THE EFFECTS OF SALINITY AND BURIAL DEPTH ON RHIZOMAL REGROWTH OF EUROPEAN BEACHGRASS (*AMMOPHILA ARENARIA* (L.) LINK)

by

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The introduction of European Beachgrass (*Ammophila arenaria* (L.) Link) along the Pacific Coast has caused considerable damage to the dune ecosystem. Agencies such as the Oregon Dunes National Recreation Area have taken chemical and mechanical measures to control the spread of beachgrass. Two of these methods, mechanical burial and salinity treatments, were assessed for their efficiency as control measures of *Ammophila*. Experiments performed included a survey of a recent burial site for amounts of regrowth and laboratory and field analysis of *Ammop*growth under various salinity treatments and burial depths. Results show no linear correlation between growth inhibition and depth of rhizomal burial; however the salinity treatments appear to significantly reduce the amount of regrowth. A combinatory approach would be the suggested treatment for agencies seeking to control *Ammophila* using the above methods.

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INTRODUCTION

The introduction of foreign species is one of the growing human impacts that threatens natural habitat. The definition of an introduced or non-native organism is one that has been transported to an area within historical time. Species introductions frequently occur when seeds, eggs, or organisms themselves are brought to new places inadvertently in cargo of ships, on other vehicles, or purposely transported for human use. Many introduced species become invasive, spreading rapidly throughout a formerly diverse habitat and outcompeting native species for resources, often causing them to become locally extinct. Invasive species characteristically have a high rate of reproduction, variable habitat requirements, wide dispersal mechanisms, propensities for disturbed areas, and tolerance of human interaction.

The effects of introduced species range in scale from local extinction to long-term changes in topography and ecological processes. For example, the invasion of the Zebra mussel *Dreissena polymorpha* in the Great Lakes region has caused considerable die-off of native mussel species by direct encrustation. High densities of *D. polymorpha* has also altered the composition of benthic invertebrates through the addition of massive amounts of metabolic wastes (Garton et. al. 1993).

In Oregon, European beachgrass *Ammophila arenaria* (Plate 1) was intentionally introduced to stabilize the blowing sand of the active coastal dunes. This provided stability for increased development and use of the coastal zone. Ammophila arenaria spread quickly away from the areas into which it was planted and has changed the Pacific Coast from blowing sand to vegetated wetlands. Various land management agencies have struggled to control and eradicate *Ammophila* without causing unnecessary harm to coastal ecological processes.

The first documented planting of *Ammophila* on the Pacific Coast was in the 1880s at Golden Gate Park (Buell, Pickart, & Stuart 1995). In 1910 it was introduced to Oregon near the Coos Bay area (Cody 1981). From there it spread rapidly throughout the Oregon dunes and increased its cover exponentially over time. In a 1995 study of Humboldt County, a 574% increase in *Ammophila* cover was found during 1939 to 1989 (Buell, Pickart, & Stuart 1995). Figure 1 shows the comparative distribution of Ammophila along the North Spit of Humboldt Bay during the years 1939/1942, 1962, and 1989 (Buell, Pickart, & Stuart 1995).

Ammophila's success as an invader can be attributed to biological characteristics that make it a good competitor and an effective pioneer species, while the dune ecosystem as a frequently disturbed area, is susceptible to biological invasion. *Ammophila* can thrive in areas with significant exposure and wave action, as well as soil with low nutrient content. An erect perennial up to 1m tall, European beachgrass has a strong horizontal and vertical rhizome system (Huiskes 1979). New shoots develop from nodes along

Plate 1. *Ammophila arenaria* hummocks on the North Siltcoos area, Oregon Dunes National Recreation Area.

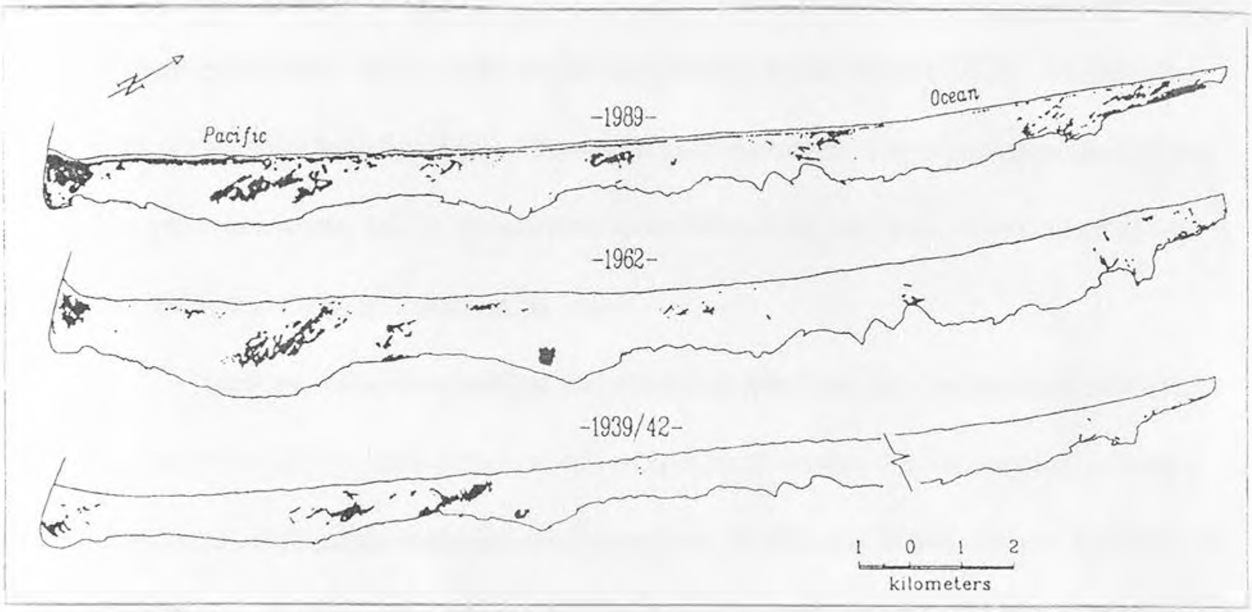

Figure 1. Distribution of *Ammophila arenaria* on the North Spit of Humboldt Bay, California, 1939/1942, 1962, and 1989. Abrupt differences in land mass are attributed to varying amounts of stereo overlap and tilt in air photos and to natural variance in coastlines over time (Buell, Pickart, & Stuart 1995)

These rhizomes and the resulting tufts of *Ammophila* form dense clumps. Reproduction occurs both clonally and from seed, most commonly from fragments washed up on the beach (Huiskes, 1979). This strong regenerative ability and marked growth plasticity also contribute to its high rate of establishment (Huiskes 1979). Figure 2 shows the various parts of *Ammophila* , including the vertical and horizontal rhizomes, internodes, dormant buds, and shoots.

European beachgrass has adapted to the harsh dune landscape and developed means of competing with other dune species. It grows vigorously in a wide range of soils including those with low organic content and can tolerate a wide range of pH (Seliskar 1992). Through symbiosis with rhizosphere bacteria, *Ammophila* is able to fix nitrogen in soil and produce the compounds needed for growth (Abdel-Wahab 1975). Unlike other dune plants, European beachgrass thrives on sand accretion. The increase in sand allows it to grow new roots, taking up nutrients more efficiently, and grow upward and escape soil pathogens (van der Putten et. al 1989).

These qualities have enabled *Ammophila* to dominate the Oregon coast and have a significant impact on dune geographics and species diversity. The dense clumps form a wind barrier that causes increases sand deposition (Willis et.al 1959). Figure 3 (Gemmell, Greig-Smith, & Gimingham 1953) shows the stages of *Ammophila* growth, the horizontal and vertical rhizome formations, that correspond with accumulation of sand. The result of this accretion is the pronounced foredune structure that was absent in Oregon prior to

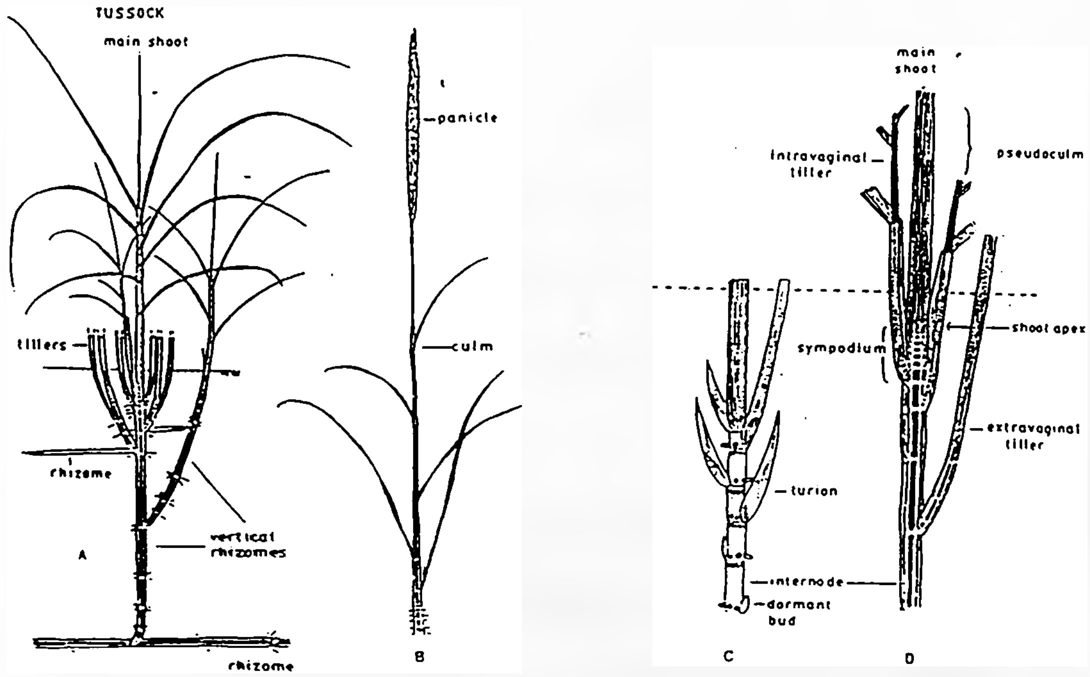

Figure 2. Diagram of plant structures of *Ammophila*. A) Structure of a tussock derived from tillering and branching of a single vertical rhizome, which itself arises from a lateral bud of a horizontal rhizome. B) Flowering culm. C) Winter dormant main shoot showing internodes, dormant buds and one tiller. D) Partial long section of a main shoot with tillers. (Baye 1990).

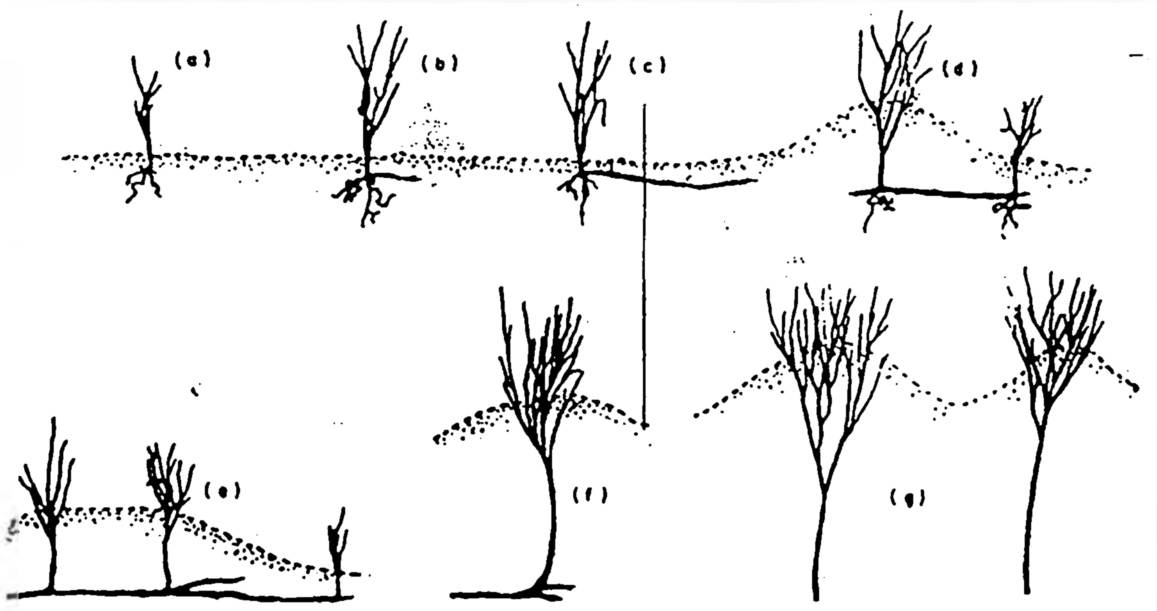

Figure 3. Diagram of successive stages (a-g) in the growth of *Ammophila arenaria* during continuous burial by sand (Gemmell, Greig-Smith & Gimingham 1953).

1940 (Wiedemann 1987). Sand no longer reaches the area behind the foredune, providing a stable area for less sand-tolerant plants to colonize. The result is altered species succession and the formation of a stable deflation plain (Boyd 1992). *Ammophila* has provided means for the expansion of the deflation plain into areas that were formerly open dunes.

Ammophila has affected various animal species as well as dune plant communities. Studies show that areas consisting primarily of beachgrass have lower arthropod diversities (Slobodchikoff & Doyen 1977, Barbour, DeJong & Johnson 1976) than surrounding vegetation regions. Much of the public and governmental agency concern about European beachgrass is tied to the endangered Western Snowy Plover. This migratory shorebird nests only on open sand. *Ammophila* has greatly reduced the amount of available nesting habitat and provides cover for nest predators (K. Palermo, Oregon Dunes National Recreation Area, pers. com.).

Public land management agencies have sought to control the spread of *Ammophila* through various mechanical and chemical treatments. Table 1 shows a summary of various treatment methods and their preliminary results. However, there are many barriers to eradication aside from the plant's resiliency. Insufficient documentation and lack of controlled experimentation has made it difficult to determine the efficacy of field treatments. The Oregon Dunes National Recreation Area is still developing a conclusive, efficient method of eradicating *Ammophila* (Segotta 1995).

The intent of my research is to provide the ODNRA and the general public with 1) an assessment of the effectiveness of two widely-used treatments and 2) new information regarding *Ammophila's* physiological limits. This project will explore the effects of salinity treatments and mechanical burial on rhizomal regrowth. Both of these control measures were recently applied to large field populations of *Ammophila.* An area of the North Spit near Reedsport, OR, was irrigated with seawater in early 1997 (B. Ries, Oregon Dunes National Recreation Area, pers. com.), while ODNRA

dug and buried a series of hummocks in North Siltcoos around February 1997 (B. Ries, pers. com.). *Ammophila* is reputedly vulnerable to soil salinity levels of over 1% (Huiskes, 1979); however, seawater inundation may not be as effective due to sand's poor water retention (Huiskes 1979) and the reduced uptake of moisture by the leaf blades (Baye, 1990). The rationale behind "scalp and burial" treatmentsis to kill the plant by depriving it of sunlight and fresh sand.

Upon reviewing these treatments, I chose to address the following questions. Is the "scalp and burial" treatment killing the *Ammophila* hummocks? At what burial depth would *Ammophila* cease to produce new growth? Will increased levels of salinity have an impact on the beachgrass? Are there ways to administer salt treatments such that physiological damage to *Ammophila* can be maximized?

Through sampling one of the sites near North Siltcoos, I was able to assess the effectiveness of mechanical burial as an eradication method and also establish some

Table 1. Some Control methods applied to *Ammophila arenaria* in various places along the Pacific Coast: Coos Bay Bureau of Land Management, Oregon, Lanphere Christensen dunes Preserve, California, and Oregon Department of Fish and Wildlife, Oregon. (Dorsey 1993, Miller 1994).

Treatment	Where Tried	Results
Prescribed fires	Coos Bay BLM	Reduces plant cover initially, vigorous growth resumes
Hand-pulling	Lanphere-Christensen ODFW	Effective but requires extensive labor, impossible for large areas
Mechanical Excavation and Burial	Coos Bay BLM Oregon Dunes NRA	Resprouts reach the surface, burial depths not sufficient to kill the plant.
Salt Treatment	Coos Bay BLM Lanphere-Christensen	Ineffective due to high rainfall and leaching.
Herbicides	Lanphere-Christensen ODFW	Effective, especially in combination with other treatments, poses health hazards and public issues

Other proposed treatments include natural pathogens, dredge material deposition, tilling, vehicular disturbance, and shading.

parameters for further experimentation. Chapter II describes the findings at various depths, as well as experiments focusing on the comparative levels of growth inhibition achieved at various burial depths. The intent of this exploration was to determine whether there was a critical depth at which rhizomes would perish and if this depth was achievable using mechanical burial methods.

Through lab and field experiments, I chose to address the specific questions regarding the effects of root and surface salinity on rhizomal regrowth of *Ammophila*. Controlled experiments were set up where *Ammophila* rhizomes were buried and irrigated with seawater and freshwater, as well as other treatments designed to maximize the plant's salinity intake. These treatments included the use of a common gardening aid, a synthetic polymer designed to retain water within the soil, and the addition of rock salt. Chapter III explains the procedures and outcomes of these experiments.

MECHANICAL BURIAL AS AN EFFECTIVE ELIMINATOR OF REGROWTH

Introduction

The expected physiological impact of *Ammophila* removal and burial would include depletion of the plant's carbohydrate reserves and an increase in ethylene production due to stress (Seliskar 1994). Higher levels of the hormone ethylene have been known to restrict stem elongation and vertical growth of terrestrial plants (Seliskar 1994). Since a buried rhizome is unable to photosynthesize, it must live off of reserves stored within its internodes.

Studies have shown, however, that stationary sand burial can actually be beneficial to *Ammophila arenaria* (Baye, 1990). As shoot vigor rapidly increases with sand accretion at the surface, the below-ground physiology of the plant also undergoes changes. Burial of a partial shoot allows for growth to begin at various nodes rather than the apical growing end. The apex produces a substance that is transported along the shoot and inhibits lateral bud formation in normal aboveground growth. Huiskes (1979) also found that *A. arenaria* reacts to burial by rapidly producing elongated internodes and increasing surface area for nutrient uptake.

Stationary sand burial limits the amount of soil and nutrients available to the roots of *Ammophila*. As the tips of the roots take in nutrients as they extend, the density of roots and amount of soil within reach would affect the amount of nutrients available. Since growth requires nutrient uptake, which can only be obtained through growth and extension into fresh soil, insufficient access to nutrients would be a likely cause of rhizome mortality.

Without continual sand deposition, *Ammophila* becomes vulnerable to pathogenic soil organisms such as nematodes and fungi that quickly colonize the root zone. Upward growth through pathogen-free sand allows *A. arenaria* to escape from pathogens and parasites (de Rooij-- van der Goes, et.al. 1995). Burial of *Ammophila* rhizomes would prevent access to fresh sand, allowing fungus and nematodes to prey on exposed root tissue.

The factors mentioned that pertain to burial as an eradication method are heretofore independent of depth. Some of the depth-dependent factors that could affect *Ammophila* growth are soil temperature, soil aeration, and pathogen migration. In this research I did not consider soil temperature or aeration as variables affecting *Ammophila* growth. Pathogens such as fungi and nematodes are able to migrate vertically through the soil to attack new root tissue (van der Putten, et. al. 1988). By burying *Ammophila* at a depth that enables pathogens to have easy access to root cells and increasing density-dependent competition for nutrients, it is feasible to inhibit new growth through sand burial.

Experiment 1: Survey of New Growth Found at a Current Mechanical Burial Site

Materials and Methods

For this experiment I sampled a burial site near North Siltcoos using a 10 m transect. Figure 4 shows a map of the North Siltcoos area with the specific burial site shown. photo taken in July 1997. Plots were dug at randomly selected distances along and extending south from the transect line. Plant material within these plots was collected and assessed for potential new growth by the visual presence of new buds and new roots. Depths were recorded to the shallowest tenth of a meter, with the limited number of samples found below 70 cm warranting their consolidation into a single category. Terminal depth for each plot was determined by the absence of plant material. A linear regression was employed to establish a possible correlation between burial depth and absence of new growth.

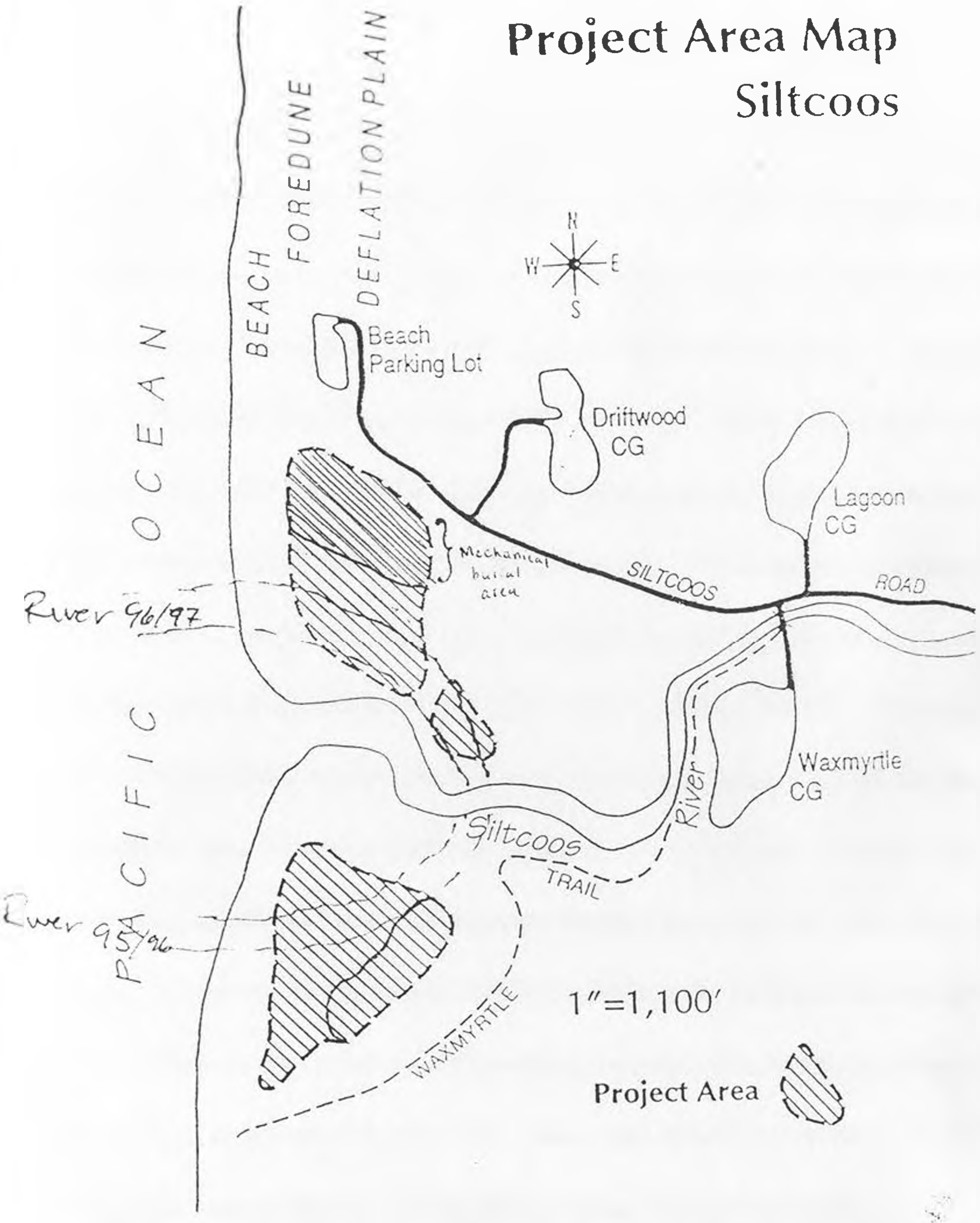

Figure 4. Map of the Siltcoos Region of the Oregon Dunes National Recreation Area with the mechanical burial site indicated.

Results

Linear regression analysis showed no correlation between burial depth and new growth. Table 2 lists the number of samples, amount of growth, and percent mortality for each depth. The number of buds, roots, total growth, and percent of rhizomes bearing growth were all plotted against depth, with no significant correlation. The percent of rhizomes bearing growth can be seen in Figure 5. The high degree of variance in the amount of growth can be attributed to the different sample sizes found at each depth rather than the impacts of burial at different depths. With a log-transformation to normalize the variance in y, I found a significant correlation between the log of the number of rhizomes with growth and depth ($r^2 = 0.544$, $t = 2.84$, $p < 0.05$). However, this correlation is likely due to the variaion in sample size. When I plotted the percent of new growth for each depth, the resulting slope was not significantly different from zero, indicating no effect of depth on the proportional amounts of new *Ammophila* growth.

The frequency distribution for both rhizome pieces found and new growth present show similar trends of high numbers found near the surface, peaking at 0.4 m, and declining at depths greater than 0.5m. The survey showed an overall mortality rate of 35%, with little variation (+/- 5%) corresponding to increasing depth.

Table 2. Numbers of samples, amounts of growth, and percentages of mortality found at each depth, Siltcoos burial site.

Depth (cm)	# of rhizomes	# rhizomes bearing growth	% mortality
10	34	22	35
20	38	24	37
30	22	13	41
40	50	34	32
50	20	15	25
60	15	10	33
70	5	3	40

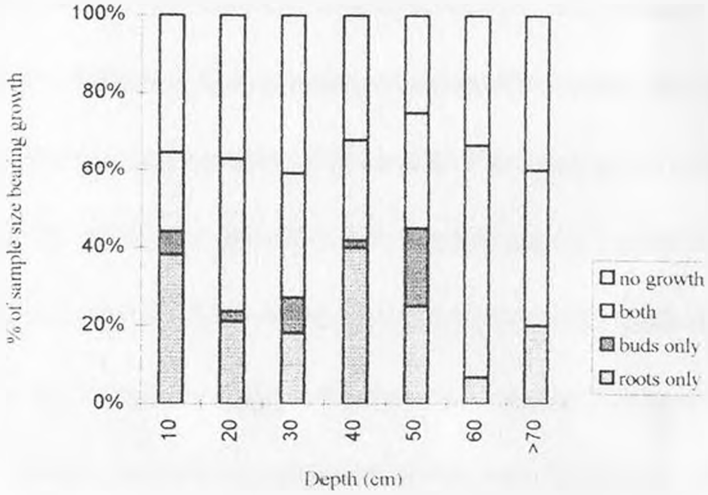

Figure 5. Graph showing the percent of rhizomes bearing new growth at each depth, Siltcoos burial site.

Discussion

The presence of new growth at depths as great as 150 cm and the persistence of a high percentage of new growth throughout depths up to 70 cm indicates that mechanical burial is of limited efficacy within these parameters. Along with this information, this experiment also provided an idea of what depths were obtained through current treatments and how much proportional regrowth to expect. Thequestion remains as to whether new *Ammophila* growth at considerable depths could feasibly produce tillers that would reach the surface and recolonize the cleared area. The extensive belowground biomass described by Huiskes (1979) consists of networks of roots that started reasonably near the surface and extended downward. The prospect of a rhizome buried at 1 m producing considerable aboveground shoots depends greatly on the initial growth reserves and the availability of nutrients for metabolite synthesis. Little is known about the time required or the environmental conditions necessary for that extent of growth to be achieved. The site was surveyed approximately 6-8 months after the initial burial, and the current aboveground growth extended from rhizomes buried no deeper than 20 cm.

Although the data shows no correlation between burial depth and growth inhibition, we should not overlook the 35% mortality achieved by sand burial. This is likely attributed to the depletion of nutrients and decreased pathogen resistence caused by sand stabilization. Evidence from previous studies (van der Putten 1989, de Rooj-- van der Goes et. al 1995) and the low variation in growth across a depth continuum suggests that the lack of motile sand is the primary inhibitor of *Ammophila* regrowth.

Experiment 2: The Effect of Burial Depth on Rhizomal Regrowth of *Ammophila*

Preliminary Growth Assessment

The purpose of this initial experiment was to determine what types of regrowth I could expect and within what time frame. Various parts of *Ammophila*, including a horizontal rhizome and a vertical rhizome with emerging tiller, were dug and buried 10 cm below the surface. After 10 days this experimental plot was redug, and the presence of new growth was confirmed.

Materials and Methods

This field experiment was designed to compliment the survey of a mechanical burial area as detailed under Experiment 1. The goal was to find a depth at which rhizomal regrowth was significantly inhibited. Plots were dug on a Coast Guard Beach site selected for sparsity of dune vegetation while remaining proximal to *Ammophila* and native beachgrass communities. Three plots were dug, 50 cm square, to an initial depth of 1 meter. Three rhizomes, from nearby *Ammophila* clumps, were stripped of roots and leaves and planted 4-5 cm apart. Plots were then filled in to a depth of 75 cm, where three additional rhizomes were planted. This procedure continued for depths of 50, 30, 20, 10, and surface level. Figure 6 shows a representative diagram of the pit structure. Surface rhizomes were covered with 4-5 cm of additional sand to prevent wind removal or erosion.

After a 3 month growing period, plots were redug and rhizome growth and survivorship recorded. A linear regression will be used to determine the effect of depth on

growth inhibition. Sand accretion was measured for the later 2 months by noting the surface level of sand on stakes located within the site. Precipitation for this experiment and Experiments 3 &4 was noted by a rain gauge posted near the study site.

Results

The results of the controlled depth experiment similarly showed no significant correlation of burial depth and rhizomal regrowth. Figures 6 and 7 show the amounts and proportions of new growth observed for each depth. Regression of the total amount of growth (roots and buds) versus depth showed no significant effect ($r^2 = 0.0397$). Analysis of variance (Tables 3 and 4) demonstrated a significant amount of growth was observed after burial ($f = 22.2338$, $df = 161$, $p < 0.01$). Similarly, analysis of variance

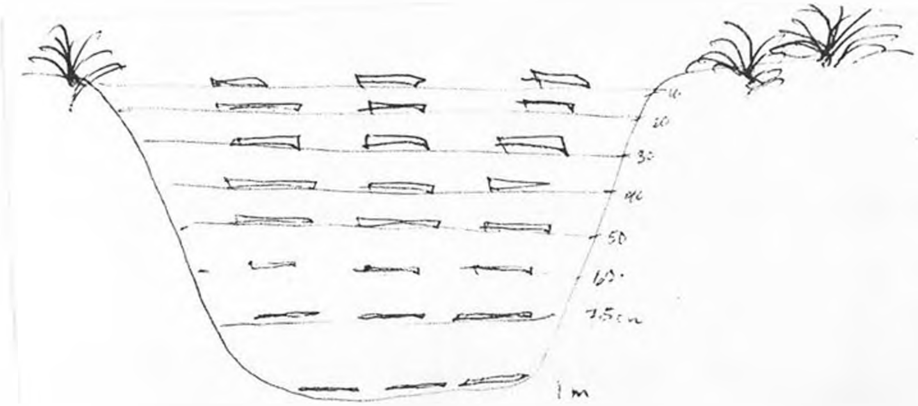

Figure 6. Diagram of *Ammophila* pit, Coast Guard Beach, Charleston, OR.

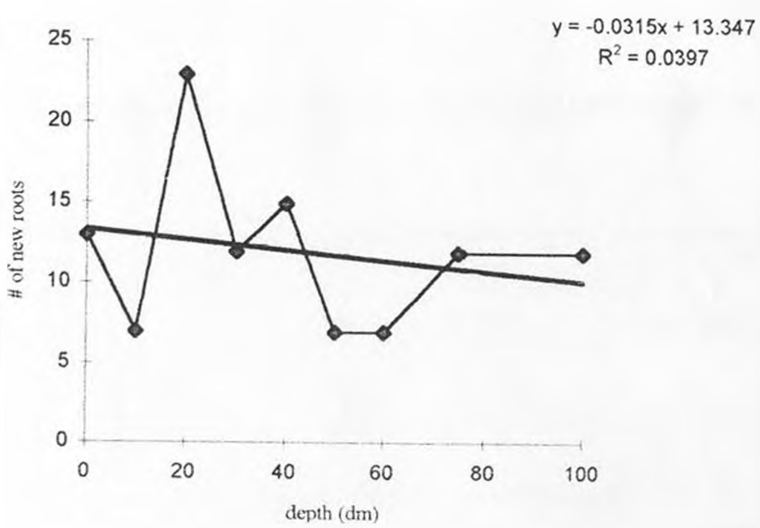

Figure 7. Linear regression of the number of new *Ammophila* roots found at each pit depth.

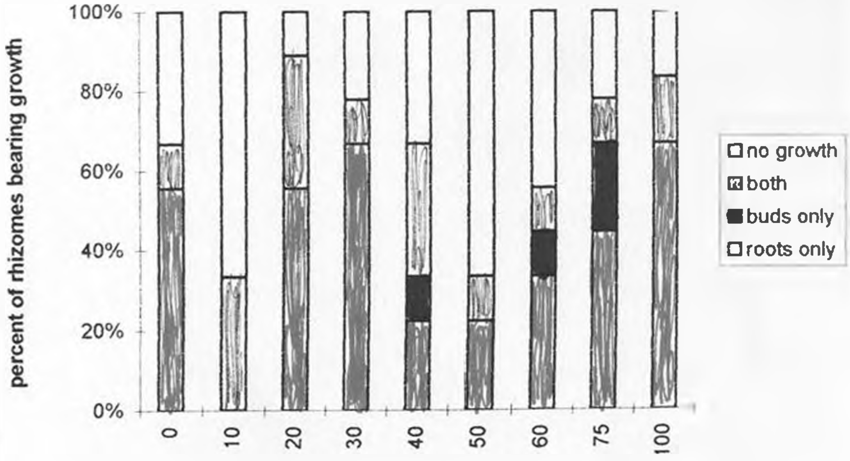

Figure 8. Graph showing the percent of rhizomes bearing new growth at each depth, Experiment 2, Coast Guard Beach.

Table 3. Analysis of Variance for the amount of growth observed after burial regardless of depth.

variation	ss	df	ms	f
between	22 888889	8	2 8611111	5.3401989
residual	39 111111	73	0 5357686	
total	62	80		p < 0 01

Table 4. Analysis of Variance for the amount of growth observed at specific depths.

variation	ss	df	ms	f
between	94 888889	1	94 888889	22 233829
residual	687 11111	161	4 2677709	
total	782	162		p < 0 01

indicated that the variation in amount of growth was highly significantly related to depth (f = 5.3402, df = 73, < 0.01); however, the correlation coefficient did not suggest a linear relationship between new growth and increasing depth. Examining rhizome mortality yielded no significant effect of depth nor could a high percentage of the variation be attributed to depth.

Discussion

Through standardization of sample size and growth potential, this experiment attempted to provide a quantitative estimate of the expected regrowth for each depth. Samples at each depth showed an increase in growth, yet there was little variation in the amount of growth and the mortality observed at different depths The process of burial appeared to stimulate *Ammophila* regrowth in this experiment, and the factors influencing growth did not differ greatly among various depths.

The consistent growth observed in this experiment can be attributed to the initial conditions of the rhizomes planted. Each piece was stripped of all current growth, leaving no exposed tissue to maintain in the face of adverse environmental conditions. Possession of leaves and extended roots would provide more surface area for water and nutrient uptake from the soil, as well as gas exchange and association with nitrogen-fixing bacteria. As a disadvantage, the removal of outgrowths likely reduced the plant's susceptibility to soil pathogens. Also the new growth produced arose out of acclimatization to the current soil conditions and may have undergone internal resource partitioning to thrive in the stable sand. There appears to be a multitude of variables affecting a rhizome's survivorship and growth in a static sand environment. Burial appeared to have no net overall impact upon regrowth when compared to surface rhizomes. The positive effects of burial that Baye (1990) reported may be negated by other variables limiting growth. Variation in amount of growth could be attributed to the availability of nutrients in specific soil layers and the density of competitors. Other possible contributors to the cumulative growth capabilities include pathogen vulnerability and individual reserve stores or amounts of nutrients required.

THE EFFECT OF SEAWATER IRRIGATION AND SOIL SALINITY ON RHIZOMAL REGROWTH OF *AMMOPHILA*

Introduction

High salinity environments can impose physiological stress on plants by the increased osmotic potential of the substrate and the toxic effects of high ion concentrations (Hale & Orcott, 1987). In a medium of high solute content, plants will face continual stress as the water will tend to diffuse out of the plant and into the soil. Depending on which ions are ubiquitous within the substrate, plants may be forced to actively transport essential ions from a diluted source in the presence of a high concentration of non-essential ions. The observed result is often a reduction in growth and yield as the process of electrolyte absorption against a concentration gradient causes a decrease in photosynthate and synthesis of organic solutes to maintain turgor (Hale & Orcott, 1987).

Ammophila arenaria has been found to be vulnerable to substrate salinity above 0.5% sea salt, with an increase in leaf senescence and reduction in growth consistent with ion accumulation in older leaves (Baye 1990). Baye's findings also described *Ammophila* seedlings increasing proportion of leaf mass and decreasing proportion of root mass in response to salinity (1990). This growth-partitioning response may be an attempt to compensate for the carbon imbalance caused by the increased demand required by ion transport (Baye 1990). Reduced root size may also limit the uptake of saline ions at the cost of water stress (Baye 1990). Root cells are normally electronegative, with a higher ionic concentration than the surrounding medium, allowing for most cations to enter passively, while sodium is actively exported back and anions transported in against the gradient (Fitter & Hay 1987).

The effectiveness of seawater and rock salt as means of eradication therefore depends on the level of substrate ion concentration attainable through specific treatment methods and applications. Ocean water typically consists of 460mM Na^+, 50 mM Mg^{2+}, and 540 mM Cl^- (Fitter & Hay, 1987). Environmental variables independent of treatment also have considerable effects on the ion uptake of *Ammophila* roots. The rate of ion transport through the soil by convection or diffusion can be considered a limiting step (Fitter & Hay 1987). If the evaporation potential is greater than the amount of precipitation, the water will move upwards through the soil and allow solutes to accumulate near the surface (Fitter & Hay 1987). There appears to be a narrow window of soil water potential necessary for solutes to diffuse through the soil and be taken up by the root surface. This level must be established and maintained for salinity toxicity to be induced in *Ammophila.*

Ammophila arenaria is classified as a high coast halophyte, noted for its ability to tolerate splashes of seawater on its shoots, but not high salt concentrations in its root zones (Waisel 1972). The reason for this is that the leaves of *Ammophila* are tightly rolled with the stomata on the inner side of the leaf, preventing water uptake or solute exchange through the shoots (Pavlik 1984). Thus these experiments focused on targeting *Ammophila* with salinity treatments near the roots rather than aboveground tillers.

Experiment 3: The Effect of Seawater Inundation and Rock Salt on Rhizomal Regrowth of *Ammophila*

Materials and Methods

Ammophila rhizomes were collected from introduced populations along the Coast Guard Beach, Charleston, Oregon, during June and July of 1997. Rhizomes were dug from five designated areas, within each of which we assumed plant material to be genetically identical. The clonal sites were selected according to environmental variables, including distance from water, wind shielding, and surrounding plant community.

Rhizomes were collected from the five clones (A-E) and the growing apexes were removed to simulate wind fragmentation and burial. Two types of fragments were used: horizontal or subterranean vertical rhizomes with 3-4 nodes, and vertical rhizomes with remnants of surface tillers, containing 1-2 nodes

The rhizome pieces were then placed in plastic bags and photocopied for exact size and initial growth parameters. Fragments were then kept in moist sand overnight to prevent desiccation before planting. Twenty by twenty-five cm pots were filled three-quarters of the way full with moist, screened beach sand taken from areas supporting *Ammophila* on the Coast Guard Beach. Ten cm of sand was removed from each pot and the rhizomes were buried. This depth was selected to account for significant sand or mechanical burial, but also to minimize mortality of plantings occurring at greater depths. Hobbs, Gimingham, & Band (1983) investigated the effect of depth and planting technique on *Ammophila* and found a mortality rate of 30-40% in rhizomes at depths of 10 and 20 cm.

Pots were randomly arranged in five two-by-six columns, for a total of sixty. Six different treatments were applied to five clones, each with two types of rhizome. After planting, each pot was given one liter of water, freshwater or seawater, according to its designation. Water was continually given two times per week, one liter each time. The only treatment given to pots 1-10 was freshwater irrigation, in order to serve as a control.

After a three month growing period (July- October) rhizomes were redug and photocopied for comparison. Figure 11 shows an example of the rhizomes before and after planting and the detail recorded by photocopying. Survivorship, root extension, shoot extension, and internode length were measured and an analysis of variance was performed. The various treatments were as follows:

Seawater Inundation

Pots 11-20 were irrigated on the twice a week schedule with one liter of usable seawater taken from the Oregon Institute of Marine Biology tank room.

Water-Retaining Polymer (Seawater and Freshwater)

A cross-linked polyacrylamide, Soilmoist brand, was applied to pots 21-40, watered with sea (21-30) and freshwater (31-40). The recommended amount for five gallon pots, two tablespoons, was mixed in with the 10 cm of removed sand. Rhizomes were buried with water-absorbent granules spread from the surface sand to the areas of root growth. After the first rain, pots containing Soilmoist were restirred as granules had aggregated on the sand surface.

This particular polymer is significantly less effective at retaining seawater than freshwater. In a laboratory test, the granules only absorbed 10% of the seawater, as opposed to 100% of the freshwater. The Soilmoist polyacrylamide has an ionicity of 20-25% (JRM Chemicals, pers. com.) which diminishes its ability to absorb highly ionic solutions.

Soil Salinity--Root and Surface Application

This treatment was divided into an examination of root and surface salinity. Pots 41-50 had two tablespoons of standard rock salt mixed in the top 10 cm of soil. The remaining pots were sprinkled on the surface with an equal amount of salt.

Results

Figure 9 shows the amount of root growth observed for each treatment. Inspection of the within treatment variation suggested the need for a transformation. On this scale, the fifth-root transformation was satisfactory to make the variances independent of the means and more closely satisfying the assumptions of the analysis of variance. Through normalization of the variance, I found that seawater inundation and rock salt burial significantly decreased survivorship and new growth of *Ammophila arenaria*. The completed ANOVAs for seawater and rock salt can be found in Tables 5 & 6.

Discussion

The results of this experiment indicate that root salinity has an inhibitory effect on new growth of *Ammophila*. This suggests that seawater inundation or rock salt would be an effective method of eradication when combined with rhizomal burial. The root tips and shoots are vulnerable to water stress and ion toxicity as induced by higher soil salinities. The difficulty in implementing a treatment based on these results is that the concentration of salinity achieved in this experiment is not known. Therefore this data does not allow us to deduce a specific soil ion concentration above which *Ammophila* is damaged.

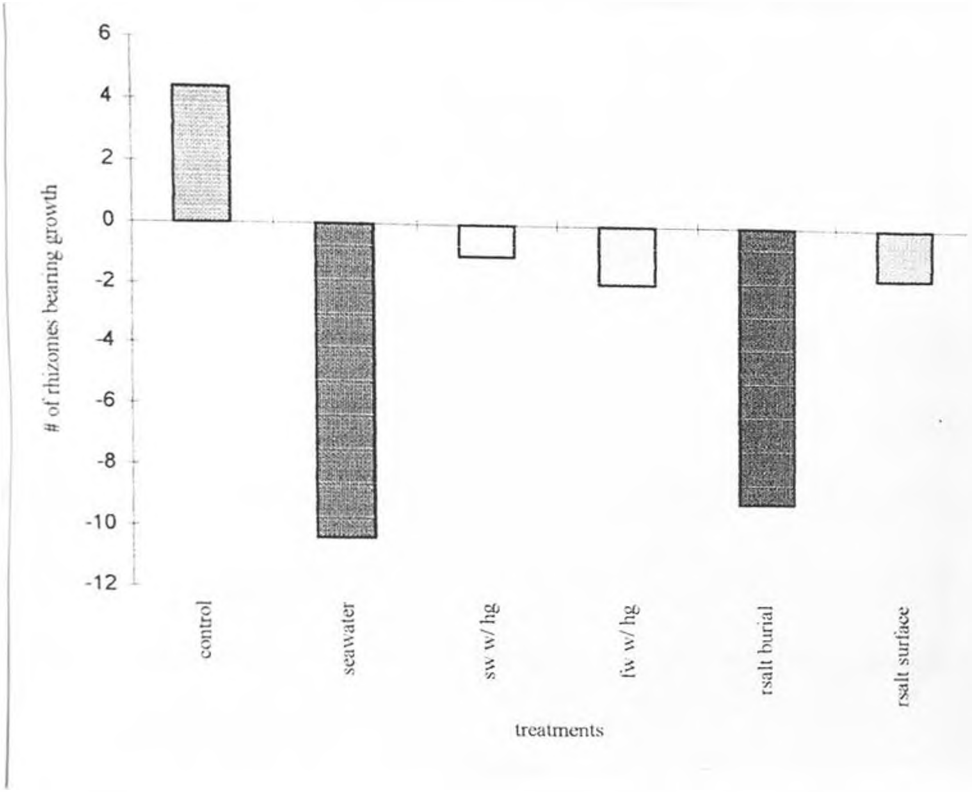

Figure 9. Graph showing the amount of new *Ammophila* growth observed for each treatment

Table 5. ANOVA table for the amount of growth observed with seawater inundation compared to the control.

	variation	df	MS	F	
between	7.31	1	7.31	12.03	
residual	23.71	39	0.61		
total	31.02	39			

Table 6. ANOVA table for the amount of growth observed with rock salt burial compared to the control.

	variation	df	MS	F	
between	5.29	1	5.29	7.01	
residual	29.43	39	0.75		
total	34.72	39		$p < 0.05$	

Similarly, rates of water convection through the soil were not measured, nor was the ion uptake by roots. An observed difference in soil osmotic potential or plant ion exchange between the seawater irrigation treatments and the rock salt burial would have suggested a difference in the efficiency of each as a method of eradication.

The laboratory nature of this experiment constrained soil conditions, density factors, and water convection properties. Each rhizome was in its own pot with little room for lateral or vertical expansion and without competition for nutrients from other plants. The pots allowed water to remain in the soil without the levels of leaching found in free dune soils.

The data demonstrated that *Ammophila* roots are vulnerable to high soil salinity, resulting in reduced growth as suggested by Waisel (1972). Baye indicated that roots are capable of excluding salts through selective ion transport, which concurs with the observed reduction in growth. An increase in internal solutes would allow for a partial recovery and stabilization, a response characterisitic of halophytes (Waisel 1972). Since growth of *Ammophila* roots was not resumed within the duration of the experiments, the data supports the hypothesis that *Ammophila* is vulnerable to salinity. The use of hydrogranules with freshwater and seawater irrigation did not significantly alter the growth of *Ammophila*. The polymer likely retained a small amount of water in the salt solution, limiting the effect of water stress by maintaining the osmotic pressure balance. With the granules' 20-25% ionicity, the partial dissolution of the polymer may have contributed more salts to the soil. This chemical breakdown may have produced more essential ions, raising the solute concentration and raising the osmotic pressure of the soil. Thus the data showed no significant effect of hydrogranules with either seawater or freshwater. The lack of increased growth with increased retention of soil moisture also suggests that the plants were not stressed.

The surface application of rock salt was ineffective at reducing Ammophila growth. This suggests that the salts did not reach or remain in the region of vulnerable roots. Insufficient water convection within the time frame of the experiment could be the cause, or an imbalance in the water evaporation versus precipitation potential which would allow for the solutes to remain on the surface.

Experiment 4: Effects of Root Salinity on Rhizomal Regrowth

Materials and Methods

This investigation focused on the possible use of rock salt as a field treatment, combined with mechanical burial. Plots were dug in the same area as Experiment 2, 50 cm square, to depths of 50 and 25 cm. These depths were selected according to the results of the mechanical burial surveys. Rhizomes were planted according to Experiment 2, and two tablespoons of rock salt was applied before burial. Sand and water accretion was also noted as in Experiment 2.

Results

A t-test comparison of the amount of growth observed in the salt pits and the pits in Experiment 2 showed no significant difference. The similarity in the amount of new growth can be seen in Figure 13

Discussion

Contrary to the results of the Experiment 3, it appears that in the field, increased soil salinity has no effect on rhizomal regrowth. This can be attributed to the different conditions under which each experiment was performed. In this experiment, rhizomes were stripped of all protruding tissue as in Experiment 2. Thus there was an absence of root tips and shoots susceptible to water stress and ion toxicity. The rhizome was able to produce new growth specifically suited for saline conditions.

The high variability of environmental conditions in the field experiments can also account for discrepancy among the results of saline treatments. It is reasonable to assume that a specific amount of regular water flow was required to dissolve the rock salt and distribute the ions throughout the soil. Too much water would allow the salt to leach out of the range of *Ammophila* roots. Too little water would result in salt crystals remaining undissolved and consequently not available within the soil.

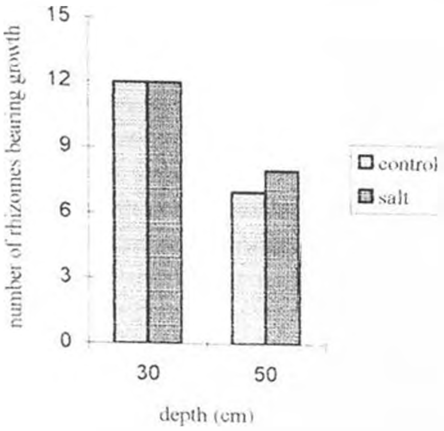

Figure 10. Graph showing the amounts of growth found at 30 cm and 50 cm in burial (Experiment 2) and salt pits (Experiment 4).

CONCLUSIONS

Ammophila arenaria rhizomes are vulnerable to high soil salinity and susceptible to burial stress. Both treatments have been shown to limit regrowth of root and shoot tissue. The most effective methods of application remain to be determined. Variation in burial depth has little effect on growth inhibition; the lack of sand accretion appears to the the main contributor to mortality. Placing the roots of *Ammophila* in a high saline environment appears to be an effective means of inducing water and ion stress. A combinatory approach encompassing burial, regular application of salinity, and sufficient irrigation could be very effective at limiting *Ammophila* regrowth. By limiting the plant's access to freshly deposited sand, the available soil nutrients and carbohydrate reserves could be depleted. Simultaneous subjection to high soil osmotic potentials in the region of the roots may result in successful control of *Ammophila* regrowth.

SUGGESTIONS FOR FURTHER STUDY

Further study is needed to evaluate the potential of burial and soil salinity as a means of controlling the spread of *Ammophila arenaria*. A thorough analysis of root physiology would allow for determination of specific limits and assessing vulnerability in the face of particular environmental conditions. Focal areas for salinity research may include specific levels of salinity tolerance and the efficiency of transfer to and induced uptake of ions by roots. Knowledge of the critical concentration of soil salinity at which *Ammophila* roots are vulnerable would be valuable information. Other studies could examine the specific ions and various concentrations that cause water and ion stress to *Ammophila* roots. Monitoring the uptake of solutes and the salinity content within the roots over time would provide an idea of of the nature and scale of the plant's physiological responses to highly saline soil.

Burial studies would be assisted by knowledge of the amount of soil nutrients required to sustain a rhizome and allow for new growth. The content of the specific soil and the factors surrounding accessible soil volume and availability of nutrients will vary from site to site. Pathogens and migration capacities will also be site-specific. The idea of a "critical depth" for a particular area where a rhizome is at maximum vulnerability is worth consideration and further exploration.

Similar experiments such as those carried out here could also be extended for greater periods of time and with the use of larger sample sizes. More combinatory approaches of salinity and burial would provide more information pertinent to developing an efficient strategy of controlling *Ammophila arenaria*. A more specific report with suggested treatment methods will be submitted to the Oregon Dunes National Recreation Area.

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