An Investigation of Salt Tolerances in the Estuarine Setting

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Abstract

Salt tolerances ranges were constructed using soil salinities of a variety of native and invasive plant species living on the Tijuana Estuary. The constructed salt tolerance range information was used to gauge the resilience of the underlying assumptions of the “sea salt hypothesis”. This hypothesis states that sea salt can be used as a management tool to control invasive plant species due to differences in salt tolerance ranges; principally that native species have broader salt tolerance ranges than non-native species due to evolutionary processes involving gene selection. Experiments involving sea salt application to both native and invasive species were designed and implemented to see how each species reacted to artificial increases in soil salinities, mimicking possible future invasive management control strategies**.** Native plant species were found to have significantly broader salt tolerance ranges than invasive plant species a majority of the time. This fact manifested itself in the success of the sea salt experiments, to actively degrade the health of the majority of non-native species while have having almost no affect on native species. Salt tolerance range construction will provide important information in pursing estuary restoration and management goals, while continued sea salt application studies could prove this method a more effective and benign invasive plant management tool.

Introduction

The Tijuana Estuary, nestled on the international border between California and Mexico, is a unique inter-tidal coastal wetland at the base of the Tijuana River watershed. It is often termed intermittent estuary because of its extreme changes in stream flow throughout the year due to floods and droughts (West, 2002). For this reason, the Tijuana Estuary is one of the nation's most dynamic and variable wetlands. With its salt marsh dominated habitat and natural daily tidal flushings, the estuary encompasses 2500 acres and is the largest salt marsh in Southern California (O'Leary, 2000). The area includes a variety of habitats, fresh and salt water alike, to create one of the most biologically productive systems on the Earth. Over 370 species of native and migratory birds find the estuary an essential breeding, feeding, and nesting ground and over 29 species of fish populate the waters (O'Leary, 2000). The reserve is also home to six endangered species of birds, several invertebrates, and one plant species (West, 2002; Big Deal with Exotics). The area has been a major wetland research site and part of the National Estuary Research Reserve System for over three decades (Chapter 3). Through monitoring of vegetation, water quality, fish, birds, and benthic invertebrates, the Tijuana Estuary has improved the understanding of estuarine settings and has contributed to improved restoration and management efforts throughout the nation (Research, Restoration). The future survival of this estuary is imperative not only for research purposes, but for the unique habitat and biodiversity that the land embraces.

Unfortunately, the Tijuana Estuary has struggled throughout the decades as the presence of human populations has imposed stresses on the land. Historically, agriculture, gravel extraction, stormwater discharge, and military facilities have abused the estuary’s diverse habitats (Tijuana River Estuary, 1998; West, 2002). Sewage oxidation ponds and discharge operations in the northern part of the estuary transpired until the early 1970’s (Tijuana River Estuary, 1998). There have also been changes in water flow regimes through water divergence and degradation of water quality. The Tijuana River has three associated dams that were constructed in the early 1900’s, which control 78% of the waters (Tijuana Hydrologic Unit Profile, 2001). A change in the flow of these headwaters alters the structures of the physical environment downstream, consequently having effects on vegetation and wildlife. Issues with water quality have plagued the river in Tijuana Mexico, in recent years, as the population has dramatically increased. Tijuana lacks an adequate infrastructure for the collection, treatment, and disposal of sewage, so the majority of this material goes directly into surfaces waters causing contamination (Tijuana Hydrologic Unit Profile, 2001). The population surge coincides with intensive industrial development associated with manufacturing and assembly plants (Tijuana Hydrologic Unit Profile, 2001). Waters from this area contribute the highest concentrations of suspended solids and heavy metals such as cadmium, copper, nickel, lead, and zinc (Tijuana Hydrologic Unit Profile, 2001). Waste products entering storm drains in the United States also inject a host of petroleum waste products, surfactants, and fertilizers into the waters and liter the region with solid wastes. The estuary is bounded on all sides by homes, farms, roads, and an airfield, all of which stress the exterior boundaries of the estuary. Naval helicopter training occurs very frequently over the northern part of the reserve. There is a state park that leases areas for agriculture and residential use, and equestrian facilities and the border patrol have an established presence in the region (Tijuana River Estuary, 1998). The aggregate of all of these human behaviors have contributed to one of the estuary's most formidable problems, the encouragement introduction, establishment, and spread of invasive plant species (Bushek and Coen). A stressed ecosystem is more susceptible to invasion by non-native plant species and since an estuarine ecosystem is one of the most heavily disturbed, as is Tijuana Estuary, it is one of the most heavily effected environments (Invasive Plants, 2005; Invasion, 2004; Bushek and Coen).

Invasive plants are a subset of non-indigenous species that did not evolve in the locations in which they currently reside. They tend to appear on disturbed ground and usually have no natural enemies, which include parasites, herbivores, or diseases, to limit their reproduction (Weeds Gone Wild, 2005; Invasive Plant?). Some invasive plants are introduced by accident, such as through overseas shipments, and many others are selected for agriculture, horticulture, and aquaculture because of their aesthetic look or resilient nature (Invasive Plants, 2005; Invasion, 2004; Bushek and Coen). A few typical characteristics shared by these plants, in terms of growth and reproduction, include their propensity for early maturation, seed dormancy, profuse reproduction, and long life within soils (Weeds Gone Wild, 2005). Many assume the title of "generalists" whom can grow in a variety of physical environments (Westbrooks). Although often times considered to create a more aesthetically pleasing landscape, these invasive plant species can have dramatic effects on local ecosystems (Invasive Plant?). Without natural predators, these plants can out-compete native vegetations for light, water, nutrients, and space (Bushek and Coen). This can increase the extinction pressure on endangered and threatened species and can ultimately displace and degrade the native plant communities as a move towards a monocultural environment occurs (Westbrooks; Invasive Plants, 2005; Invasive Plants?). Consequently there can be a reduction in biodiversity and a loss of habitat for native birds, fish, insects, and invertebrates (Westbrooks; Bushek and Coen). Many native fauna rely on specific native plant types for food and residence, so vegetative changes can disrupt wildlife communities (Big Deal with Exotics). Consequently, communities can be restructured and ecosystem functions can change Bushek and Coen). Referred to as biological pollution, these invasive species can also disrupt erosion and sedimentation rates, local hydrology, and soil structure and chemistry (Invasion, 2004).

There are a variety of options that can be taken to alleviate the problems caused by invasive species that encroach into the estuarine habitat. Currently the Tijuana Estuary employs mechanical and chemical controls to effectively rid sites of problematic exotic plant species (Crooks, 2006). Mechanical means of non-indigenous plant removal are successful at removing the vegetation, however with low numbers of hired and volunteer individuals, these actions require long periods of time for results (Crooks, 2006). When dealing with such a large amount of land at the reserve and the rate of reinvasion of exotic species, only small areas of the reserve receive focused attention. For chemical controls, herbicides containing Glyphosate are employed in a directed spray method to affectively "spot treat" areas of the reserve. The herbicide, typically known as Rodeo (Crooks, 2006), is 53.8% Glyphosate and is a broad-spectrum herbicide that is absorbed by plant leaves (Safety). It works by effectively inhibiting the synthesis of three amino acids necessary for plant growth (Pesticide, 1994). The symptoms of injury occur anywhere from a few weeks in herbaceous plants, all the way up to a year for woody vegetation (Safety). This particular product is desirable for use because Glyphosate is highly adsorbed on most soils quickly, making it unavailable herbicidal activity via the absorption by plant roots (Pesticide, 1994). Glyphosate does not contain a surfactant and is readily biodegraded by microorganisms, thus it does not persist in soil or water (Safety). This method is spot treatment only and must be kept away from native plant species since all plant varieties are susceptible. Although fairly environmentally friendly the materials safety data sheet for the chemical advises that the use of large quantities should be kept away from waterways and can have a slightly toxic effect on aquatic plant species and bird species (Material Safety, 2001; Pesticide, 1994). Both mechanical and chemical mechanisms for invasive plant control are typically coupled with restoration efforts in which native species are reintroduced to restoration sites to minimize the chances that an area will be reinvaded.

Although both mechanical species removal and chemical spot treatment are effective means of non-native plant control**,** their lack of efficacy and negative side-effects suggest there is opportunity for further improvement. A possible management control that is currently in the beginning stages of discussion and research is the use of natural sea salt as an eradication method to control invasive plant species. Sodium and chloride, the main constituents of sea salt, are plant nutrients at low levels, but at high enough levels can be toxic to plants. With increases in salt concentration in the soil comes an increase in osmotic pressure of the soil solution, therefore the amount of water available for plant uptake decreases causing desiccation (Salinity Notes, 2005). These excess salts can also reduce plant growth by causing ion-specific toxicities or imbalances within the cells of the plant (Salinity Notes, 2005). Plants have varying abilities to deal with changes in salt concentrations in the soils because of a gene that codes for a protein called the Na^+/H^+ antiport (Easton, 1999). This protein "prevents the sodium ions from salt from harming the cell and creates a balance of ions in the cell that draws water into the plant cell by osmosis (Easton, 1999)." The Na^+/H^+ antiport gene is present in plants that have evolved in environments with high soil salinities (Easton, 1999). This differentiation between native and invasive plant species, reference to the presence of the gene, could be exploited through salting methods, whereby and increase soil salinities would effectively push the exotic species out of its salt tolerance range, eradicating the plant. In this way, a generalized salting could occur alleviating the need to cautiously and meticulously applying chemical agents to individual plants. The native species, having evolved in the saline estuary environment and containing the gene would survive the artificially increased salinity, whereas the invasive non-native, without the gene, would not. This method could hypothetically minimize the amount of labor needed to treat these plants, principally by eliminating the need for removal, and sea salt could be obtained with minimal or no cost from the South Bay Salt Flats. This area, known as the San Diego Bay National Wildlife Refuge, South San Diego Bay Unit, encompasses approximately 2300 acres of land, where some of the state owned lands include active solar salt evaporation ponds (San Diego Bay, 2006).

Experiments using salt as an extermination tool are very uncommon in the literature. Salting methods were utilized in New South Wales Australia where an invasive “aquarium strain” of marine green seaweed, Caulerpa taxifolia, was infesting the soft sediments of the waters (Glasby, Creese). The strain is found from 0.5 to 10 meters depth in waters, with average salinities of 27-36 parts per thousand (ppt) at less than 0.5 meters depth (Creese). Applications of coarse sea salt were employed at 50, 100, 150, and 200 kg/m^2 in study areas of a variety of sizes (Glasby). The results varied, principally with size of application area, being the most successful at a few hectares. “In small-scale trials, the average number of fronds (i.e. leaves) of C. taxifolia decreased by 70 - 95% one week after salting and showed no signs of recovery after 6 months (Westbrooks).” Although sea grass and invertebrates were also negatively affected by the sea salt, their numbers recovered after about six months (Westbrooks). If a similar type of salt treatment were applied to invasive plants within the estuarine setting, there are both direct and inferred assumptions that can be made about the effect that this process would have on the estuarine study setting. Initially the palpable difference between the experiments in the two environments, is that salt was applied submarine in the aforementioned study with Caulerpa taxifolia, whereas at the Tijuana Estuary, a majority of the invasive plants are found above the water line. Initially it would seem as though more salt would have to be used in the submerged setting because of increased dissolution, but the applied salt on the ocean floor did not readily dissipate. The substrate in both areas is analogous, being composed of soft sediments. The plants of study are both halophytic, and in some cases the estuary plants are not specifically halophytic but are inclined to survive in soils with a relatively high degree of salt when compared to that of other environments. Since the water above Australian study sites ranged in salinity from about 27-36ppt and the estuary has soil salinities ranging from a few parts per thousand at higher elevation, to well over 100ppt in salt marsh habitats, the average salinity environments in each of the two settings are comparable. An optimistic aspect revealed by the original study is that native communities survived the intensive salting regiment. This fact has positive implications for future generic salting methods whereby hypothetically the natives, due to their broad salt tolerance ranges, could survive increases in soil salinities whereas the non-native could not.

I hypothesize that the natural sea salting of plant communities comprised of both invasive and native plant species in the Tijuana Estuary, will be a successful method in controlling the unwanted non-indigenous species while proving not particularly destructive to the native vegetation and ecosystem. I suggest that native plants have a broader range in salt tolerances, specifically within the higher ranges of salinity, due to the dynamic intermittent estuary environment in which they have evolved. The exotics, being more of a breed of generalists, have a narrower range of salt tolerances and therefore will not survive a dramatic increase in soil salinities.

Experimental Overview

Three different studies were done over the course of a five month period, beginning in February and completing at the end of May. The first study involved the analysis of soil samples to extract information on soil salinities so that ranges of salt tolerances for the native and invasive species living on those soils could be constructed. This allowed comments to be made about the assumptions of the sea salt hypothesis, specifically about the differences in salt tolerances between native and non-native plant types. Next a series of salting experiments was completed at a selected number of sites involving both native and invasive species, where the effects of increased soil salinities were catalogued in the form of reactions for the different plant species. This study will serve as a stepping-stone to making further decisions on the structure of future salting experiments. Finally, a study was conducted involving the re-sampling of salted sites to observe the effect that the salting experiments had on natural soil salinities.

The study area was chosen primarily on proximity to areas of human impact; particularly those with a high frequency of invasive plant species. The part of the reserve that was chosen borders the backyards of residences, thick with non-native species. The migration paths of these species can be observed trending the downhill slope from the residences to the estuary lands. Residents have also chosen to plant particularly invasive species outside of their property line to quarantine themselves in the event of a fire on the estuary. These exotic species have grown from their region of origin, down slope, into the reserve. A final reason why this location has a high frequency of exotic plants is due to its relationship to a street that funnels runoff onto the reserve via two channels. The first is curb inlet flow which incorporates debris and vegetation from nearby lawns and injects the material directly atop the soils, especially in low lying areas. This water increases erosion through downcutting, thereby increasing the quantity of microenvironments for exotic plant growth to occur. The second is a subaerial flow fed by storm drain outlets. This underground release of fresh water hypothetically would have the effect of lowering soil salinities and creating a more hospitable environment for exotic growth. To the north, the study area is bounded by two large storm drain openings that expel flow into a tidally affected channel. To the south, the study area is contiguous with the northern end of the Ream Airfield. In total, the study area spans about a quarter of a mile in length and 10 meters in width at the northern end of the site, to 60 meters in at the southern edge.

Four specific habitats were found within the sampled study area. These include salt marsh, transition, salt panne, and upland (Tijuana River Estuary, 1998; Crooks, 2006). The salt marsh is one of the areas of lowest elevation with one of the highest soil salinities and is twice daily submerged by high tides, particularly from a water body moving upslope. These soils are fine grained as expected by this low energy environment and the "well known" native salt marsh plants are found in this area. This habitat grades upward into the transition, where there is a rapid change in elevation accompanied with decreases in soil moisture and soil salinity. This habitat is host to many of the same native plants found in the salt marsh. The transition grades into the upland or the non-tidal wetland, where the gradient in elevation decreases to near zero. The final habitat type sampled is the salt panne that differs from the salt marsh in that there is a typical a lack of vegetation. Sometimes this habitat is dry and characteristic polygonal mud cracking patterns are evident, other times the soils are softened by being moistened from depth by salt water intrusion.

Experimental A

Specific sites of study were chosen within the study area by their distance to both invasive and native plant species of interest. Multiple plants of the same species were chosen in various locations throughout the study area in order to accrue soil salinities from which salt tolerance ranges could be constructed. Soil samples were removed at 59 locations using a consistent methodical technique involving a manual coring device. The technique for using this tool involved the implantation of the lower portion of the instrument into the selected soil area, followed by a twisting of the instrument to sink the tool to depth. When the interior soil core reached the top of the cavity, the whole device was removed from the surrounding soil, including a soil sample depth of 10 centimeters. This depth was chosen to represent the zone of feeder root activity of herbaceous plants and was based on an average of researched root zone depths (Root Depth, Salinity Notes, 2005). Down to this soil depth, greater than 50% of herbaceous plant roots exist indicates that the majority of waters acquired by the plant are removed from the sampled 10 centimeters of soil (Pennings and Callaway, 1992). Hence the constructed salt tolerances from these soil salinities are an accurate representation of the tolerance range of the specific plant species. Once the sample had been removed, the soil was immediately bagged, sealed, and labeled with its corresponding site and habitat information. Plant data was collected for each of the sites based on distance from the soil removal site. When the rate of change in elevation was relatively low, plant samples were from 0 to 0.5 meters distance from the sampled site. This sampling range, with respect to elevation, was built on the assumption that a soil's salinity is affected by salt water intrusion from the ocean and this intrusion is directly related to elevation (Pennings and Callaway, 1992). Hence changes in elevation signify changes in soil salinities. For soil samples taken in areas of rapidly changing elevation, such as the transition zone, plant samples were limited to a radius of less than 0.25 meters. Some sites were dominated by one solitary species so that soil salinity sample was only indicative of the one species. Other sites had up to six species of interest so each of those species acquired that salinity measurement in their salt tolerance range. The accumulation of soil salinities for the species in multiple locations with different soil salinities, created the salt tolerance ranges for each species.

Soil samples began processing while the soil was still in the collection bags. Here the soils were thoroughly mixed to ensure that removal of any portion of sample would be representative of the total sample taken. Foil covered tins were then prepared and two tablespoons of each soil sample placed into an individual alcove. Large pieces of vegetation including branches and roots were removed before drying, as were large rocks and other debris. The oven was preheated to 105 degrees Celsius and the samples dried for 24 hours (Zedler and Callaway, 1997). Once removed, the soils were cooled to room temperature and re-bagged to avoid the collection of moisture. The samples were processed within a set of guidelines known as the Soil Paste Method. When an individual sample was ready to be processed, two tablespoons of the soil was removed and gently ground to break up the clots that had formed during drying. The soil was then passed through a 2mm sieve to ensure uniformity in grain size. At this point, deionized water was added to the soil dropwise with an eyedropper. Deionized water was used to ensure that no addition of ions occurred that could cause erroneous affects on salinity readings.

The water was added slowing, with thorough mixing between the additions, which continued until the soil reached saturation; this is the point where the soil had absorbed as much water as possible. The saturation point can visually be observed as the soil glistening. The glistening is due to the free water accumulating on the outside of the soil. If the soil became oversaturated and the water started to flow, more dried soil was added to the sample. When the appropriate amount of water had been added, the soil was set aside for five minutes to allow time for the salt within the soil to go into solution. After five minutes the soil was ready to be analyzed. If the soil had dried too much during the five minute period, more water was added to reach saturation again. During this waiting period, a 5 milliliter plastic syringe was prepared with two layers of filter paper in the interior base. About 3-5mL of the saturated soil was placed into a syringe and the plunger used to extract the soil water from the sample. This extracted water was analyzed by an instrument known as a refractometer.

The type of refractometer used in these salinity experiments was an Extech RF20 Handheld Salinity Refractometer with automatic temperature compensation. The scale of this instrument ranged from zero to one hundred parts per thousand with a resolution of one part per thousand. Samples were read by placing the extracted drops from the syringe on the glass prism and closing the cover plate. When closed, the prism face was always completely covered with the extracted liquid to ensure accuracy of the instrument. About 3 drops of liquid were needed to meet this criterion. The refractometer was then held underneath and perpendicular to a light source, which maximized the contrast of the shadow-line seen in the eyepiece. Visible within the eye piece is the zero to one hundred parts per thousand scale and the shadow line which is articulated as where the white and blue portions of the background that meet on the horizon. The clarity of the scale can be adjusted by rotating the knurled portion of the refractometer around the midsection of the instrument. The clarity of the shadow-line however cannot be sharpened with this adjustment. Definition of this line is usually lost due to sediment particles in the extracted saline solution which refract the incoming light. This can only be corrected preparing more saline solution drops from the sample. This can be done by remixing a new soil sample in the method described above or by turning the syringe extraction side down and allowing the particles in the solution to settle in the tip of the syringe where they can be removed in a single waste drop. Then the solution in the upper portion of the tip can be used for analysis. Typically very fine grained soils such as those found in the salt panne and along portions of the salt marsh region where flowing water were found, occasionally were found to have this problem. If the problem was persistent with a sample, three pieces of filter paper were used to ensure a sediment free solution. Before initial use of the refractometer, a zero adjustment was done by placing distilled water on the prism, and adjusting the “adjustment screw” so that the light/dark boundary, known as the shadow-line was even with the zero line. A check of the zero line was made every three readings to ensure that the instrument was calibrated correctly and that the data collected was accurate.

Results and Discussion A

Found in Table 1 is a complete list of all the studied species by site and their corresponding soil salinities. Included in this chart is the habitat type of each site as well as whether the species is question is native or invasive.

Table 1: Study sites

SITE NUMBER	**HABITAT**	**COMMON NAME**	**SCIENTIFIC NAME**	**NATIVE OR INVASIVE**	**SOIL SALINITY ‰**
1	upland	Brazilian Peppertree	*Schinus terebinthifolius Raddi*	I	5
1	upland	Dock	*Rumex crispus*	I	5
1	upland	Brome Grasses	*Bromus inermis*	I	5
2	transition/upland	Alkali weed	*Cressa truxillensis*	N	31
2	transition/upland	Palmer's Seaheath	*Frankenia palmeri S. Wats.*	N	31
2	transition/upland	Pickleweed	*Salicornia virginica*	N	31
2	transition/upland	saltbush	*Atriplex watsonii*	N	31
2	transition/upland	Alkali heath	*Frankenia salina*	N	31
3	salt marsh	palmer's seaheath	*Frankenia palmeri S. Wats.*	N	58
3	salt marsh	Arrow grass	*Triglochin concinna*	N	58
3	salt marsh	Saltwort	*Batis maritima*	N	58
3	salt marsh	Pickleweed	*Salicornia virginica*	N	58
3	salt marsh	salty susan	*Jaumea carnosa*	N	58
4	upland	Goldenbush	*Isocoma menziesii*	N	2.5
5	upland	Boxthorn	*Lycium calfiornicum*	I	2
5	upland	Alkali weed	*Cressa truxillensis*	N	2
5	upland	Brome Grasses	*Bromus inermis*	I	2
6	upland	Medusahead	*Taeniatherum caput-medusae*	I	1
7	upland	Russian thistle	*Salsola Kali L.*	I	3.5
8	salt panne	Pickleweed	*Salicornia virginica*	N	>135
9	salt panne	Saltwort	*Batis maritima*	N	50
9	salt panne	Pickleweed	*Salicornia virginica*	N	50
10	upland	Atriplex semibaccata	*Australian saltbush creeping sb*	I	11
11	upland	Croceum ice plant	*Malephora crocea*	I	2
12	upland	Saltbush	*Atriplex watsonii*	I	1
13	upland	mexican fan palm	*washingtonia obusta*	I	2
14	upland	Clover	*Trifolium l.*	I	2
15	upland	Iris	*Iri L.*	I	0.5
15	upland	Brazilian Peppertree	*Schinus terebinthifolius Raddi*	I	0.5
16	upland	Ornamental Aloe	*Aloe L.*	I	3
17	upland	Aeonium Spathulatum	*Aeonium spathulatum*	I	1.5
18	upland	Brome Grasses	*Bromus inermis*	I	1

19	upland	Estuary Sea-Blite	*Suaeda esteroa*	N	28
20	upland	Salt marsh lavender	*Limonium californicum*	N	2
20	upland	California Buckwheat	*Eriogonum fascicul atum*	N	2
21	upland	Little mallow	*Malva parviflora*	I	2
22	upland	Freeway ice plant/Hottentot fig	*Carpobrotus edulis*	I	7.5
23	upland	Croceum ice plant	*Malephora crocea*	I	11
24	upland	little mallow	*Malva parviflora*	I	1.5
25	upland	healtleaf ice plant red apple	*Aptenia cordifolia (L.F.) Schwant.*	I	3.5
26	upland	Prickly Pear	*Opuntia sp.*	I	3
27	upland	Jade Tree	*Crassula ovata*	I	2.5
29	transition/upland	Palmer's seaheath	*Frankenia palmeri S. Wats.*	N	3
29	transition/upland	Shoregrass	*Monanthochloe littoralis*	N	3
29	transition/upland	Annual Pickleweed	*Salicornia bigelovii*	N	3
30	transition	Palmer's seaheath	*Frankenia palmeri S. Wats.*	N	55.5
30	transition	Saltwort	*Batis maritima*	N	55.5
30	transition	Palmer's seaheath	*Frankenia palmeri S. Wats.*	N	55.5
31	transition	Pickleweed	*Salicornia virginica*	N	35
31	transition	Salty susan	*Jaumea carnosa*	N	35
31	transition	Shoregrass	*Monanthochloe littoralis*	N	35
32	salt marsh	Alkali heath	*Frankenia salina*	N	86.5
32	salt marsh	Arrow grass	*Triglochin concinna*	N	86.5
32	salt marsh	Salty susan	*Jaumea carnosa*	N	86.5
32	salt marsh	Pickleweed	*Salicornia virginica*	N	86.5
33	transition	Pickleweed	*Salicornia virginica*	N	125
33	transition	Saltwort	*Batis maritima*	N	125
34	salt marsh	Pickleweed	*Salicornia virginica*	N	103.5
35	upland	Glasswort	*Salicornia subterminalis*	N	20
35	upland	Russian thistle	*Salsola Kali L.*	I	20
35	upland	Palmer's seaheath	*Frankenia palmeri S. Wats.*	N	20
36	transtion/upland	Alkali heath	*Frankenia salina*	N	64
36	transtion/upland	Pickleweed	*Salicornia virginica*	N	64
36	transtion/upland	Shoregrass	*Monanthochloe littoralis*	N	64
38	upland	Pickleweed	*Salicornia virginica*	N	5
38	upland	Palmer's seaheath	*Frankenia palmeri S. Wats.*	N	5
38	upland	Dock	*Rumex crispus*	I	5
38	upland	Brome Grasses	*Bromus inermis*	I	5
39	transition	Palmer's seaheath	*Frankenia palmeri S. Wats.*	N	24
39	transition	Pickleweed	*Salicornia virginica*	N	24
39	transition	Shoregrass	*Monanthochloe littoralis*	N	24
41	upland	Glasswort	*Salicornia subterminalis*	N	8
41	upland	Pickleweed	*Salicornia virginica*	N	8
42	transition	Estuary Sea-Blite	*Suaeda esteroa*	N	55
42	transition	Annual pickleweed	*Salicornia virginica*	N	55
42	transition	Palmer's seaheath	*Frankenia palmeri S. Wats.*	N	55
42	transition	Shoregrass	*Monanthochloe littoralis*	N	55
42	transition	Salty susan	*Jaumea carnosa*	N	55
43	transition	Annual Pickleweed	*Salicornia subterminalis*	N	10
43	transition	Estuary Sea-Blite	*Suaeda esteroa*	N	10

43	transition	Shoregrass	*Monanthochloe littoralis*	N	10
43	transition	Alkali heath	*Frankenia salina*	N	10
45	transition	Alkali heath	*Frankenia salina*	N	26
45	transition	Pickleweed	*Salicornia virginica*	N	26
45	transition	Palmer's seaheath	*Frankenia palmeri S. Wats.*	N	26
48	upland	Glasswort	*Salicornia subterminalis*	N	71.5
50	upland	Brome Grasses	*Bromus inermis*	I	4.5
53	upland	Alkali heath	*Frankenia salina*	N	7
53	upland	Pickleweed	*Salicornia virginica*	N	7
54	transition/upland	Brome Grasses	*Bromus inermis*	I	2
54	transition/upland	Alkali weed	*Cressa truxillensis*	N	2
54	transition/upland	Medusahead	*taeniatherum caput-medusae*	I	2
54	transition/upland	Salty susan	*Jaumea carnosa*	N	2
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60	salt marsh	Alkali heath	*Frankenia salina*	N	25
60	salt marsh	Salty susan	*Jaumea carnosa*	N	25
60	upland	Medusahead	*taeniatherum caput-medusae*	I	25
60	upland	Atriplex semibaccata	*Australian saltbush creeping sb*	I	25
65	upland	Saltmarsh lavender	*Limonium californicum*	N	2.5
65	upland	Brome Grasses	*Bromus inermis*	I	2.5
65	upland	Medusahead	*taeniatherum caput-medusae*	I	2.5
73	upland	Alkali weed	*Cressa truxillensis*	N	2
73	upland	Brome Grasses	*Bromus inermis*	I	2
73	upland	Atriplex semibaccata	*Australian saltbush creeping sb*	I	2
73	upland	Dock	*Rumex crispus*	I	2
74	upland	Alkali weed	*Cressa truxillensis*	N	3
74	upland	Dock	*Rumex crispus*	I	3
74	upland	Brome Grasses	*Bromus inermis*	I	3
78	upland	Glasswort	*Salicornia subterminalis*	N	47
78	upland	Alkali heath	*Frankenia salina*	N	47
78	upland	Russian thistle	*Salsola Kali L.*	I	47
78	upland	Shoregrass	*Monanthochloe littoralis*	N	47
82	upland/transiton	Saltwort	*Batis maritima*	N	>135
84	salt panne	Saltwort	*Batis maritima*	N	95
85	salt panne	Pickleweed	*Salicornia virginica*	N	>135
85	salt panne	Shoregrass	*Monanthochloe littoralis*	N	>135
91	salt panne	Glasswort	*Salicornia virginica*	N	5
91	salt panne	Brome Grasses	*bromus inermis*	I	5
93	salt panne	Saltwort	*Batis maritima*	N	104
93	salt panne	Pickleweed	*Salicornia virginica*	N	104
94	salt panne	Pickleweed	*Salicornia virginica*	N	14
95	salt panne	Pickleweed	*Salicornia virginica*	N	59
96	upland	Saltbush	*Atriplex watsonii*	N	6
96	upland	Brome Grasses	*Bromus inermis*	I	6
96	upland	Alkali weed	*Cressa truxillensis*	N	6
96	upland	Pickleweed	*Salicornia virginica*	N	6

99	transition	Pickleweed	*Salicornia virginica*	N	53
99	transition	Alkali weed	*Cressa truxillensis*	N	53
99	transition	Dock	*Rumex crispus*	I	53
99	transition	Palmer's seaheath	*Frankenia palmeri S. Wats.*	N	53
100	upland	Brome grasses	*Bromus inermis*	I	1.5
100	upland	Brazilian Peppertree	*Schinus terebinthifolius Raddi*	I	1.5

(West, 2002; Crooks, 2006)

Each species salt tolerance range was constructed from the aggregate of the salinity measurements shown in Table 1. For some species of plants only points are listed for their salt tolerance ranges instead of a breath of salinities. These plant species were only found in a single study location on the estuary and therefore had only one corresponding salinity reading to report. Also of note are those species with salt tolerance ranges that are bounded by >135, as listed in Table 2. The specific salinity samples that create the utmost point of these ranges were too high to be read with the scale of the salinity refractometer used in the experiment. Although the refractometer scale was only labeled from one to one hundred parts per thousand, the scale could be extrapolated upward to 135, which was the top of the optical view. Although these salinities could be established as greater than 135ppt with certainty, exactly how much greater is not known.

Table 2: Salinity Ranges of Plant Species

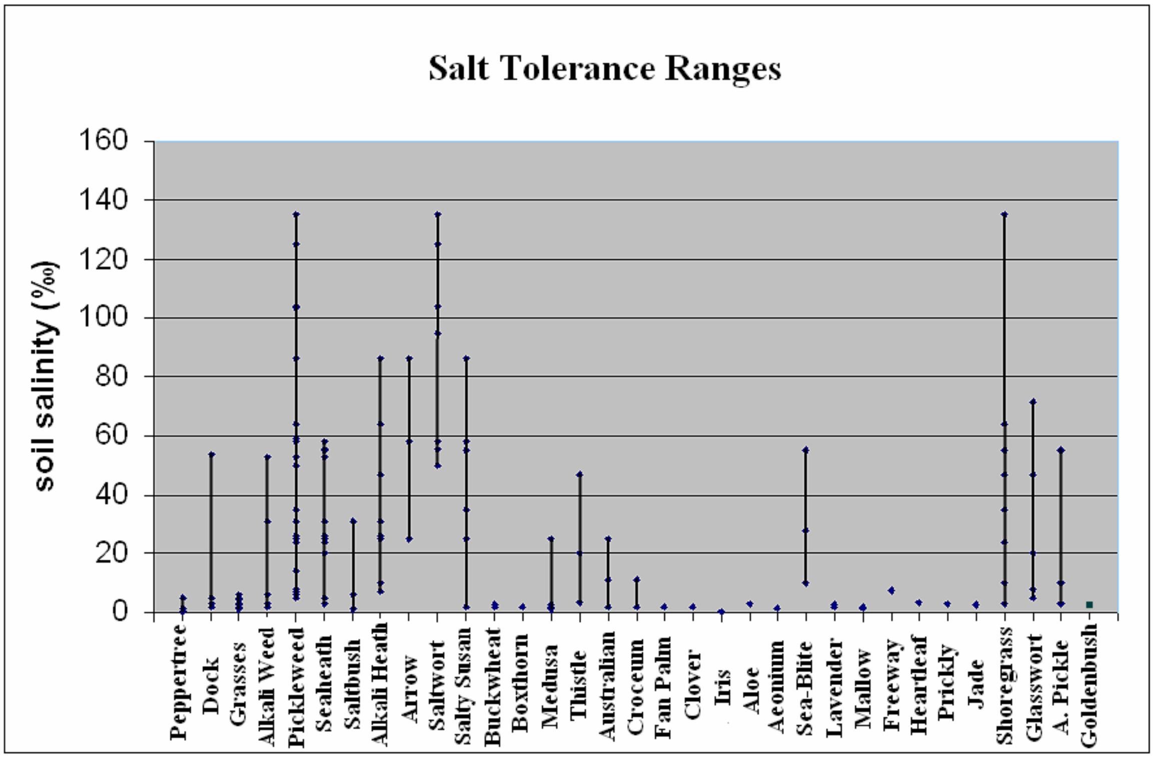
COMMON NAME	**SCIENTIFIC NAME**	**SALT TOLERANCE RANGE**
Aeonium spathulatum	*Aeonium spathulatum*	1.5
Ornamental aloe	*Aloe L.*	3
Healtleaf ice plant/red apple	*Aptenia cordifolia (L.F.) Schwant.*	3.5
Saltbush	*Atriplex watsonii*	1 to 31
Atriplex semibaccata	*Australian saltbush creeping sb*	2 to 25
Saltwort	*Batis maritima*	50 to >135

Brome grasses	*Bromus inermis*	1 to 6
Freeway ice plant/Hottentot fig	*Carpobrotus edulis*	7.5
Jade tree	*Crassula ovata*	2.5
Alkali weed	*Cressa truxillensis*	2 to 53
California Buckwheat	*Eriogonum fascicul atum*	2
Palmer's seaheath	*Frankenia palmeri S. Wats.*	3 to 58
Alkali heath	*Frankenia salina*	7 to 86.5
Iris	*Iri L.*	0.5
Goldenbush	*Isocoma menziesii*	2.5
Salty susan	*Jaumea carnosa*	2 to 86.5
Saltmarsh lavender	*Limonium californicum*	2 to 2.5
Boxthorn	*Lycium calfiornicum*	2
Croceum iceplant	*Malephora crocea*	2 to 11
Little mallow	*Malva parviflora*	1.5 to 2
Shoregrass	*Monanthochloe littoralis*	3 to >135
Prickly pear	*Opuntia sp.*	3
Dock	*Rumex crispus*	2 to 53.5
Annual pickleweed	*Salicornia bigelovii*	3 to 55
Glasswort	*Salicornia subterminalis*	5 to 71.5
Pickleweed	*Salicornia virginica*	6 to >135
Russian thistle	*Salsola Kali L.*	3.5 to 47
Brazilian Peppertree	*Schinus terebinthifolius Raddi*	0.5 to 5
Estuary Sea-Blite	*Suaeda esteroa*	10 to 55
Medusahead	*taeniatherum caput-medusae*	1 to 25
Clover	*Trifolium l.*	2
Arrow grass	*Triglochin concinna*	25 to 86.5
Mexican fan palm	*Washingtonia obusta*	2

A graph of the salt tolerances of all of the studies plant species was created using the ranges listed in Table 2. Comparisons of ranges can be made using Graph 1 below. The most noticeable result from this plot is that native plant species had the largest salt tolerances of all of the sampled plants. The native Shoregrass had the largest range of all the 34 species sampled with a salt tolerance from 3 to >135ppt. It is important to note than Picklweed and Saltwort also had ranges ending in >135ppt and since the exact amount of those salinity readings are not known, there is a possibility that either species could surpass Shoregrass as the largest salt tolerance range. Nine of the fifteen native plants had ranges that began in low salinities of a few parts per thousand and continued through to high salinities >50ppt. Only two of the native species were found from mid to high or only in high salinities. This included the Arrow Grass with a range from 25 – 86.5ppt and the Saltwort with a range from 50 to >135ppt. Three species of natives in the upland habitat were only found in areas of very low salinity. The first was the Sea Marsh Lavender with a range from 2 to 2.5ppt. The Goldenbush and the Buckwheat had very low point range salinities of 2ppt and 2.5ppt. The majority of native plant species studied were found within the lower more saline reaches of the marsh habitat. Twelve of the eighteen exotic plant species were found with salt tolerance ranges below 10ppt. Of those that crossed this threshold, two rose significantly over this mark. Dock and Russian thistle had ranges of 2 to 53.5ppt and 3.5 to 47ppt.

The three native plants with small salt tolerance ranges are of particular importance in that their lower salinity ranges might be indicative of a propensity for decreased health during generic salting experiments. It is particularly important to point out that the majority of invasive plant species were found on the upland low salinity habitat that is home to these three native species, making the area more prone to salting controls. The natives also share upland soils with invasive plant species that have higher constructed salt tolerances ranges than they do. This would suggest that salting would have to be significantly high to essentially push these invasive species out of their salt tolerance ranges which could consequently push these native plants out of their salinity ranges as well. However, as future sampling continues, there is the possibility that these native plants will increase the breath of their salt tolerance ranges. More sampling is needed for all plants, to accurately quantify the breath of salt tolerance ranges.

Graph 1: Salinity Ranges of Plant Species in graphical form



The results prove the assumption suggested in the salting hypothesis, with a small stipulation. The hypothesis rests on the assumption that it is plausible to use sea salt to control invasive species because invasive species have a smaller range of salt tolerances than that of native species. The data shows that native species do have the largest salt tolerance ranges of the species involved in the study, however a small subgroup of native species have relatively low salt tolerance ranges. Based on these few exceptions, considerations may need to be made about the location of salting, specifically that the highest areas of the upland habitat may need to be removed from this form of management. Possibly the avoidance of the Buckwheat, Salt Marsh Sea Lavender, and Goldenbush species during salting would be sufficient. The next study involving the salting of a host of native and invasive species will reveal more about the nuisances of plant reactions to increases in soil salinities.

Experimental B

A series of salting experiments were conducted in 25 of the 59 specific study locations chosen in experiment A. One particular plant species in each of the 25 locations was chosen to be subjected to a standardized salting procedure involving the direct injection of a specified amount of sea salt into the soil. It is important to note that at two sites, the size and spacing of the plant species allowed for more than one species to be salted concurrently. All locations had a different species of plant chosen for the salting experiment, except in two cases where the same species was used. In all cases, those plants subjected to salting were of one of the same species examined in the previous study. The specific sites were chosen principally based on vicinity to an adequate control site of the same elevation and inferred soil salinity. If many choices were available, as is the case with common species such as Pickleweed, then the decision was an arbitrary one made by the researcher. The goal of this study is to acquire information in order to make future informed decisions about the ability, effectiveness, and plausibility of future sea salting experiments. The results are designed to provide a springboard for future studies.

In general, sea salt is an unrefined salt and so lacks the stringent chemical formula and anti-caking agents of that of its table salt counterparts (Edible Salt). It contains natural traces of other minerals, including iron, magnesium, calcium, potassium, manganese, zinc and iodine (Salt Information). It is derived directly from sea water and is harvested through channeling ocean water into large clay trays and allowing the sun and wind to evaporate it naturally. Sea salt was chosen for the palpable fact that the study area is a salt water marsh that is inundated daily by tidal movements containing the same chemical. In essence the concentrations of this naturally occurring estuarine component are merely being increased in certain selected areas.

To begin, three separate core samples were removed from each of the specific plant sites chosen. The manual coring device that was utilized during the collection of soil samples during the first study was employed in this procedure to remove soil cores to a constant depth of 10cm equivalent to that of the root zone of halophytic plants (Root Depth, Salinity Notes, 2005). The cores were taken no more than 5 centimeters from the base of the plant or plants within the study area. Since root depth increases with distance from plant base, cores were removed close enough to the root system to ensure that the salt would be collected by a majority of the roots within the root system of the plant or plants in question, but not too close as not to harm the plant itself. To the three cored holes were added one cup of sea salt and then filled with tap water up to ground level. Water was added specifically to begin the dissolution of the salt. This dissolution would allow for the salt to combine with the current soil solutions, thereby increasing the salinity of the entire ground solution available to the plant immediately. The rate of subsidence of the water into the soil dictated whether the holes were refilled with water. The idea was to have the water seep into the soil slow enough to give time for some of the sea salt to go into solution and be carried into the soil. Once the water amounts within the cored holes did not decrease at a visible rate, the holes were covered with the removed core soil to avoid evaporation of the water. Each site was revisited within the hour to completely cover the salted holes with the remaining soil after the water had been absorbed. Solid salt was used instead of a salt solution for this experiment specifically because the study took place in the winter months typified by increased precipitation, whose tendency would be to leach salts from the soils. This would easily flush an applied salt solution away principally because only a small amount of salt would be able to go into solution with the amounts of water used in the experiment. To dissolve a large amount of sea salt, greater amounts of water would be needed which could not be accommodated by the size of the cored voids. The rain could be used to the advantage of the study however by using solid sea salt, because the rains would continually add water to the soil, dissolving the salt gradually over a prolonged period of time. This design would supply a prolonged amount of salt to the soils and thereby a lengthy exposure of salt to the plant.

Results and Discussion B

The specific native and invasive species involved in the sea salting experiments are listed in Table 3, as are their initial soil salinities and corresponding habitats. The qualitative effects that each plant exhibited after having their soil salinities increased by the sea salt, are show on the far right column. Each salted site was revisited starting at 10 days after the injection of the salt into the soils. After the initial check-up, the sites were revisited every five days for a total of 25 days in total. The physical changes experienced by the each plant species and viewed on the first 10 day visit, were indicative of the total change over the course of all check ups. For this reason only the descriptions of the initial checkup were included in Table 3.

Table 3: Qualitative Results of Salted Plant Species

SITE NUMBER	HABITAT	COMMON NAME	NATIVE OR INVASIVE	SOIL SALINITY ‰	QUALITATIVE EFFECTS OF SALT AFTER 10 DAYS
1	U	Brazilian Peppertree	I	5	yellow and browning of leaves, some leaves falling off, desiccation of berries
2	U/T	Palmer's seaheath	N	31	None
2	U/T	Alkali heath	N	31	None
3	SM	Palmer's seaheath	N	58	None
3	SM	Saltwort	N	58	None
3	SM	Pickleweed	N	58	None
4	U	Goldbush	N	2.5	None
5	U	Boxthorn	I	2	woody stems have become brittle, dropped Vegetation
6	U	Medusahead	I	1	turning yellow-brown inside of sheaths, sheaths themselves have picked up red colors, limp Extremities
7	U	Russian thistle	I	3.5	slightly brittle, two are relatively yellow-brown through mid-section
8	SP	Pickleweed	N	135	None
9	SP	Saltwort	N	50	desiccation of leaves
9	SP	Pickleweed	N	50	None
10	U	Atriplex semibaccata	I	11	increased brittleness, yellowing throughout
11	U	Croceum ice plant	I	2	picking up colors of yellow, orange, and red; 2 of 5 flowers dead and other 3 partially closed
12	U	Saltbush	I	1	slight yellowing, brittle
14	U	Clover	I	2	complete yellowing of plant, limp
15	U	Iris	I	0.5	None
16	U	Ornamental aloe	I	3	yellowing around exterior portions of vegetation, picking up red-purple colors
18	U	Brome grasses	I	1	brown, limp
19	U	Estuary Sea-Blite	N	28	picking up colors of yellow and a bit more red
20	U	California Buckwheat	N	2	burnt orange and brown, brittle, dead
21	U	Little mallow	I	2	None
22	U	Freeway ice plant/hottentot fig	I	7.5	desiccation of vegetation; some areas dry and brown, other yellow orange and wrinkly
23	U	Croceum ice plant	I	11	reddening
24	U	Little mallow	I	1.5	none to tiniest bit of yellowing
25	U	Healtleaf ice plant/red apple	I	3.5	yellowing of vegetation
26	U	Prickly pear	I	3	reddening in color, desiccation at exterior tip, limp

27	U	Jade tree	I	2.5	None

It is important to note that all of the salt marsh, salt panne, and transition habitat species that were tested with increased salt concentrations were native species. This is presumably due to the fact that these areas have very high soil salinities which make it harder for invasive species whom are generalists of non-evolutionary origin to survive. None of these native species showed any physical changes or signs of distress during the observational period except one species in one location. The *Batis maritima,* common name Saltwort, located in the salt panne showed desiccation in its vegetation. However, with close inspection, this specific plant was found to have a broken appendage. This structure trauma is sufficient enough to cause decreased water movement to the extremities of this plant. For this reason the decreased health of the Saltwort is attributed to this injury, as opposed to increases in salt concentrations. The rest of the species, 21 in total, where all found within the upland habitat. Sixteen of these showed some signs of decreased health and or discoloration due to the salt. Noting the color changes was important because a reddening of the plant tissue is a physical manifestation of the effect of salt on a plant. Five of these upland species, or ~25%, exhibited no reaction to the salt content of the soils. It is important to note that the Iris at site 15 had a half meter diameter base. The traditional salting method was changed a bit to compensate for this size, by focusing the salting in one specific area. The hope was to effectively salt only one iris bulb (the underground organ used for plant storage) in the plant aggregate.

Looking at the qualitative data, an arbitrary scaling system from one through five was constructed to describe the intensity of the effect that the salt had on the plant species in question. The construction of this system allowed for a quantitative analysis of the qualitative data that was collected. A one was given to those plants that exhibited no affects to the salt. A two was given to those plants that only showed signs of change in color but no decrease in physical health. This color change was specifically due to increases in salt in the plant tissues which manifested itself as a reddening in color. A three was given to those species that showed color changes and had either increased brittleness or limpness. A four was given to those plants which showed significant signs of desiccation, included dead flowers, dried berries, and the dropping of leaves or other forms of vegetation. Finally category five was reserved for those species who were extremely affected by the salt, either being near death or already dead. This category was only used twice, once for the patch of Brome Grasses in plot 18 and once for the California Buckwheat at site 20. Table 4 shows the common names of all salted species by site with their corresponding salt deterioration rating.

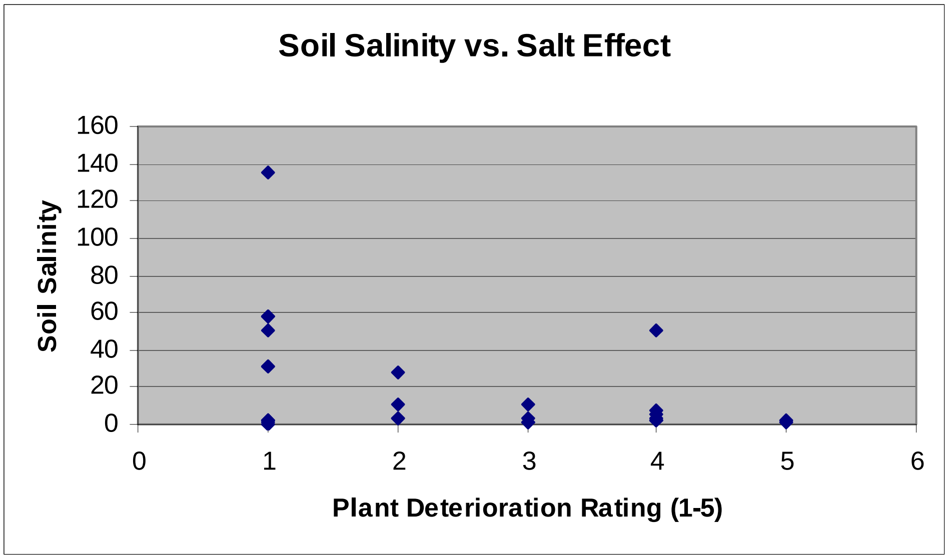
Table 4: Common name of salted species and corresponding Salt Deterioration Rating

SITE NUMBER	COMMON NAME	SALT EFFECT RATING
1	Brazilian Peppertree	4
2	Palmer's seaheath	1
2	Alkali heath	1
3	Palmer's seaheath	1
3	Saltwort	1
3	Pickleweed	1
4	Goldenbush	1
5	Boxthorn	4
6	Medusahead	3
7	Russian thistle	3
8	Pickleweed	1
9	Saltwort	4
9	Pickleweed	1
10	Atriplex semibaccata	3
11	Croceum ice plant	3
12	Saltbush	3
14	Clover	4

15	Iris	1
16	Ornamental aloe	2
18	Brome grasses	5
19	Estuary Sea-Blite	2
20	California Buckwheat	5
21	Little mallow	1
22	Freeway ice plant/Hottentot fig	4
23	Croceum ice plant	2
24	Little mallow	1
25	Healtleaf ice plant/red apple	2
26	Prickly pear	3
27	Jade tree	1

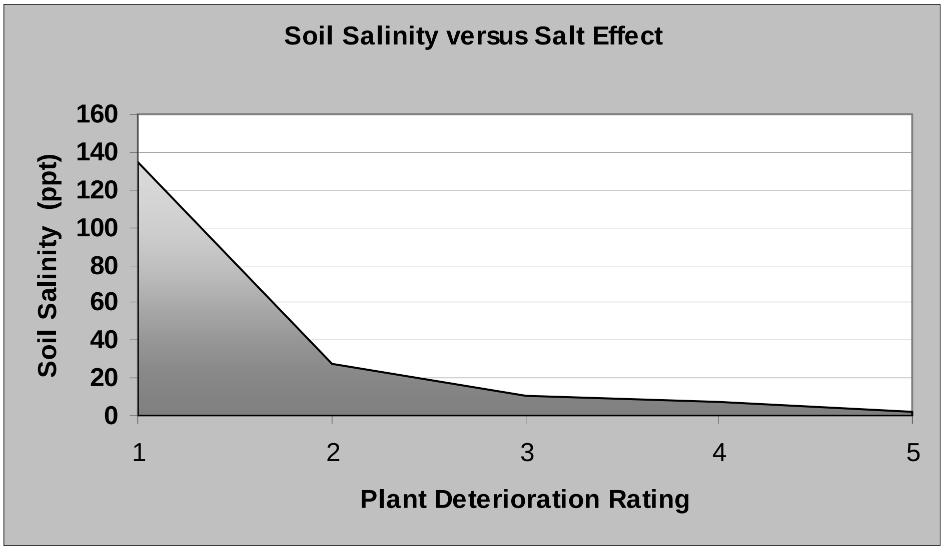
A graph of the salt deterioration rating information in Table 4 and the soil salinities in Table 3 was constructed in Graph 2. This graph reveals a decreasing step-wise trend in soil salinities with increases in salt deterioration. The results show that plant species growing in higher soil salinities were less affected by the artificial salt additions to the soils than were the species growing in areas of lower salinity.

Graph 2: Soil Salinity vs. Salt Effect



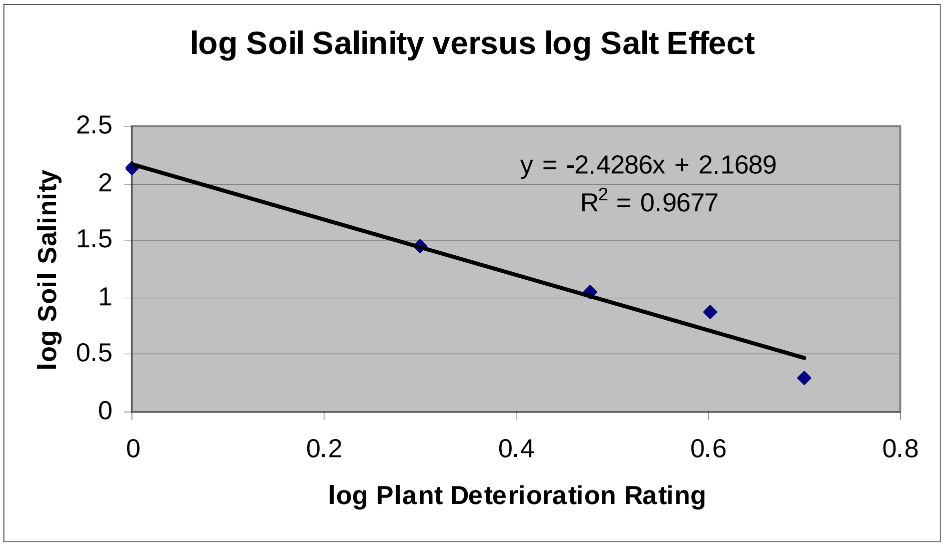
To illustrate this point more effectively an area plot was constructed in Graph 3 using the highest soil salinity measurement found for each of the five plant deterioration rating categories. It is important to note that the outlier in plant deterioration rating category 4, the injured Saltwort was removed from the data in Graph 3.

Graph 3: Area graph of Soil Salinity versus Salt Effect with outlier removed



To investigate the changing slope of graph 3, the logarithm of the uppermost salinity ranges for each of the five categories of plant deterioration and the logarithm of the plant deterioration rating were plotted together to reveal the linearity between the two factors.

Graph 4: Logarithmic plot of Uppermost soil Salinities and Salt Effect Rating



The R-squared value is the square of the correlation coefficient which is the measure of the reliability of the linear relationship between the x and y values (Odom, 2001). A value of R = 1 indicates an exact linear relationship between x and y. The linearity of this function/data fit being 0.9677 shows an excellent linear reliability between the logarithms of soil salinity and plant deterioration. The trend of the corresponding graph shows that as salt effects increase, the propensity for those affected species to be those located on soils of high salt salinities, decreases at an exponential rate. The reason behind this outcome is a logical one. Species subjected to naturally high soil salinities are having their salinities changed artificially by the salt only small percentages of the total, relatively speaking. Those species with low soil salinities are in many instances doubling and tripling their soil salinities, increasing their relative percentages by factors of 100 or greater. Although on an absolute scale the changes may appear to be the same, relative percentages are truly indicative of the magnitude of the affect of the change.

No definitive answers can be given to whether salting is a plausible means of exotic plant eradication. The salting experiments have showed us that the highly salt tolerant native species were not affected by the increases in salt concentration; however one native species with a lower and narrower salt tolerance range did show some affliction. Of the three native plant species listed in experiment A as having low salt tolerance ranges, two of these species, the California Buckwheat and the Goldenbush, were subjected to sea salt soil injections. The Goldenbush showed no signs of negative changes in health due to the increases in salt. The Buckwheat however was severely affected by the salt, as evident by its plant deterioration rating of 5. This plant species is found on the utmost portion of the upland marsh and presumably this species could be avoided if salting controls are employed. There is a question of whether affected natives can rebound as the native species did in the researched experiment with the Caulerpa taxifolia. To discover this answer more salting experiments using upland low salt tolerant native plant species are needed. Additional experiments should also be done involving an increased number and type of exotic species. By subjecting many plants (in varying salinities) of a certain species to salting, deterioration effects can be observed as a function of original soil salinity. It would become more evident in these experiments, how position, in reference to current soil salinity, of a species within salt tolerance range affects the deterioration behavior of the plant. As an important reminder, the salting experiments here were not designed to kill the exotic species, only to observe how each species reacted to the increases in soil salt concentrations. To answer the question of eradication, further experiments with increased amounts salt application will be needed to reach that threshold.

Experimental C

The third study involved the re-sampling of the salted sites in experiment B, during the month of May, three months after the salting experiments had occurred. Two of the sites were not sampled because the change in vegetation after the winter storms proved it impossible to locate the exact area of salting, even with help from the global positioning system device. In the same method as utilized in experiment A, the manual coring device was used to remove the soil sample from the desired location, retrieving a soil depth to 10 centimeters. The 10 centimeter depth was employed principally because the span of depth possesses the majority of the root system used in solution extraction. It is not assumed that salt does not leach past this depth line, only that leaching at this level is less important to plant water uptake due to decreased root percentages. Each location was sampled in two areas. One area, the “salted” sample, was taken 0.25m down slope from the area that had been salted in the prior experiment. The idea was that the winter rains would leach the salt moving it in a downhill direction due to gravity, which could consequently be picked up through sampling. The second sample, the “control”, was taken 0.75m nearby in an area of similar slope as that of the salted area. A similar slope was chosen to avoid gravitational movement of salt water into the location and natural variations of salinity to do elevation. This control sample was imperative to obtain because natural changes in salinity due to environmental factors were important to know so the actual change in salt concentration due to the salting experiments could be obtained. Once the sample had been removed, the soil was immediately bagged, sealed, and labeled with its corresponding information. All soil samples were processed by the guidelines of the Soil Paste Methods as outlined in the Experimental A section.

Results and Discussion C

Each of the three soil samples taken over the course of the 4 month period, which include the original, salted, and control samples, are listed in Table 5 for each of the salted sites.

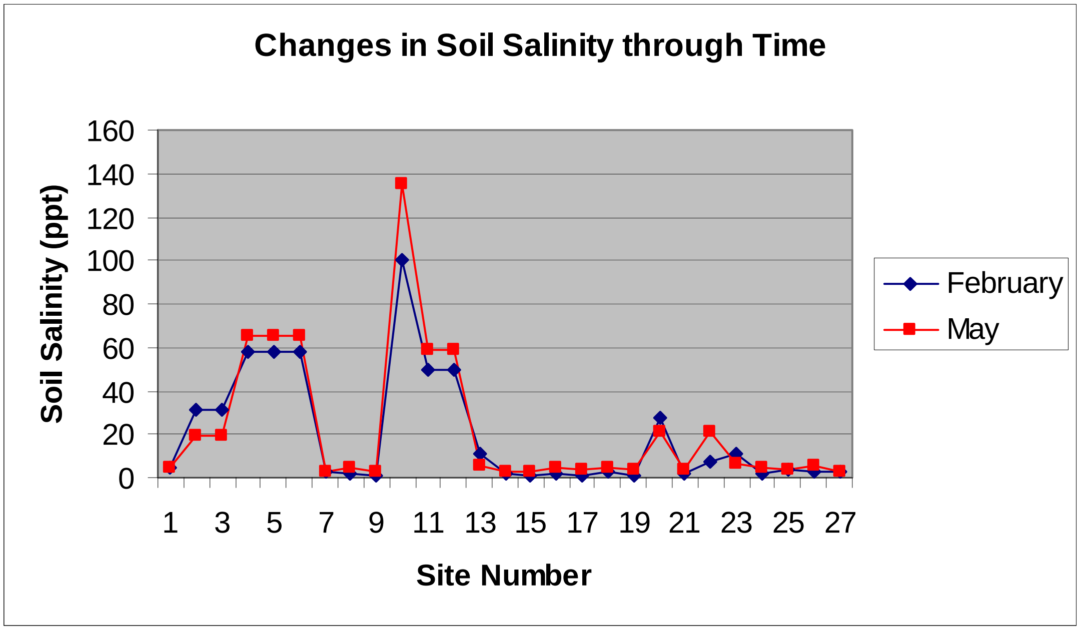
Table 5: Lists of all three soil samples taken over the course of three months and the changes between each

SITE NUMBER	SOIL SALINITY ‰	CONTROL ‰	SALTED ‰	CONTROL ‰	CHANGE SALTED VS CONTROL ‰	CHANGE IN CONTROLS ‰	CHANGE IN ORIGINAL SAMPLE AND SALT ‰
1	5	5	5	5	0	0	0
2	31	19	38	19	19	-12	7
2	31	19	38	19	19	-12	7
3	58	65	66	65	1	7	8
3	58	65	66	65	1	7	8
3	58	65	66	65	1	7	8
4	2.5	3	3.5	3	0.5	0.5	1
5	2	5	10	5	5	3	8
6	1	2.5	3	2.5	0.5	1.5	2
8	100	135	90	135	-45	35	-10
9	50	59	46.5	59	-12.5	9	-3.5
9	50	59	46.5	59	-12.5	9	-3.5
10	11	5.5	6	5.5	0.5	-5.5	-5
11	2	3	5.5	3	2.5	1	3.5
12	1	2.5	2.5	2.5	0	1.5	1.5
14	2	4.5	4	4.5	-0.5	2.5	2
15	0.5	3.5	3.5	3.5	0	3	3
16	3	4.5	7.5	4.5	3	1.5	4.5
18	1	4	5	4	1	3	4
19	28	21	13	21	-8	-7	-15
20	2	3.5	5	3.5	1.5	1.5	3
22	7.5	21	22	21	1	13.5	14.5

23	11	6	7	6	1	-5	-4
24	1.5	4.5	5	4.5	0.5	3	3.5
25	3.5	3.5	4	3.5	0.5	0	0.5
26	3	5.5	27.5	5.5	22	2.5	24.5
27	2.5	3	39.5	3	36.5	0.5	37

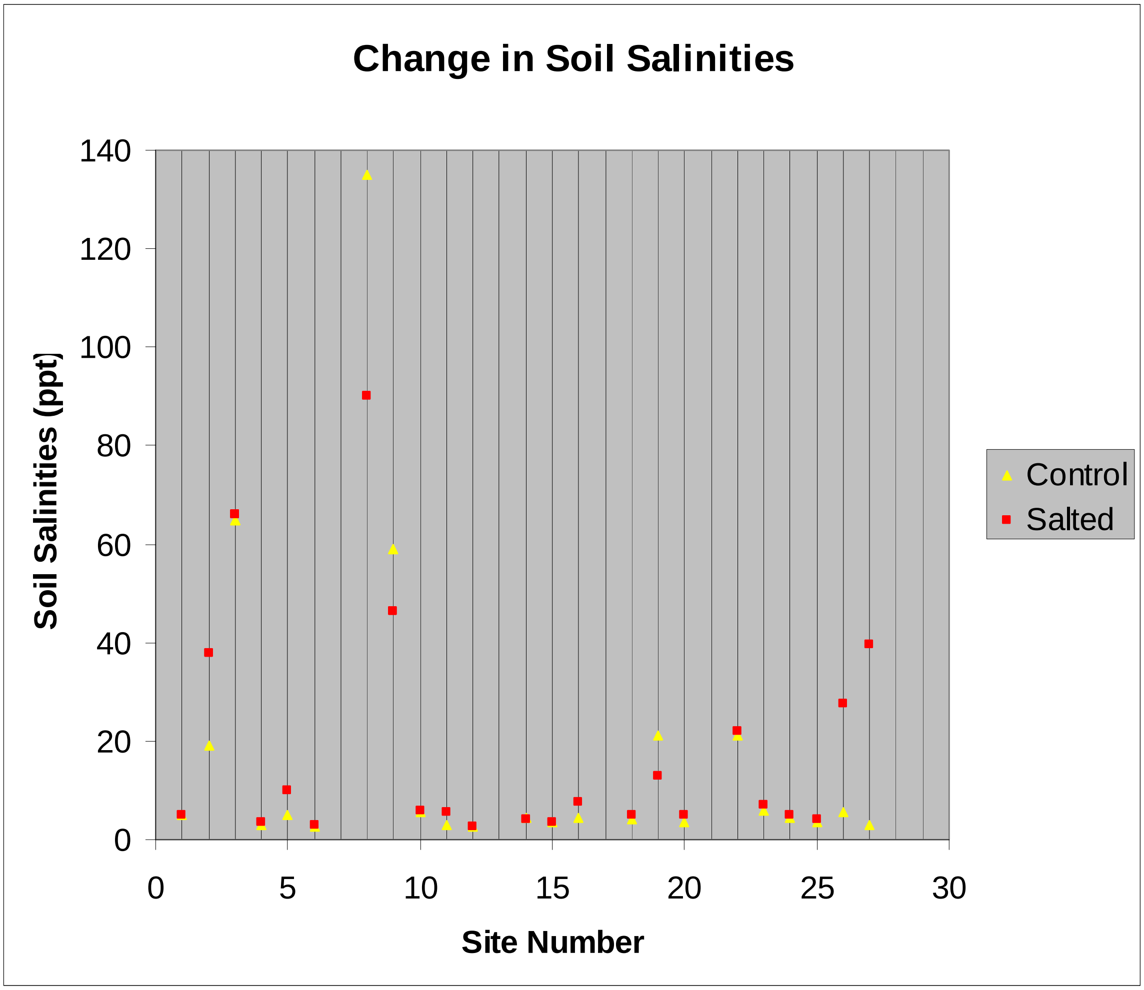
When comparing the original sample to that of the control, 17 out of the 23 sites saw increases in soil salinities in their controls, as evident in Graph 5. Although the estuary did receive fresh water input from rains, this was not enough to counteract the explosion of herbaceous plant growth. The large increase in the number of plant species had that the affect of removing waters from the soil and concentrating the salts for a net increase in soil salinity (Salinity Notes, 2005). Interestingly enough, three of the four sites that experienced decreases in soil salinity were located in the zone found directly adjacent to the dead end street. Fresh water flows introduced to this area via the subaerial storm drain and curb runoff caused flooding during rains, aiding in the leaching of salts from these soils.

Graph 5: Changes in Soil Salinity due to natural environmental effects



The differences between the salted and control soil salinities taken at the 23 sites were minimal on an absolute scale. Twelve of the sites that were sampled had less than or equal to a 1ppt increase in soil salinity. Four even showed decreases in soil salinity between the two sampled regions. Only at three sites were there found to be dramatic increases in salinity measurements.

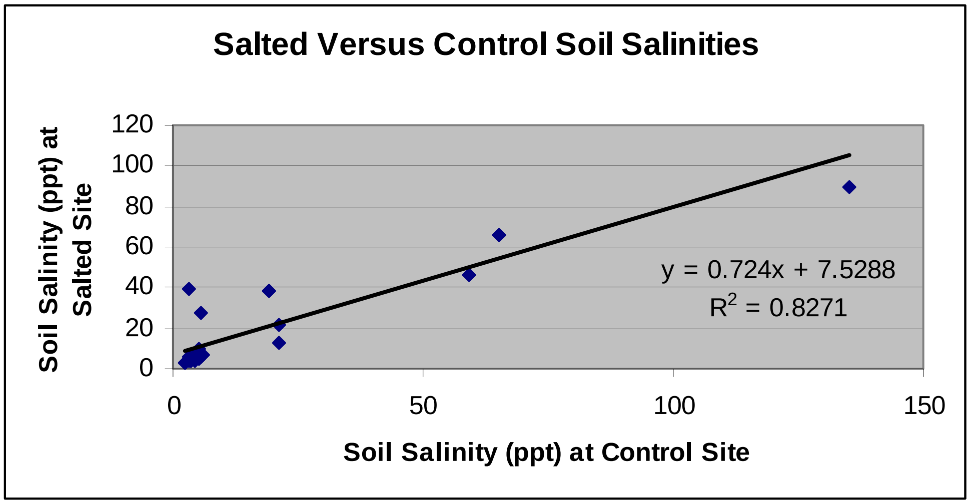
Graph 6: Differences in Soil Salinities between Salted and Control samples



Site 2 showed an increase of 19ppt from that of the control sample taken. This site is located in the span of reserve that is downstream from the underground storm drain outlet. The salted site was located adjacent to a downcut channel caused by runoff from the street. All fresh water runoff in this area was diverted into that channeled. This had the affect of decreasing the soil salinity of the control sample but not that of the salted area. Throughout the course of the season as rains caused flooding in this region, the salted site never received increased leaching because of its higher elevation as compared to the channelized areas. Evidence of this can be seen by comparing the control sample taken in May to the sample taken in February. The February sample was found to be 31ppt and the control sample taken in May was 19ppt for a decrease of 12ppt. Comparing the original sample to that of the salted sample, change was only an increase of 7ppt. However, the typical change in soil salinities between controls was found to be an increase of a few parts per thousand. If we take this into consideration with the original control, and ignore the fact that this site is located in an anomalous location, the expected control salinity would have been around 34ppt. When comparing this salinity amount to the salted region of 38ppt, there is only a net change between the two of about 4ppt. So technically only 2 of all of the 25 sites showed increases in soil salinities due to the artificial salting methods employed by the experiments.

The soil salinity readings taken from the control and salted areas were plotted against one another in Graph 7 to extract the linearity between the two factors. The closer the R^2 value is to one, in this case, reveals a decreasing effect of artificial salt emplacement on changes in soil salinities. A value of one would reveal no change. A value of 0.8271, shows that there are some minimal changes in soil salinities due to the sea salt injections.

Graph 7: Salted versus control soil salinities



The change in soil salinity is important because we do not want artificial salting to raise the salinity so high that no plant species will be unable to inhabit that area. However, we do want soil salinities to stay at increased levels for a period of time to thoroughly eradicate the unwanted species and to discourage recovery of other exotic plant species in that site. It is hard to say exactly how long soil salinities should remain elevated and what elevations are appropriate. The answer to the latter question might even end up being a subjective one that changes depending on the researcher in question. Further studies will be needed to understand the accumulation and dissipation rates of salts in the soils and their movements in the soils through time. Studies involving variable salt concentrations will inevitably increase the changes between control and salted samples. These changes will have to be studied with re-infestation abilities of exotics and reintroduction of native species onto the soils. This will prove to be a complicated web of connections, involving cause and affect relationships. Only further studies will be able to tell if artificial changes in soil salinity will have a negative effect on vegetation.

Conclusions

Eleven of the fifteen native plants sampled in the first study had ranges that spanned >45ppt. Three species of natives in the upland habitat however were only found in areas of very low salinity. This included the Sea Marsh Lavender with a range from 2 to 2.5ppt, and the Goldenbush and Buckwheat whose point range salinities were 2ppt and 2.5ppt. Twelve of the eighteen exotic plant species were found with salt tolerance ranges below 10ppt. Of those that crossed this threshold, the Dock and Russian thistle had ranges of 2 to 53.5ppt and 3.5 to 47ppt, which is each a significantly large salt tolerance range relative to the majority of exotic plants. These two exotic plant species fall into lowest of the large range salt tolerances exclusively dominated by native species as shown in Table 6.

Table 6: Breath of Salt Tolerance Ranges of Native and Invasive plant species

COMMON NAME	Breath of Range	Native/Invasive	COMMON NAME	Breath of Range	Native/Invasive
Saltmarsh Lavender	0.5	N	Iris	0.5	I
California Buckwheat	2	N	Little mallow	0.5	I
Goldenbush	2.5	N	Aeonium spathulatum	1.5	I
Saltbush	30	N	Boxthorn	2	I
Estuary Sea-Blite	45	N	Croceum ice plant	2	I
Alkali weed	51	N	Clover	2	I
Annual Pickleweed	52	N	Mexican fan palm	2	I
palmer's seaheath	55	N	Jade tree	2.5	I
Arrow grass	61.5	N	Ornamental aloe	3	I
Glasswort	66.5	N	Prickly pear	3	I

Alkali heath	79.5	N	Healtleaf ice plant red apple	3.5	I
Salty susan	84.5	N	Brazilian Peppertree	4.5	I
Pickleweed	>129	N	Brome grasses	5	I
Shoregrass	>133	N	Freeway ice plant/Hottentot fig	7.5	I
Saltwort	>85	N	Atriplex semibaccata	23	I
			Medusahead	24	I
			Russian thistle	43.5	I
			Dock	51.5	I

Although native species do have larger salt tolerance ranges than invasive species, there are exceptions to this rule. As illustrated above, there is a subgroup of native species that have relatively low and narrow ranges and two exotic species with salt tolerances ranges of significant breath. The assumption suggested in the sea salting hypothesis stated that it is plausible to use sea salt as an invasive species control mechanism because non-native species have a narrower range of salt tolerances than that of native species. This was found to be true the majority of the time, but as with all things, nature included, there are exceptions. More experiments are needed to refine the salt tolerance ranges for both the native and invasive species. Ranges will more than likely expand in size as continued sampling for each species occurs. This hypothesis rests on the assumption that the frequency of plant species decreases within the range as the edges of the salt tolerance range are neared, principally because of the movement away from the optimal mid-range environment.

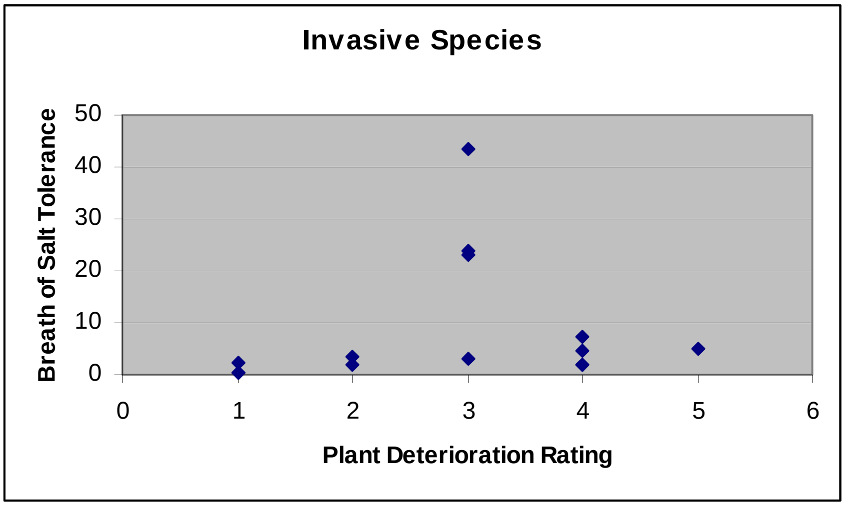
At the conclusion of the salting experiments, none of native species with large salt tolerance ranges showed any physical changes or signs of distress during the observational period except one species in one location. The species however was affected by injury, not increases in salt concentration. Of the narrow salt tolerant native species, two of these species, the California Buckwheat and the Goldenbush, were subjected to sea salt soil injections. The Goldenbush showed no signs of negative changes in health due to the increases in salt. The Buckwheat however was severely affected by the salt, as evident by its plant deterioration rating of 5. A subset of experiments should take place involving only native species with narrow salt tolerance ranges. These plants are of particular interest because they are prone to decreased health due to artificial salt injections as suggested by their ranges. They are also found in the upland habitat where the majority of exotic species grow, hence the likelihood of salting in areas, with these low salt tolerant natives, is high. There is the possibility that affected natives species can rebound as the native species did in the researched experiment with the Caulerpa taxifolia. To ascertain this answer more salting experiments using upland low salt tolerant native plant species are needed.

The overall trend found with salting demonstrated that as salt effects increase, the propensity for those affected species to be those located on soils of high salt salinities, decreases at an exponential rate. This effect was to be expected when looking at soil salinity changes with respect to the control sample. After being salted, plant species subjected to naturally occurring high soil salinities are having their salinities artificially changed by the salt only small percentages of the total soil salinity in that area. However, those species with low soil salinities are in many instances increasing their relative percentages by factors of 100 or greater. Although on an absolute scale the changes may appear to be the same, relative percentages are truly indicative of the magnitude of the affect of the change.

Combining the data from the first and second studies, Graph 8 was creating, showing the breath of salt tolerance ranges as a function of plant deterioration rating.

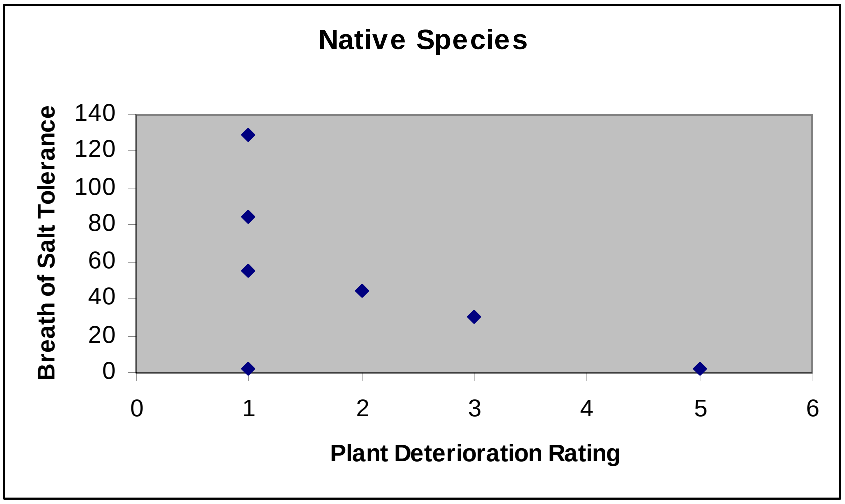
Three of the 14 invasive plant species showed no affects to the increases soil salinities due to sea salting. Presumably there would be a pattern of increasing deterioration ratings with decreases in breath of ranges, but overall there is no coherent pattern to the relationship between plant deterioration and salt tolerance breath. This could be because of a lack of data from which the salt tolerance ranges were constructed but more plausibly this is due to the location of a particular plant within its species salt tolerance range. This would affect the outcome of the graph because species near the uppermost portion of their salt tolerance ranges are going to behave more drastically to increases in soil salinities as the plant is moved farther away from its optimal environmental conditions. Even though a species might have a fairly large range, it might be near enough to the topmost boundary that it is affected more than a narrow salt tolerance species at the lower end of its range.

Graph 8: Breath of Salt Tolerance Ranges vs. the Plant Deterioration Rating Invasive Plant Species



The natives showed a bit more of a comprehensive trend, revealing that decreases in salt tolerance breath increased plant deterioration factors due to artificial soil salinity increases. However for the natives there were a few species whose salt tolerance ranges were narrow yet still showed no signs of deterioration. This is attributed to lack of sampling and therefore information from which salt tolerances have been constructed as well as location of that species within its salt tolerance range.

Graph 8: Breath of Salt Tolerance Ranges vs. the Plant Deterioration Rating Native Plant Species



Additional experiments should be done involving an increased number and type of exotic and native species. Specifically of interest are those invasive species with broad salt tolerances such as Dock and Russian Thistle. This would be one of the most important subsets to study because in theory, they will be the ones who need higher amounts of applied salts to see decreased plant health. This could have important implications on those native species found in the same areas that have a propensity to be negatively affected by increased soil salts. To reiterate, the salting experiments here were not designed to eradicate the exotic species, only to observe the reaction of each species to increases in soil salt concentrations. Further experiments with increased application of salt will be needed for this purpose.

Re-sampling of the salted areas found a change increases in control soil samples through time at a majority of the sampled locations. This is attributed to the explosion of herbaceous plant growth that had that the affect of removing waters from the soil and concentrating the salts for a net increase in soil salinity. Three of the four sites that experienced decreases in soil salinity were located in the zone found directly adjacent to the dead end street, whose fresh water flows aided in the leaching of salts from these soils.

The differences between the salted and control soil salinities taken at 23 of the salted sites were found to be minimal on an absolute scale. Twelve of the sites that were sampled had less than or equal to a 1ppt increase in soil salinity, with four even showing decreases in soil salinity between the two sampled regions. Only at three sites were there found to be dramatic increases in salinity measurements. One of those three sites however, one had uncharacteristic behavior due to its proximity to storm drain activity, so technically only 2 of all of the 25 sites showed increases in soil salinities due to the artificial salting methods employed by the experiments.

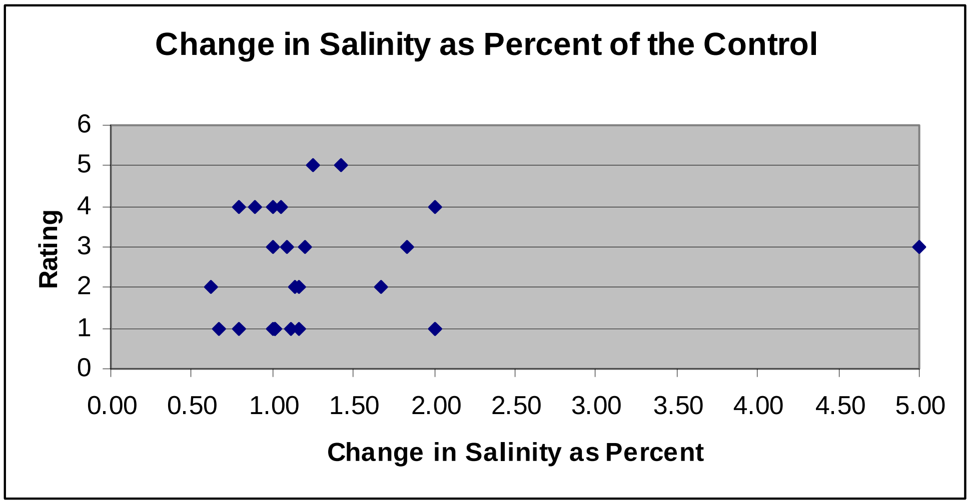
Instead of viewing the change in salinity on an absolute scale it may be beneficial to view this information as a percent of the control soil sample. The changes between the salted and control samples as a percentage of the control sample are listed for each of the salted sites in Table 7.

Table 7: Change between salted and control salinities as a percentage of the control

SITE NUMBER	Change as Percentage of Whole	SITE NUMBER	Change as Percentage of Whole
1	1.00	12	1.00
2	2.00	14	0.89
2	2.00	15	1.00
3	1.02	16	1.67
3	1.02	18	1.25
3	1.02	19	0.62
4	1.17	20	1.43
5	2.00	22	1.05
6	1.20	23	1.17
8	0.67	24	1.11
9	0.79	25	1.14
9	0.79	26	5.00
10	1.09	27	13.17
11	1.83		

It becomes apparent in graph 9 that by only taking the percent change in soil salinity into account; the resultant amount of deterioration of the plant cannot be directly inferred. This would suggest that there are more complicated and important factors involved such as the location of the plant within its salt tolerance range.

Graph 9: Change in salinity between salted and control sites as a percent of the control



A more complete analysis of this information taking into account location of the plant within its salt tolerance range would not be worthwhile at this point specifically because of the minimal numbers of samples that were used to create these ranges. Once larger more accurate salt tolerance ranges are constructed using a multitude of salinity measurements, viewing deterioration due to salting while referencing plant location within a species salt tolerance range will prove beneficial.

As for the question of the negative effects of artificially raising soil salinities, that question remains to be answered. From these studies, it is hard to say exactly how long soil salinities should remain elevated and what elevations are appropriate. Further studies will be needed to understand the accumulation and dissipation rates of salts in the soils through time, as well as the success of re-infestation of exotics and reintroduction of native species.

The future investigation of salt tolerances of native and invasive plant species found on the Tijuana Estuary will be an important factor when considering future management decisions. The Tijuana estuary’s Comprehensive Management Plan states that "the control of exotic species is critically important to maintaining and enhancing resource values throughout the reserve" (Laws and Regulations;1999). Improving and expanding current literature on the salt tolerance ranges of invasive species will provide important information relating to this management plan. By sampling soils in critical locations (specifically those involved in restoration efforts), a basic idea of the soil salinities in that area can be ascertained and from these, a variety of inferences made using the constructed salt tolerance ranges. This includes the ability of plant species to sustain life in that area, to migrate to adjacent regions, and assumptions on recolonization (natural and artificial). It is important to note that the characteristics of an environment for colonization are slightly different from that of an environment in which continued survival of a particular plant species is sustained, so constructed ranges could only be used as a general guideline in this instance. Comments can also be made on the degree of the before mentioned factors and characteristics by looking at where a specific soil salinity measurement resides within a species salt tolerance range.

The addition of sea salts into soils has the potential to be included in the prospective approaches of the Invasive Management Plan. Generalized salting of large restoration areas has the proposed potential to eradicate large numbers of exotic species without the destruction of native vegetation. This method could potentially involve a significant decrease in human labor, as well as minimal costs associated with the acquisition of sea salt. Preliminary studies suggest that due to differences in salt tolerance ranges, salting could be an effective management tool in a variety of habitats, however further studies and experiments are needed before any concrete decisions are made regarding the inclusion of salting into management plans.

The future management of the Tijuana Estuary is illuminated by a variety of prospective projects that will provide insight, enlightenment, and a unique and progressive prospective to the many facets of invasive species management. The stimulation of more public and private interest as well as increased educational involvement will provide important opportunities for advancement in the future of management and research for the Tijuana Estuary Reserve.

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