- Estrada Marsh found to resemble a managed marsh rather than a natural marsh

**Key**
- Present = ______
- Future = ______ or options
Fig. 5: A survey map of Estrada Marsh, North Marsh from 1920 when it was used as a hunting club.
1: Estrada Marsh
2: Berm separating Estrada and North Marsh
3: North Marsh 4: Elkhorn Slough Main Channel

Fig. 6: Aerial photograph of Estrada Marsh and North Marsh taken in April 2003.
1: Estrada Marsh 5: Kirby Park
2: Berm 6: Elkhorn Slough Main Channel
3: North Marsh 7: Elkhorn Road
4: Railroad and Berm
Currently, there is not a systematic approach to restoring salt marshes for the sustainability of coastal floral species such as *Salicornia* (Molles, 2002; Williams et al. 2002). In some cases, there might be a succession of managing entities that believe that their restoration methods are more suitable than their predecessors (Williams et al., 2002). The net effect is that different approaches are taken to restore the same piece of property with each new effort affecting the results of the past efforts. In the most extreme situation, salt marsh restoration can take up to 15 years or more to take affect (Molles, 2002; Williams et al. 2002). On the other hand, given such a lengthy time line for restoration, incorrect initial methods may have been implemented and found to be unproductive. In the San Francisco Bay, for example, the first generation of methods called for a direct influence by humans to restore salt marshes, and the second method, called for a “hands-off” method to assess if “mother nature” would do a better job (Williams et al. 2002).

**1.4 Project Goals**

The net goal of ESNERR is to restore Estrada Marsh to a vital habitat that will one day support healthy *Salicornia virginica* (Fig. 4). It has been reported that the upper growth elevation limits for pickleweed are 0.42 m and lower growth limit is 0.13 m above mean high water (MHW)* (Seliskar, 1985). However, before restoration can begin, data such as the current elevation of Estrada Marsh and with respect to MHW be established (Fig. 3). By determining the present topography of Estrada Marsh, a systematic assessment can be made to ascertain the best method to restore the marshland back to a fruitful habitat. For instance, stripping the marshland and using dredged fill as an elevation buffer or allowing small pockets of tidal water to soak the marsh

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*Note: All elevations are reported as meters above mean high water (NAVD88), unless otherwise indicated. See appendix I for data taken from NOAA tidal gauge at Elkhorn Road B.*
resedimentation can occur over time (Williams 2002), thus elevating the marsh. For instance, the North Marsh (located next to the Estrada Marsh) was “restored” in the 1950’s to a managed marshland (Fig. 4). A tidal gate was installed at the entrance of the channel to allow enough tidal flow onto North Marsh without flooding Elkhorn Road (Fig. 7; VanDyke, 2003). Restoration was primarily done by removing the existing vegetation cover and placing dredged back-fill on the land to raise its elevation above mean sea level, and replacing the vegetation by manually planting pickleweed and allowing propagation through natural means (VanDyke, 2003). Today, the North Marsh is a good example of what a managed, productive marshland can look like that is designed to favor Salicornia virginica (Fig. 7)

Fig. 7: Aerial photograph of Estrada and North Marsh taken in April 2003.
1: Estrada Marsh  5: Elkhorn Slough Main Channel
2: Berm  6: Railroad and Berm
3: North Marsh  7: Elkhorn Road
4: Location of tide gate in North Marsh
One restoration option is the removal of a dike separating Estrada Marsh from the full tidal flow of the main Estrada channel (Fig. 4). However, allowing full tidal access to one of the few remaining areas that harbor endangered species could negatively impact marshlands unique ecosystem framework. If the marsh’s elevation were lower than mean high water, and the marsh were inundated with saline water, hyper-saline conditions may occur through cycles of seawater flooding and evaporation. The salt does not get cycled through the atmosphere during the evaporation process it simply gets left behind. The goal of this project is to determine the present elevation of Estrada Marsh in relation to mean sea level, and to assess the impact of four competing management alternatives for optimizing pickleweed habitat: 1) leave Estrada in current state, 2) make a direct tidal channel from Estrada to North Marsh 3) make a direct tidal channel to Elkhorn Slough, 4) make a direct channel to Elkhorn Slough, but with a tidal gate to restrict flow (Fig. 3). This project will allow ESNERR to better assess its restoration strategies for Estrada Marsh for having vital habitat for native coastal, estuarine species.

It is my hypothesis that the upper and lower elevation limits for pickleweed in Estrada Marsh are higher than the limits in North Marsh. Thus, the net result will leave Estrada Marsh to resemble a managed marshland rather than a natural one.

2 Methods

Light detection and ranging (LIDAR) ground elevation data were obtained to develop a digital terrain model of the study area. This model topography was compared to various tidal levels to determine the change in pickleweed habitat associated with the various tidal flooding scenarios. Two ancillary studies were preformed to 1) “ground
truth” the accuracy and precision of the LIDAR elevation data and, 2) determine the present elevation limits of pickleweed in the study area.

2.1 Study Site

Estrada Marsh is located in the Elkhorn Slough on the Central Coast of California. Estrada Marsh is east of the slough and north of North Marsh (Fig 2). It is separated from the slough by a raised railroad grade and Kirby Park its eastern border, and is separated from North Marsh by an unbroken berm (Fig. 6 and Fig. 7).

2.2 Data Sources

2.2.a Aerial Photographs and Maps

A collection of photographs was obtained from the Elkhorn Slough National Estuarine Research Reserve: 1872 Southern Pacific Railroad map, 1920 Empire Gun Club map, may 1931 panchromatic aerial photograph, November 1937 panchromatic aerial photograph, August 1949 panchromatic aerial photograph, June 1956 panchromatic aerial photograph, July 1966 panchromatic aerial photograph, May 1971 panchromatic aerial photograph, April 1987 color infrared aerial photograph December 1999 panchromatic digital ortho photos, April 2003 true color aerial photographs. All photos and maps were goereferenced by Eric VanDyke (ESNERR), and the coordinate system is UTM zone 10N, WGS84 in meters.

2.2.b NOAA LIDAR data

Light detection and ranging (LIDAR) data were collected by NOAA, and processed by CSUMB’s Sea Floor Mapping Lab.
2.2.c **Tidal data**

Tidal elevation flow data were obtained from NOAA’s gauge station located at Elkhorn Road B (Appendix I).

2.2.d **Preexisting benchmarks**

In order to conduct a survey in Estrada Marsh, several permanent and temporary benchmarks needed to be established, and previous benchmarks needed to be located (Fig. 8). Eric VanDyke, an ESNERR intern, and I established three permanent benchmarks in Estrada by driving iron rebar 1 meter into the ground, and pouring cement around them to provide a stable surface. A brass cap was centered on top of the cement to allow for a continuous survey platform.

Previously established benchmarks that were already in place needed to be located to aid in the “ground truthing” of the LIDAR data (Fig. 8). These benchmarks were: one Fish and Game benchmark located at the entrance of Kirby Park, one NOAA tidal benchmark located north of Estrada and railroad benchmark located adjacent to a railroad signal.
2.2.e Total station and RTK GPS surveys

Over the course of two days, Dr. Doug Smith, Eric VanDyke and I conducted surveys utilizing two types of instruments in Estrada Marsh: Topcon 210 Total Station and a Trimble Real Time Kinetic (RTK) GPS unit to “ground-truth” the LIDAR data. Total Station was employed in field by first inspecting the marsh for the most advantageous location in order to obtain the maximum number of points. This location was named “occupied point #1”. From there, the total station was aimed at one of the benchmarks located on the railroad tracks (a nail head), and this point was used to assess the precision of the survey points taken over several days. Also, the survey points taken using the total station utilized previously installed benchmarks, and visual references that were easily located using a picture of the LIDAR data. Some of the visual reference points that appear on the LIDAR image are not permanent, and may move over time, i.e.
the portable latrine in the parking lot, the concrete pylons located north and south of the
parking lot and the metal bunker located within Estrada Marsh. The total station was
moved five times; a back shot was taken to reestablish proper reference after each move.
The RTK GPS unit was utilized in a similar manner to the total station, and was used to
gleoreference the total station survey points.

2.2.f  Rotating laser level surveys

2.2.f.1 Implementation of Rotating Laser Level

A rotating laser level is used to measure the elevation of the land with respect to a
reference of choice. The typical precision of the elevation is less than 0.01 m.

I initially set up the rotating laser for the best vantage point to observe Estrada
and North Marsh. The location was along the transecting berm that separates Estrada
from North Marsh (Fig. 9). This was done in an attempt to minimize the number of times
that the rotating laser would need to be moved. In order to determine the height of the
rotating laser, a permanent benchmark was chosen (Estrada #3), because of its known
vertical elevation that was determined previously. To test the vertical precision of the
rotating laser at long distances, several “test shots” were performed. Repeated readings
differed by less than 1 cm.
2.2.f.2  Sampling Method for Upper and Lower Elevation Limits of *Salicornia virginica*

Over the course of two days, I collected data using a Topcon Rotating Laser Level to evaluate if there is a difference in colonizing heights for *Salicornia virginica* between its upper and lower growth limits in both Estrada and North Marsh. The upper growth limit can be defined as the location where the pickleweed ceases to grow at its upper limits. Conversely, the lower limits can be defined as the location where the pickleweed ceases to grow at its lower limits (Fig 10). To do this, a random sampling method was employed by dividing each of the marshes into fifteen grids on an aerial photograph (Fig. 9). Each of the grids was given a value of 1 – 15, starting from the southwest corner and continuing in a clockwise fashion. Choosing a random number between one and fifteen
determined the grid to be sampled. A 10 meter transect tape was laid perpendicular to either the upper or lower edges of the pickleweed, and a random number was chosen between 0 – 10. A second, 20 meter, transect tape was then laid perpendicular to the first transect tape at the random number chosen. If the area to be sampled did not allow for upper and lower elevation limits, an opportunistic sample was taken within the grid. A sample was taken every four meters for a total of five elevation points. A total of eight grids were sampled.

![Diagram of pickleweed growth limits](image)

**Upper Limit = highest elevation where pickleweed grows**

**Lower Limit = lowest elevation where pickleweed grows**

### 2.2.f.3 Sampling Method for Water Heights

An opportunistic method was utilized to compare the freestanding water heights in Estrada and North Marsh on October 9th and 10th 2004. Data were collected using the rotating laser level during the pickleweed elevation survey project.

### 2.3 Data analysis

#### 2.3.a NOAA LIDAR data

The LIDAR data were processed by CSUMB to create a digital elevation model (DEM) hillshade in ArcGIS. I then took the LIDAR data and transformed it into a virtual
three-dimensional, rotatable model using Fledermaus’ D-Magic. And, Fledermaus was used to drape aerial photographs of Estrada and North Marsh over the LIDAR data set.

2.3.b Total Station and RTK GPS

The three dimensional spatial data of 91 points obtained from the RTK GPS and total station were placed into a spreadsheet and evaluated to establish the accuracy of the LIDAR data (Appendix II). A visible reference point in the LIDAR data was subtracted from the instrument height.

2.3.c Rotating Laser

A students t-test was used to compare the habitat elevations of pickleweed at Estrada Marsh vs. North Marsh, within each of the marshes and compare the water heights between the marshes.

3 Results

3.1 3-Dimensional Rotational Model

The three-dimensional model provides several images of Estrada Marsh given various tidal flows. Most of the scenarios depict situations that would lead to net loss of pickleweed in Estrada Marsh. The one scenario that would lead to productive pickleweed habitat is removing the berm between Estrada and North Marsh.

3.1.a Representation of Mean High Water (MHW) in Elkhorn Slough

This analysis would suggest that if Estrada Marsh were influenced by a partial tidal cycle in Elkhorn Slough, the current upper and lower pickleweed habitats would be completely submerged (Fig. 11). This scenario indicates a total loss of pickleweed habitat given the current elevation of Estrada Marsh.
3.1.b Mean Tidal Level (MTL) in Elkhorn Slough

This analysis shows that Estrada Marsh would be almost entirely covered by water (Fig. 12). This scenario would suggest that the marsh is below mean tidal level. This scenario would indicate that only a small ring of pickleweed habitat would be able to survive given the current elevation of Estrada Marsh.
### 3.1.c Effect of breeching the berm that separates Estrada and North Marsh

Currently, valves operated by ESNEER manage the water level in North Marsh. The maximum water level in North Marsh is limited to 0.748 m to avoid flooding a low spot in Elkhorn Road.

If the two marshes were to be one contiguous marshland, the lowest point in Elkhorn Road also limits the amount of managed water flow that can be allowed onto Estrada Marsh. Thus, using the lowest point in Elkhorn Road depicts that enough water will be introduced into Estrada marsh (Fig. 13) to create a ring of pickleweed habitat. This scenario would suggest that using this boundary to mitigate the tidal levels would be beneficial to a sustainable habitat in the marsh, because there would be a sufficient amount of water to inundate Estrada.

![Diagram of Estrada Marsh](image)

**Fig. 13**: A 3-D image depicting Estrada Marsh with a plane inserted to represent what managed water levels would be if Elkhorn Road were used as an elevation boundary. Water elevations taken from the NOAA tidal gauge station at Elkhorn Road B.
### 3.2 Statistical Results

The mean of pickleweed upper and lower growth limits in Estrada are 0.806 m and 0.607 m (Table 1), with a standard deviation of 0.194 m and 0.128 m (Table 1). The mean of pickleweed upper and lower growth limits in North Marsh are 0.783 m and 0.573 m (Table 1), with a standard deviation of 0.156 m and 0.139 m (Table 1).

<table>
<thead>
<tr>
<th>Pickleweed upper limit</th>
<th>Estrada Marsh</th>
<th>North Marsh</th>
<th>Comparison</th>
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<td>N</td>
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<td>Sd (m)</td>
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<td>0.21</td>
<td>1.45E-08</td>
</tr>
</tbody>
</table>

Table 1: Comparison of upper and lower growth limits in Estrada and North Marsh in meters above mean sea level.

n= # of observations
sd= standard deviation
95%= standard error of difference
Difference= difference in means
p-value= probability of rejecting the null hypothesis

![Graph showing the distribution of pickleweed elevations in North and Estrada Marsh in meters above mean sea level.](image)
3.2.a Comparing the upper elevation edges of *Salicornia virginica* in Estrada and North Marsh

A t-test indicates that there is no difference in the colonization of the upper elevation boundary of pickleweed between Estrada and North Marsh (n = 40, p = 0.542, df = 75) (Table 1). The data suggest that any elevation differences between North and Estrada Marsh do not influence the colonization of *Salicornia virginica* on its upper boundaries.

3.2.b Comparing the lower elevation edges of *Salicornia virginica* in Estrada and North Marsh

A t-test indicates that there is no difference in the colonization of the lower elevation boundary of pickleweed between Estrada and North Marsh (n = 40, p = 0.262, df = 77) (Table 1). The data suggest that any elevation differences between North and Estrada Marsh do not influence the colonization of *Salicornia virginica* on its lower boundaries.

3.2.c Comparing upper and lower pickleweed elevation limits

A t-test indicates a clear difference between upper and lower elevation limits in Estrada Marsh (0.2 m +/- 0.1 m, p < 0.05). North Marsh pickleweed has a similar habitat range (0.2 m +/- 0.1 m, p < 0.05).

3.2.d Comparing the water heights in North and Estrada Marsh

North Marsh is a managed marsh with tidal access mitigated through installed tide gates and Estrada Marsh is considered an unrestored marsh removed from any tidal access.
By comparing the water heights in North and Estrada Marsh, one can have an understanding where, with respect to elevation, the current water levels are on the days that were sampled. The results suggest that, on the days data were collected, North Marsh had higher water elevations than Estrada \((n = 30, \ p = 0.00, \ df = 56)\) (Table 2).

<table>
<thead>
<tr>
<th>Water Elevation</th>
<th>Estrada Marsh</th>
<th>North Marsh</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>30</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Mean (m)</td>
<td>0.541</td>
<td>0.627</td>
<td>Difference (m) = -0.086</td>
</tr>
<tr>
<td>Sd (m)</td>
<td>0.070</td>
<td>0.085</td>
<td>p-value = 5.8E-05</td>
</tr>
<tr>
<td>95%</td>
<td>0.026</td>
<td>0.032</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Comparison of water heights in Estrada and North Marsh in meters above mean sea level.

3.2.e Comparing Estrada Marsh with Seliskar’s reported pickleweed elevations

Seliskar (1985) reported, the optimized pickleweed habitat in a natural state is from 0.13 m to 0.42 m above mean high water. This analysis indicates that the pickleweed in Estrada and North Marsh is significantly below the model for a natural state (Fig. 16).
Fig. 16: Graph showing the distribution of pickleweed elevations in North and Estrada Marsh vs. Seliskar's reported pickleweed for 1.9 m above MHW for the upper elevation, and 1.6 m above mean sea level.

3.2.f Assessing the accuracy of LIDAR with respect to higher resolution survey techniques

The LIDAR precision was assessed by comparing 91 points between the LIDAR, RTK GPS and total station, and was found to be 0.052 m +/- 0.054 m. When assessing the accuracy of the LIDAR, a treadline was added and found to have an $R^2$ value of 0.948 with the leverage point and 0.931 with the leverage point removed (Fig. 17 & Fig. 18).
Fig. 17: Scatterplot of LIDAR vs. total station and RTK GPS surveys depicting a treadline. $R^2$ value is close to 1.0, which would suggest a high degree of accuracy.

Fig. 18: Scatterplot of LIDAR vs. total station and RTK GPS survey with leverage point removed. $R^2$ value is still close to 1.0, which denotes a high level of accuracy.
4 Discussion

4.1 3-Dimensional Model Layering

When two-dimensional pictures are layered on top of the LIDAR image, it appeared that there was a discrepancy in the vertical elevation (Fig. 19 and Fig. 20). That is to say, when a plane was inserted at Mean Tidal Level, a majority of Estrada Marsh was shown to be underwater. And, when an aerial photograph was placed on top of the model, the net result was that the photograph was falsely elevated + .4 meter. This scenario would suggest that the water elevation level in Estrada is lower with an aerial photographed inserted than on the LIDAR data only. This error may be a miscalculation within the Fledermaus software, e.g. the software may be trying to average the draped image in reference to the LIDAR image. However, the exact cause has not been determined.

Fig. 19: A 3-D image showing Estrada Marsh with a plain inserted to represent mean tidal levels. Water elevation taken from the NOAA tidal gauge station at Elkhorn Road B.
4.2 Rotating Laser

In collecting the data for the statistical analysis, some concerns arose about the most efficient way to collect the data. Since the North Marsh was already considered to be a managed, restored salt marsh, it was an ideal candidate with which to compare Estrada. However, since North Marsh is kept flooded, the area is extremely muddy. On four separate locations around North Marsh an attempt to gain entry to the interior was made. However, the terrain was impassible due to the deep mud. This made it impossible to traverse to the center of North Marsh and collect data needed for water heights and lower boundaries for pickleweed. Conversely, since Estrada marsh has not been influenced as much by water, the mud depth only reached to just below the knee. This made it easy to survey the entire portion of Estrada. So, the data that were collected only represents the outer ring of North Marsh, as opposed to the entire area of Estrada Marsh. It may be the case that North Marsh may have different elevation boundaries toward the center of the marsh. There were several small islands with defined boundaries on them.
5 Conclusion

5.1 Recommendations

The data show that Estrada Marsh is below Mean Tidal Level. And, if Estrada Marsh were to be exposed to the natural tidal cycle, it would be nothing more than a standing pool of seawater at higher tides, but empty at lower tides. This brings about the next question: what method of restoration would be more beneficial to Estrada Marsh given the restoration goal of maximizing pickleweed?

5.1.a Removal of the berm separating North and Estrada Marsh

This study has provided several management options. One scenario would be to remove the berm that separates North Marsh from Estrada, and allow managed water level to both marshes. Overall, this is the best management option that can be employed by ESNEER. Removal of the berm will allow for a ring of sustainable pickleweed habitat to develop around the incoming water from North Marsh. And, this option will be the most cost effective with respect to creating channels through or under the railroad.

5.1.b Creating a channel to Estrada directly from Elkhorn Slough

This scenario is to create a channel that directly links Estrada to Elkhorn Slough. This situation would entail burrowing a tunnel under the railroad tracks, and going around or through Kirby Park. And, this could potentially create problems with the railroad company that still uses those tracks, and the visitors that use the park. However, a direct channel was made in the 1950’s to link North Marsh with Elkhorn Slough. Instead of creating one large channel, in this situation, two smaller channels could be created that circumvents Kirby Park and could potentially cause less disturbance to the structural integrity railroad. As with North Marsh, tide gates can be placed at the entrance to the channels to manipulate the level of seawater entering Estrada. If there is a concern
that flooding may occur over Kirby Park or the railroad due to storm surges or other phenomena, then the gates can be manipulated accordingly. The best outcome for this scenario would be to install a tidal gate to manage inundation (given the lower colonizing limit in Estrada being .566 m). The gate can be opened during mean high water, and closed once Estrada has reached the maximum water elevation for pickleweed habitat. However, the financial costs associated with this endeavor would be greater than removing the low earthen berm.

5.1.c Leaving Estrada as it is

This situation would entail doing nothing. Leave the berm intact, and do not install tidal channels to Estrada. This would be the case where nature is allowed to render its own verdict on Estrada without outside influence. The outcome may result, over time, in a positive impact to pickleweed, negative impact to pickleweed or draw. However, the current situation of Estrada is that of being stressed. The marshland has become more hyper-saline due to the lack of flushing, and this would eventually lead to an eradication of the remaining pickleweed over time.

5.2 Possible Future Studies

This study is only the beginning in what is to be a long process. Now that there is an understanding of where, in relation to mean sea level, Estrada is situated, more studies can be done to investigate the other aspects of restoring this salt marsh.

5.2.a What may be the desired number of channels?

One future study can look at the impact of creating one or more channels from the slough to Estrada. That is, what would be the most desired effect in terms of cost and impact to the railroad and Kirby Park with respect to optimizing pickleweed habitat?
5.2.b What factors that can lead to subsidence?

There is a possibility that there could be outside influences that could be creating subsidence in the marsh. Vibrations make wetland sediments expel water and compact to a lower volume (Ford et al. 199). One natural influence could be the earthquake activity that is typically associated with this region of California. One unnatural influence could be the possibility that subsidence could be occurring, over time, with the passage of the trains that run next the marshes (they are passenger and commercial trains).
Appendix

I  NOAA tidal gauge data taken from Elkhorn Road B.

Elevation Information For FID = 683198, VM = 01681
Station_ID --- 9413663

--- MHW      =  5.55 feet
5       --- HW =  4.82 feet

3       --- ML =  2.04 feet
            --- NVD92 =  2.17 feet

2       --- LW =  1.06 feet
1

0       --- MLW =  0.00 feet        --- MLLW =  0.04 feet

-1

The NHNO E and the NAVO 23 elevations related to MLUL were computed from Bench Mark, 941 3663 # TIDAL, at the station.

Displayed tidal datum are Mean Higher High Water (MHHW),
Mean High Water (MHW), Mean Tide Level (MTL), Mean Low Water (MLW),
and Mean Lower Low Water (MLLW) referenced on 1983-2001 Epoch.
### Table of pickleweed elevation in North and Estrada Marsh

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<thead>
<tr>
<th>Lower Pickleweed:</th>
<th>Upper Pickleweed:</th>
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<td>North H (m)</td>
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<tr>
<td>0.430</td>
<td>0.503</td>
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### Table water heights in North and Estrada Marsh

<table>
<thead>
<tr>
<th></th>
<th>Water Heights:</th>
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<tr>
<td>Estrada</td>
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<tr>
<td>H (m)</td>
<td>H (m)</td>
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<td>0.479</td>
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Acknowledgements:

I would like to take this opportunity to thank the various people and groups that have helped this study to become reality: Eric VanDyke for allowing me the opportunity to explore this study, Dr. Doug Smith for his infinite patience and guidance in making this study a reality, ESNERR and CSUMB’s Sea Floor Mapping Lab.
Literature Cited:


M. Page. 1997. Importance of vascular plant and algal production to macro-invertebrate consumers in a Southern California Marsh. Estuarine, Coastal and Shelf Science: 823-834

