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An Assessment of Feasibility of Using High-Calcium Quicklime as an Experimental Tool for Research Into Kelp Bed/Sea Urchin Ecosystems in Nova Scotia

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January 1982

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and
Resource Branch
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January 1982

AN ASSESSMENT OF FEASIBILITY OF USING HIGH-CALCIUM QUICKLIME AS AN EXPERIMENTAL TOOL FOR RESEARCH INTO KELP BED/SEA URCHIN ECOSYSTEMS IN NOVA SCOTIA

by

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Issued under contract to

Department of Supply
and Services
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and

Resource Branch
Department of Fisheries
and Oceans
Halifax, N.S. B3J 2S7

PREFACE

The study reported here resulted from a Department of Supply and Services unsolicited proposal awarded to Welsford Research Group. The study was funded jointly by the Canadian Departments of Supply and Services and Fisheries and Oceans.

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Richard W. Welsford
Research Group Limited

"LETTER OF TRANSMITTAL"

October 30, 1981

Her Majesty, Queen Elizabeth II
c/o Dr. Robert Miller
Fisheries and Oceans Canada
P. O. Box 550
Halifax, Nova Scotia
B3J 2S7

Your Gracious Majesty:

I humbly beg the favour of your most benevolent attention and that you accept, with the magnanimous and indulgent benignity for which you are justly famed, the result of our devoted efforts in your behalf, to wit, "An Assessment of the Feasibility of Using High Calcium Quicklime as an Experimental Tool for Research into Kelp Bed/Sea Urchin Ecosystems in Nova Scotia". Not deeming ourselves knowledgeable in that most exacting art practiced by Your Majesty's typesetters, we have caused to be made a manuscript which Your Majesty's most excellent scribes can fashion into the form best suited for technical reports.

Since I am aware that Your Royal Majesty's attention is occupied with matters of great moment and trenchant import, I will briefly summarize our labours by saying that the aforesaid Quicklime did grievously smite the spiny enemies of Your glorious empire in such a fashion that most of them perished as they so richly deserved. We again thank Your Majesty for Her merciful consideration which allowed us to perform service to the empire.

We remain forever your most meek and devoted servants.

Sincerely,

Brock B. Bernstein

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Senior Project Manager

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ABSTRACT

Bernstein, B.B. and R.W. Welsford. 1982. An assessment of feasibility of using high-calcium quicklime as an experimental tool for research into kelp bed/sea urchin ecosystems in Nova Scotia. Can. Tech. Rep. Fish. Aquat. Sci. 968: ix + 51 p.

Quicklime, which is made by heating limestone, has been used to control starfish in oyster beds and sea urchins in commercially harvested kelp beds. It releases heat when combined with water and kills echinoderms by causing epidermal lesions that permit bacteria to enter the coelomic fluid. Affected animals die of the resultant infections from a few days to several weeks after treatment, depending on dosage and water temperature. This report presents results of a study that reviewed the extensive use of quicklime in California to control sea urchins, and adapted techniques developed there for use in Nova Scotia. The goal of this study was to assess the feasibility of using quicklime as an experimental tool in Nova Scotia.

In California, the Department of Fish and Game and Kelco Company use quicklime to reduce sea urchin populations that would otherwise destroy commercially harvested kelp beds. They achieve kill rates in excess of 95% with an apparatus that mixes quicklime with sea water at the surface and then pumps the slurry through a hose to the bottom, where a diver directs the flow onto sea urchins. They apply between one and two tons per acre, and can treat up to two acres per day. Data from

California Fish and Game surveys indicate that quicklime also affects other echinoderms, but to a lesser extent than sea urchins. Quicklime does not harm lobsters or fish.

We built and field tested a liming apparatus in Nova Scotia. We achieved a kill rate of greater than 70%, using approximately four tons per acre. We recommend modifications in the equipment and application procedures that will probably raise the kill rate to at least 80%. This is much lower than in California because the much lower water temperature retards bacterial infection and because the much higher relief of the sea floor in Nova Scotia prevents quicklime from reaching all the sea urchins. As in California, effects on other organisms were much less severe than on sea urchins.

Kill rates of 70% in California were enough to permit the re-establishment of kelp beds. We therefore conclude that quickliming is a feasible experimental tool for studying the resettlement of algal beds and for manipulating sea urchin densities to examine their role in benthic communities.

Key words: sea urchins, quicklime, kelp.

RÉSUMÉ

Bernstein, B.B. and R.W. Welsford. 1982. An assessment of feasibility of using high-calcium quicklime as an experimental tool for research into kelp bed/sea urchin ecosystems in Nova Scotia. Can. Tech. Rep. Fish. Aquat. Sci. 968: ix + 51 p.

On a utilisé la chaux vive, fàbriquée par chauffage de la pierre à chaux dans le contrôle de l'étoile de mer sur les huîtrières et de l'oursin commun sur les lits de varech exploités commercialement. Combinée à l'eau, la chaux vive dégage de la chaleur et tue les échinodermes en causant des lésions épidermiques qui permettent aux bactéries d'envahir le liquide coelomique. L'infection qui en résulte tue les animaux affectés après une période de quelques jours à plusieurs semaines, selon la dose et la température de l'eau. Le rapport qui suit présente les résultats d'une revue de l'usage très répandu de la chaux vive en Californie dans le contôle de l'oursin et d'une étude visant à adapter à la Nouvelle-Écosse les techniques mises au point dans cet Etat. On voulait surtout évaluer la possibilité d'utiliser la chaux vive comme outil expérimental en Nouvelle-Écosse.

En Californie, le Department of Fish and Game et la Kelco Company utilisent la chaux vive pour réduire les populations d'oursins qui, autrement, détruiraient les lits de varech exploités commercialement. Les mortalités atteignent 95% avec un dispositif qui mélange la chaux vive avec l'eau de mer à la surface. A l'aide d'une pompe et d'un boyau, le coulis est envoyé au fond, où un plongeur dirige le jet sur les oursins. On applique entre une et deux tonnes à l'acre par jour. Les relevés du California Fish and Game indiquent que la chaux vive agit également sur les autres échinodermes, mais à un degré moindre que sur les oursins. Elle ne nuit ni aux homards ni aux poissons.

Nous avons construit et testé sur le terrain un appareil en Nouvelle-Écosse. Nous avons réussi des taux de mortalités de 70% ou plus, avec environ quatre tonnes à l'acre. Nous recommandons certains modifications à apporter à l'équipement et à la méthode d'application, qui devraient faire passer les mortalités à 80% au moins. Ce pourcentage est de beaucoup inférieur à celui réalisé en Californie. C'est que les températures plus basses retardent l'infection bactérienne et que les fonds plus accidentés en Nouvelle-Écosse empêchent la chaux vive d'atteindre tous les oursins. Comme en Californie, les effets sur les autres organismes sont moins prononcés que sur les oursins.

Des taux de mortalité de 70% en Californie on suffi au rétablissement des lits de varech. Nous concluons donc que l'application de chaux vive est un ontil expérimental potentiel pour l'étude du rétablissement des lits d'algues et la manipulation de la densité des oursins dans l'étude de leur rôle dans les commanautés benthiques.

INTRODUCTION

Much recent scientific evidence strongly suggests that Nova Scotia's subtidal algal resources have been severely damaged as a result of overgrazing by the herbivorous sea urchin (Strongylocentrotus droebachiensis) (Breen and Mann, 1976; Wharton, 1980). This evidence does suggest that the remaining algal resource is potentially subject to the same damage. This situation and its potential effect on commercial fisheries was the subject of two recent conferences (spring, 1979; fall, 1980) in Halifax, Nova Scotia.

The most recent of these conferences, September 11-12, 1980, at the Bedford Institute of Oceanography, reviewed current knowledge of urchin-algal interaction and discussed alternatives for the future study and management of kelp bed resources. A concensus was developed that an appropriate next step in the investigation of this system would be a large-scale perturbation experiment. The experiment would involve using high-calcium quicklime to clear a large area of sea urchins, then performing a variety of intensive research projects as the ecological system responded to the removal of sea urchins. The benefits of this experimental approach were seen to be:

1) a greater understanding of the ecological interactions maintaining barrens in their current low productivity state; and

2) insight into the mechanisms that would operate in any reversal from urchin-denuded areas to healthy kelp beds.

This is necessary information to support a more active management role. Before such a perturbation experiment or any intervention using quicklime can be performed, an assessment of the feasibility of quickliming in Nova Scotia must be made and techniques developed which are appropriate to Nova Scotia's habitats.

Quicklime has been used successfully in southern California (Duffy, 1976; 1978; Duffy and Hoban, 1979; Parsons and Duffy, 1977) for more than ten years as a sea urchin control measure and as part of a broader strategy of management of kelp bed resources. This represents a wealth of experience and information which should be tapped as part of any effort to develop quickliming techniques for Nova Scotia.

The goals of this project were to review all previous quickliming experience in California, evaluate it in light of Nova Scotia's environment, assess the environmental impacts, and carry out a field test to refine techniques and evaluate their effectiveness. We have combined this information in a practical manual of quickliming for Nova Scotia that includes:

a) techniques of quickliming to control sea urchins,
b) effectiveness of quickliming,
c) environmental impacts of quickliming,
d) adaptation of quickliming techniques to Nova Scotia, and
e) field testing of quickliming techniques in Nova Scotia.

TECHNIQUES OF QUICKLIMING

QUICKLIME

Description

Quicklime (CaO) is produced by heating limestone. When subsequently mixed with water, CaO is rapidly converted to $Ca(OH)_2$ (calcium hydroxide), liberating heat. This reaction takes place quickly in seawater and is complete in a matter of minutes. Within five days, virtually all of the $Ca(OH)_2$ has been converted to harmless $CaCo_3$ (calcium carbonate), a common structural component of shelled marine animals and calcareous plants (North and Schaefer, 1963).

Dispersal of quicklime has no detectable effect on either the pH or the calcium content of the water column (North and Schaefer, 1963). Water samples taken 2 cm and 3 m above the bottom before and 15 minutes after treatment were all within the normal range of pH - 7.8 to 8.0. Calcium levels in all samples were about 380 ppm.

Mechanism of effect

The Kelp Habitat Improvement Project performed extensive investigations of quicklime's effect on urchins (North and Schaefer, 1963); their results and conclusions are summarized below. The following sequence of events occurs after quicklime contacts the surface of a sea urchin:

1) withdrawal of tube feet and tetanus of the musculature which operates the spines and pedicellariae;

2) loss of epidermis and spines during the next few days, beginning in the area of test receiving the heaviest dose; and

3) death.

Accompanying these external changes are internal effects, including alteration in pH, loss of clot-forming ability, and an abrupt increase in bacteria in the coelomic fluid.

Although loss of spines is the most visible manifestation of quicklime's effects, this is not the primary cause of death. Experimental removal of spines and other epidermal structures resulted in death only when more than one-third of the test surface was cleared, while limed urchins died when less than that fraction of the test area was affected. The researchers for the Kelp Habitat Improvement Project concluded that bacterial infection of the coelomic fluid was the ultimate cause of death. The hot quicklime damages urchins' tube feet and leaves the podial pores open. These openings permit free communication between the coelomic fluid and the environment and allow micro-organisms entry to the coelomic fluid. The rate of bacterial increases, and thus the time until death, is temperature dependent. Figure 1 (from North and Schaefer, 1963) shows the effects of higher temperatures on shortening the survival time of limed urchins.

HISTORY OF USE

Because of its toxic effects on echinoderms, quicklime has long been used to control starfish in oyster beds (Loosanoff and Engle, 1942; Needler, 1940). A field test in San Diego, California, in 1962 demonstrated that quickliming was extremely toxic to urchins (North and Schaefer, 1963). As a result, quickliming became one of the cornerstones of efforts to regenerate and maintain extensive nearshore beds of the giant kelp, _Macrocystis pyrifera_. Clearing dense aggregations of urchins allowed the settlement and survival of kelp. These efforts were coordinated by the Kelp Habitat Improvement Project from 1962 to 1977 and involved, among others, the Scripps Institution of Oceanography, the California Department of Fish and Game, California Institute of Technology, and the Kelco Company. Since 1977, liming activities have been carried out by the Kelco Company under the supervision of the California Department of Fish and Game.

Figure 2 shows yearly tonnage of lime applied to control urchins in southern California from 1963 through 1979. Lime was applied at the rate of one to two tons per acre.

TECHNIQUES OF APPLICATION

Storage

Since quicklime reacts with water, extreme care must be taken to keep the lime dry during shipment and storage. This can be accomplished by packing the lime in plastic or plastic-lined bags.

Figure 1 12 S. purpuratus were treated with a total of 8 g CaO to determine effects of temperature. After 7 min exposure they were rinsed and placed in one of three constant temperature baths. One individual at 10°C recovered. The effect of higher temperature in shortening survival time was clearly demonstrated (from North and Schaefer 1963)

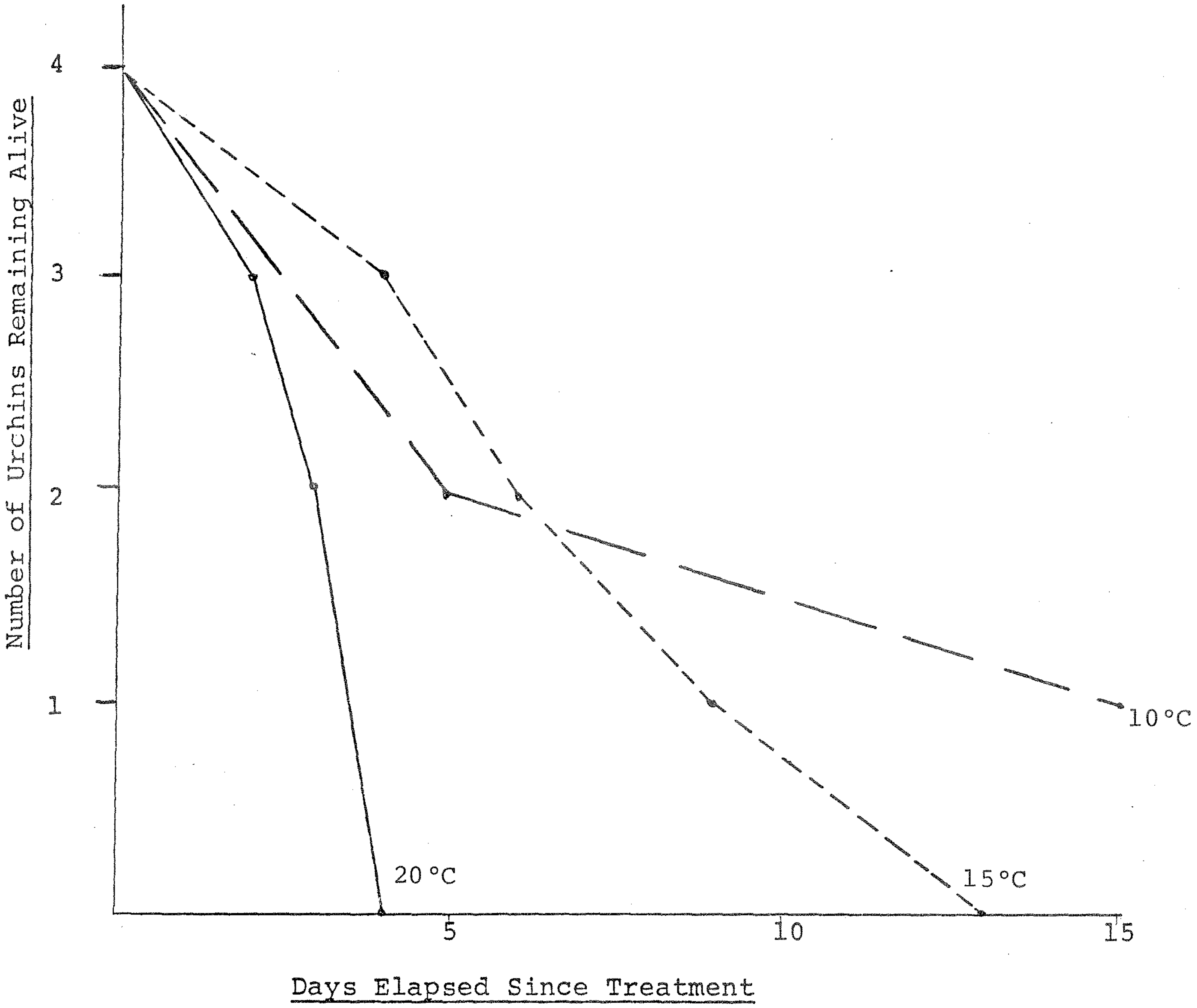
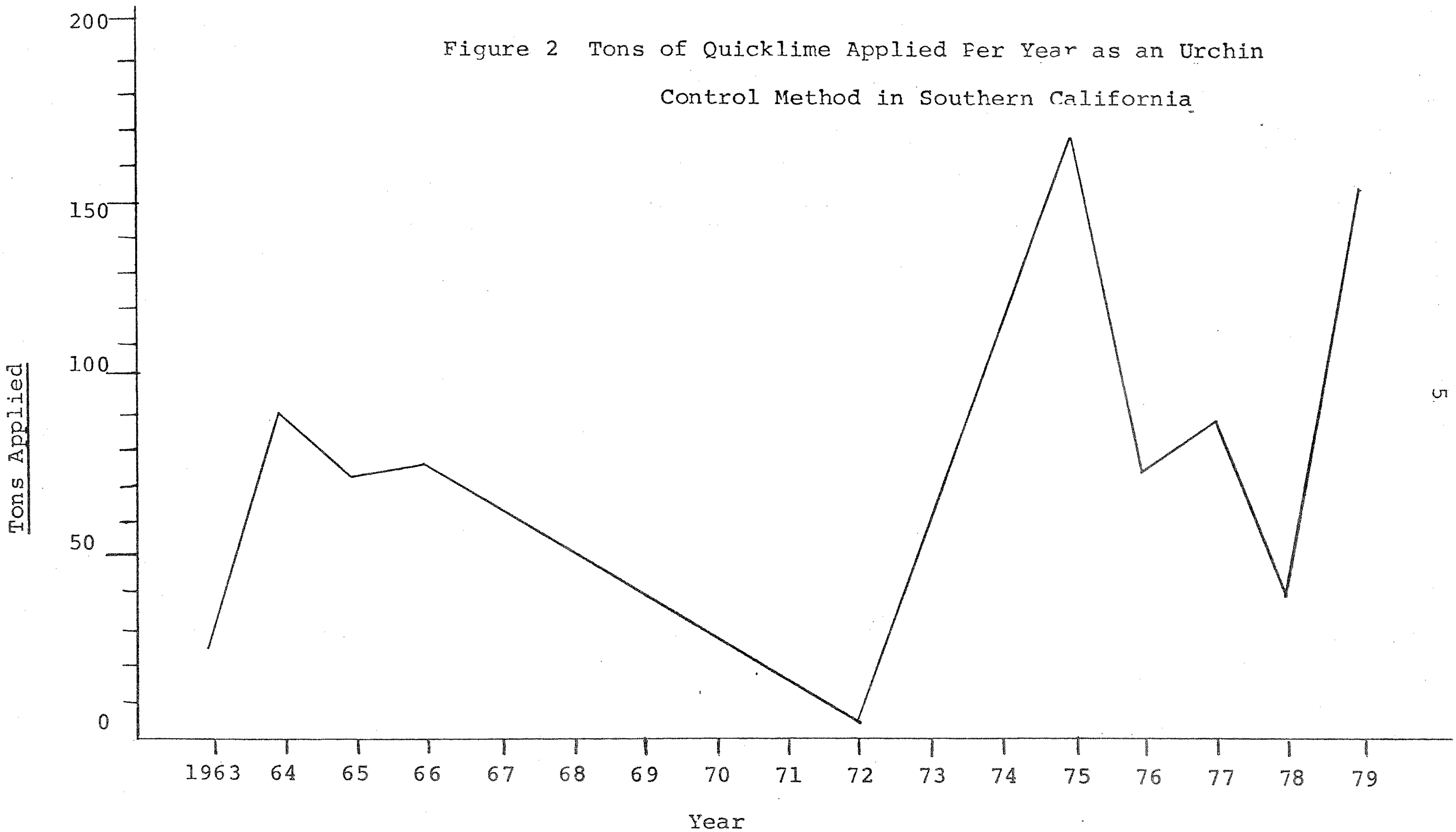


Figure 2 Tons of Quicklime Applied Per Year as an Urchin Control Method in Southern California



The rate at which quicklime reacts with water is dependent on the particle size. Powdered lime reacts extremely rapidly and remains in suspension rather than settling to the bottom where the urchins are. Kelco Company has determined that a particle size of approximately 12 mm is most effective for pumped dispersal.

Surface dispersal

From 1963 through the end of 1975, quicklime was dispersed by being dumped over the stern, into the propeller wash of a slowly moving boat. This spread lime in a path of about 3 to 5 m wide. The boat traversed the treatment area in a grid pattern, running back and forth parallel to the swells.

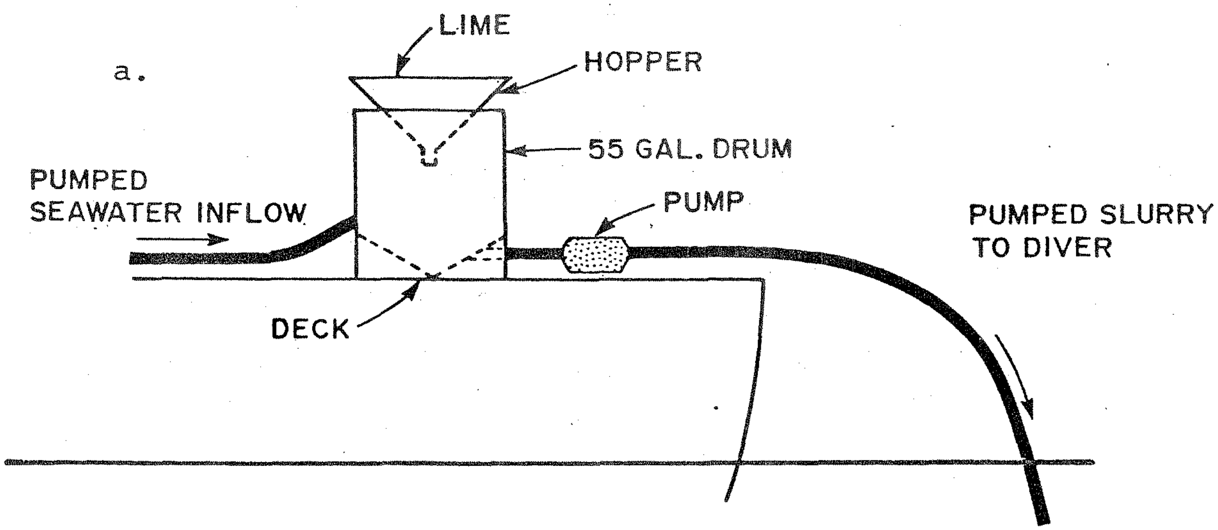
This method of liming was effective in reducing urchin densities and permitting the re-establishment of kelp (see "Effectiveness" below). This approach suffers from several drawbacks, however. Because the lime reacts as it sinks through the water column, it has dissipated much of its heat by the time it reaches the bottom. This requires the use of heavy dosages (about 2 tons/acre) to ensure high urchin mortality rates, or alternatively, the acceptance of a lower mortality rate. In addition, because the lime is dispersed from the surface, it is applied to the entire area as a blanket treatment. This increases side effects on other organisms. It also does not permit focussing the application on particularly dense urchin concentrations, avoiding areas where urchins are sparse, nor does it allow lime to be applied under ledges and overhangs and to vertical surfaces - areas that are inaccessible to lime settling from the surface.

Pumped dispersal at the bottom

These problems were overcome by the adoption in January, 1976, of a new technique of lime application (Parsons and Duffy, 1977). This involves mixing the lime with water on the surface and sending it down a hose to the bottom, where the hot slurry is applied directly to urchins by a diver. Figure 3a illustrates the components of this system.

Seawater is pumped into a 55 gal drum on the deck of the vessel. Lime is poured into the hopper above the barrel, and the flow of lime is regulated by the size of the hole at the bottom of the funnel. Once the slurry is formed, it can either be drawn by gravity or pumped into the hose extending to the bottom. Pumping the slurry to the bottom allows the use of a longer hose (up to 60 m) and permits the diver to cover a much larger area before the boat must be repositioned and reanchored.

a.



b.

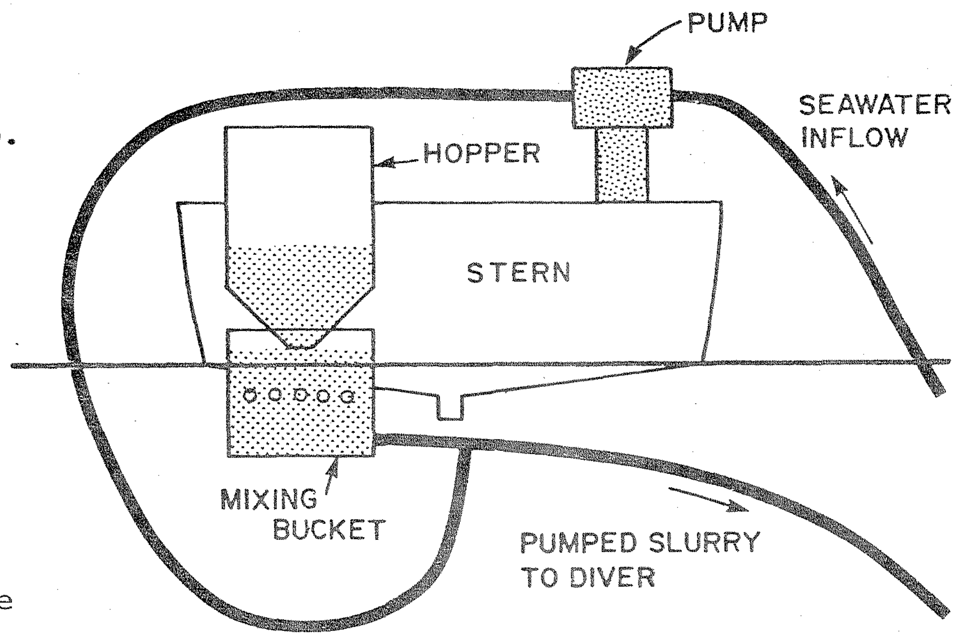


Figure 3. Schematics of the liming apparatus used by a) Kelco Co. and b) California Fish and Game. Both involve a pumped flow of lime slurry to the diver on the bottom.

The gravity-fed system can operate with a 5-10 cm diameter hose up to 30 m in length. The pump-driven system worked best with a smaller, 5 cm diameter hose. The hose should be flexible but not overly so. If the hose is too flexible, kinks will form and the hot slurry will burn a hole through the hose. Corrugated plastic hose provided the best results.

Because of the potential for kinking and other problems, Kelco Co. found it beneficial for the diver to be in direct voice communication with the surface. For this purpose, they utilize Kirby Morgan Band Masks with a surface air supply. This allows the diver applying the lime to direct the rate of flow of lime and to cut it off as he moves between concentrations of urchins. Kelco Co. has been able to apply a maximum of 2 tons of lime over almost 0.8 hectares in one day, using the pump-driven system with a 60 m hose.

The system described above has been modified by the California Department of Fish and Game to allow liming to be carried out from a small boat. This alternative is shown in Figure 3b. The lime is mixed in a half-submerged bucket attached to the stern of the boat. The flow of lime into the bucket is controlled by an adjustable gate at the bottom of the hopper. One-way valves in the side of the bucket permit water to enter and prevent the slurry from escaping. A pumped flow of water fed into the hose below the bucket then sucks the slurry into the hose and carries it to the bottom.

Application

The following methods of application apply to both the gravity-fed and pump-driven systems described above. It is important that the diver keeps the hose at least 0.5-1.0 m above the bottom. This allows the slurry to settle to the bottom and stick to the urchins. If the hose is held too close to the substrate, the momentum of the flow will cause the slurry to rebound from the bottom and billow ineffectively into the water. The diver should move slowly along, swinging the hose from side to side to obtain good coverage. If the lime contains a high proportion of powder as a result of long storage, these small particles will remain in suspension and form a cloud along the bottom. In this case, the diver can move backwards, glancing over his/her shoulder to maintain visibility and direction. The flow of lime can also be directed under ledges and into crevices to ensure high urchin mortality. The application does not need to cover 100% of the bottom, because a few particles landing on an urchin will cause mortality. The formation of a white crust on the substrate is an indication of an excessively heavy application.

If the area to be limed is small, the boat may be anchored in one place so that the diver can apply lime in a grid pattern around the boat. If the area is large, the boat may set between bow and stern anchors and be winched slowly along in a line as the diver works back and forth to the limits of the hose length (Fig. 4). When the boat reaches the bow anchor, both anchors must be retrieved, reset, and the operation repeated. This allows much more area to be covered that the single-point anchore procedure. The boat must be anchored because a diver applying lime cannot keep pace with even a slowly moving boat.

EFFECTIVENESS OF QUICKLIMING

SOURCES AND METHODS

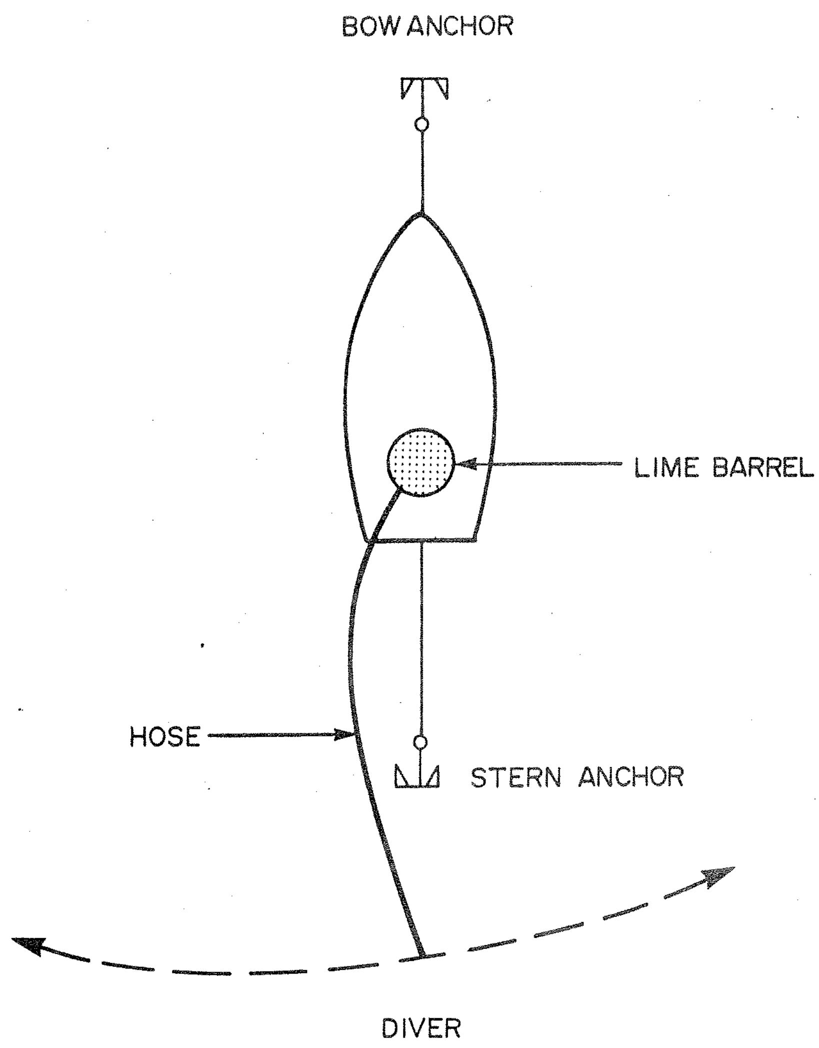
There are two sources of data on the effectiveness of quicklime as an urchin control agent. The first of these is the reports of the Kelp Habitat Improvement Project (North and Shaefer, 1963). The second is the yearly reports of the California Department of Fish and Game, presented to the California Fish and Game Commission (Duffy, 1976; 1978; 1980; Duffy and Hoban, 1979; Parsons and Duffy, 1977).

Kelp Habitat Improvement Project

The Project performed laboratory studies and both small-scale (a few hundred m^2) and large-scale (0.4 hectare and greater) experimental field limings. These were designed to measure the kill rates at different dosages of lime. They found that conditions in the field differed so widely between field and laboratory studies that it was impossible to apply laboratory findings to actual field operations except in broad terms. We will therefore discuss the results of only the field studies below.

The Project evaluated the effectiveness of their field liming operations in two ways: by quantitative sampling, and by divers' subjective visual estimates of reduction in urchins' density. Since the goal of the Project was the reestablishment of kelp, most of their sampling effort was directed toward measuring kelp settlement and growth rather than urchin densities. The quantitative estimates of quicklime's effectiveness were obtained by making between five and 25 blind casts of a 1 m^2 quadrat in the treatment area before and after liming.

Figure 4. Application of Quicklime to Large Area



California Fish and Game

In January, 1975, the California Fish and Game Commission adopted regulations requiring that both pre-liming and post-liming surveys be performed to assess effects on urchins and other kelp bed organisms. The results of these surveys are presented in yearly reports to the Fish and Game Commission (Duffy, 1976; 1978; 1980; Duffy and Hoban, 1979; Parsons and Duffy, 1977).

The Department of Fish and Game performed surveys in each area to be limed. A transect line was placed on the bottom and divers enumerated all macrobiota within 1 m of either side of the line. In 1975 and 1976 these transects were 50 m long (Duffy, 1976; Parsons and Duffy, 1977); in 1977-1979, they were shortened to 25 m (Duffy, 1978; 1980; Duffy and Hoban, 1979). These surveys represent the most complete field data available on the effectiveness of quicklime in reducing populations of urchins.

From 1975 to 1979, quickliming and the Fish and Game surveys were carried out in two areas. One of these was San Clemente Island, 33.44 km off the coast of southern California. The kelp beds surrounding this Island are rather narrow, since the bottom drops rapidly into deep water. The other area was the mainland at San Diego, California. Kelp beds in this area typically extend far from shore and often form dense canopies. Because the two areas represent different habitats, results of the surveys for each are presented separately below.

Problems in evaluating effectiveness

There are several factors which complicate both an evaluation of liming's effectiveness and a comparison of the different methods of application. Most important is the fact that post-liming surveys were not conducted at uniform times after liming. The period between liming and the first post-liming survey ranges from 2 to 240 days. This makes it impossible to separate the effects of liming from changes in urchin density due to migration or the reestablishment of kelp, which can result in even further decreases in urchin abundance (North and Shaefer, 1963). Since the first post-liming surveys took place an average of 105 days after liming, the observed reductions in urchin density could result from any combination of liming, mortality, urchin migration, and kelp resettlement.

Another problem is the lack of control transects in the Fish and Game surveys. There is thus no means of determining what portion of the post-liming changes in urchin density were due to seasonal or longer-term changes in the population as a whole. This is an important concern in view of the usually long elapsed time between lime application and the post-liming surveys.

The Kelp Habitat Improvement Project (North and Shaefer, 1963) found that environmental conditions such as currents and swell influenced the effectiveness of liming, especially when utilizing surface dispersal. Moderate currents or swell helped spread the lime under ledges and into crevices and increased the kill rate. Strong currents, however, swept the lime out of the treatment area before it reached the bottom, thereby lowering the kill rate. These effects are difficult to quantify, and undoubtedly account for much of the variability in kill rates among different liming treatments.

The lack of controls and the varied time between lime application and post-liming surveys make statistical analysis of the results of these surveys unfeasible. We therefore simply present the survey results and discuss them with respect to the liming technique employed. We present results for the two most abundant species of urchin separately, since laboratory studies showed them to have somewhat different susceptibility to lime (North and Shaefer, 1963). We also present results for San Clemente Island and the mainland at San Diego separately, since these represent distinct habitats.

RESULTS

Survey data

Figures 5-7 show the density of urchins of two species at various times after lime application. All data except for the three quadrat surveys in Figure 5d are from the California Department of Fish and Game transect surveys. Each line on the graph (except for the three mentioned above) represents a separate permanent transect line in a lime treatment area. Areas ranged from less than 0.4 hectare to a few hectares. It is not possible to place confidence limits on any of these estimates of urchin density because there were no replicate transects sampled in any of the treatment areas.

Average kill rates

Table 1 presents the average kill rates for each method of lime application and for both species of urchin on the mainland and at San Clemente Island. Because of the wide range in the time between liming and the first post-liming survey, it was not possible to calculate kill rates which avoided the biases mentioned above ("Problems in Evaluating Effectiveness"). For

Figure 5a. Densities of Strongylocentrotus franciscanus before and after liming at San Clemente Island, California. Surface dispersal. (Source: Duffy 1976)

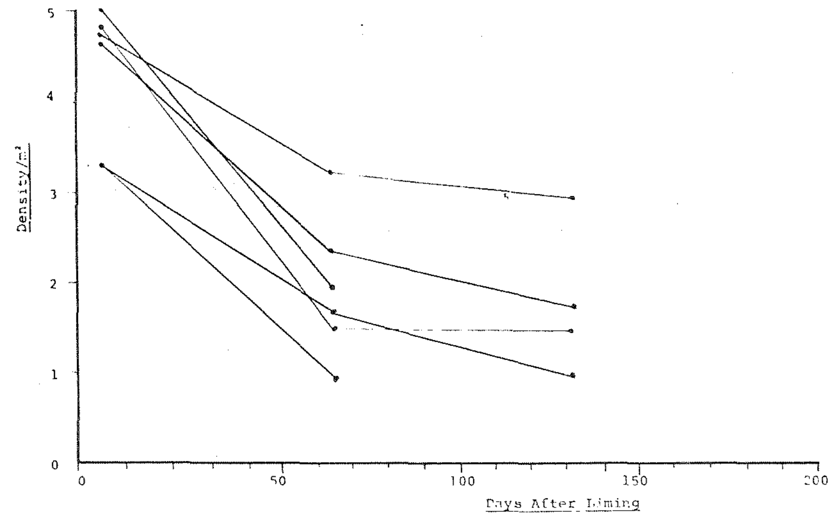


Figure 5b. Densities of Strongylocentrotus franciscanus before and after liming in San Diego, California. Surface dispersal. (Source: Duffy 1976)

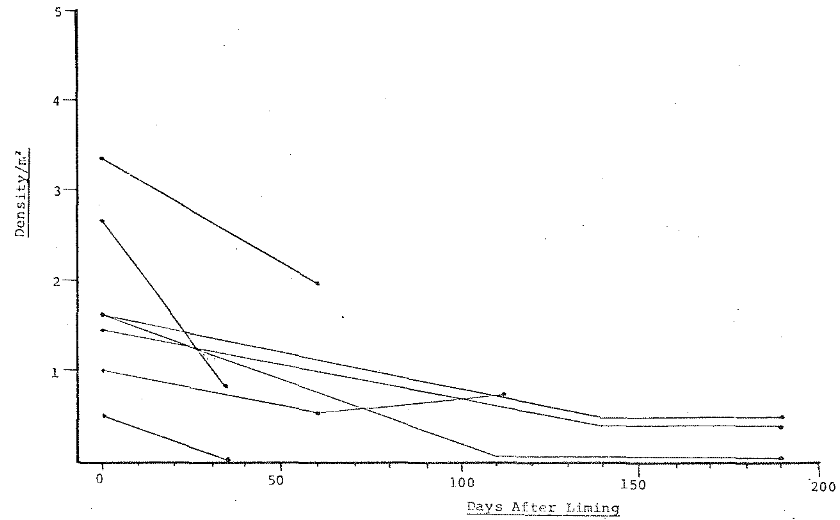


Figure 5c. Densities of Strongylocentrotus purpuratus before and after liming at San Clemente Island, California. Surface dispersal. (Source: Duffy 1976)

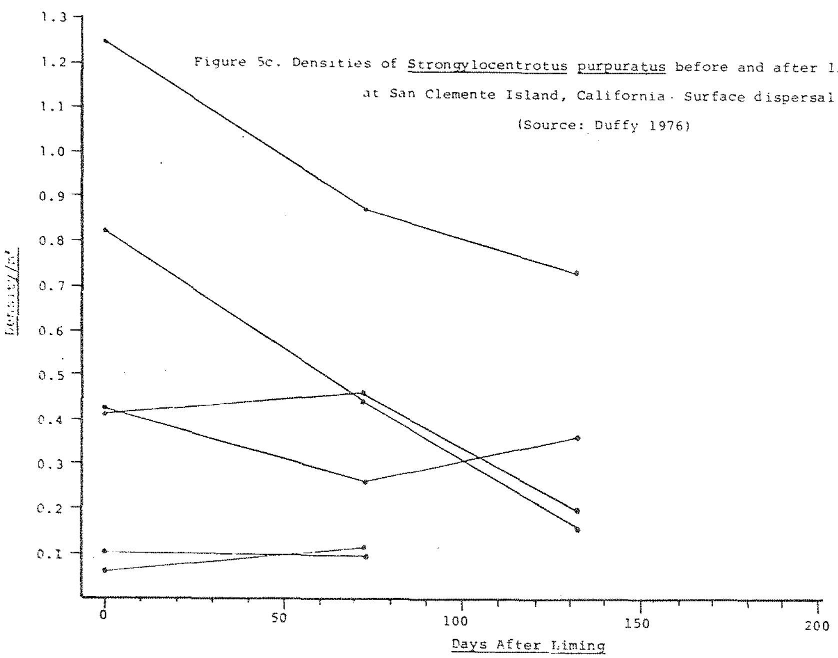
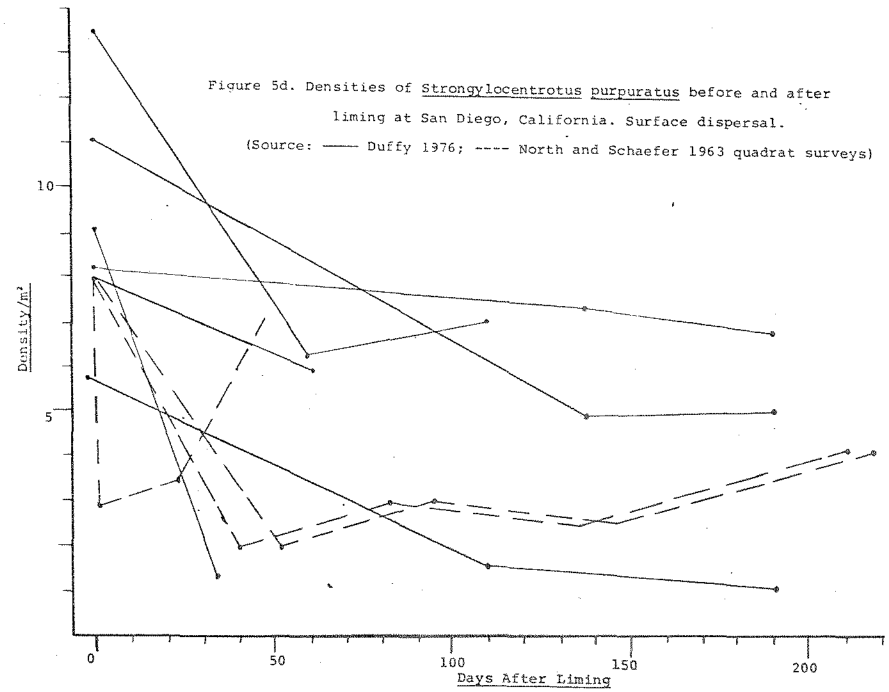


Figure 5d. Densities of Strongylocentrotus purpuratus before and after liming at San Diego, California. Surface dispersal. (Source: —— Duffy 1976; ---- North and Schaefer 1963 quadrat surveys)



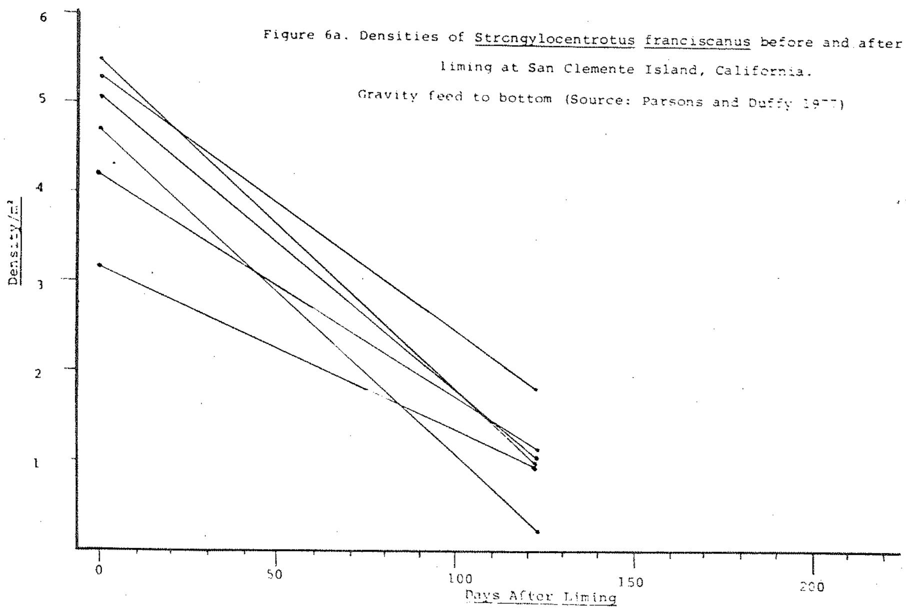


Figure 6a. Densities of Strongylocentrotus franciscanus before and after liming at San Clemente Island, California. Gravity feed to bottom (Source: Parsons and Duffy 1977)

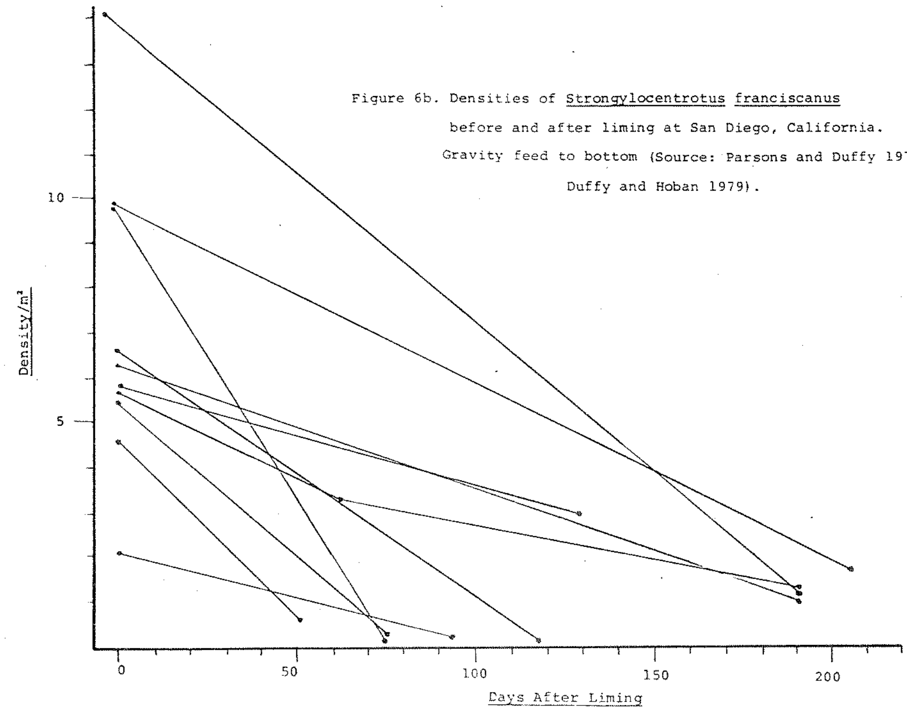


Figure 6b. Densities of Strongylocentrotus franciscanus before and after liming at San Diego, California. Gravity feed to bottom (Source: Parsons and Duffy 1977, Duffy and Hoban 1979).

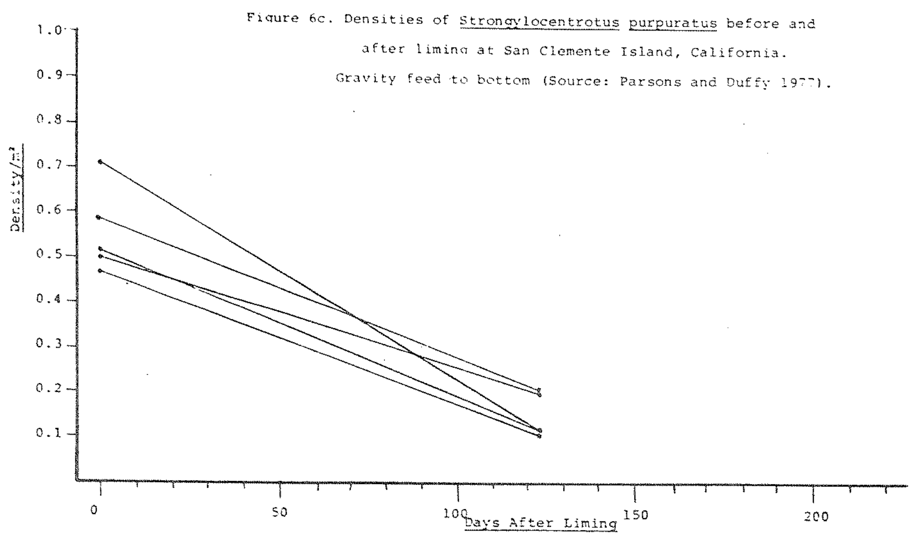


Figure 6c. Densities of Strongylocentrotus purpuratus before and after liming at San Clemente Island, California. Gravity feed to bottom (Source: Parsons and Duffy 1977).

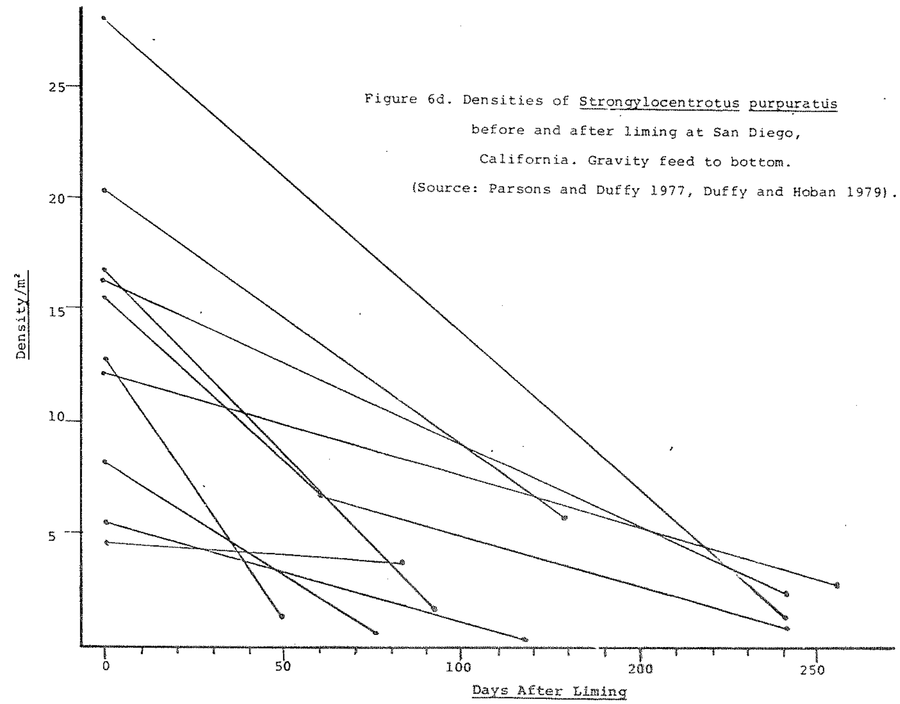


Figure 6d. Densities of Strongylocentrotus purpuratus before and after liming at San Diego, California. Gravity feed to bottom. (Source: Parsons and Duffy 1977, Duffy and Hoban 1979).

Figure 7a. Densities of Strongylocentrotus franciscanus before and after liming at San Diego, California. Pumped to bottom. (Source: Duffy 1980).

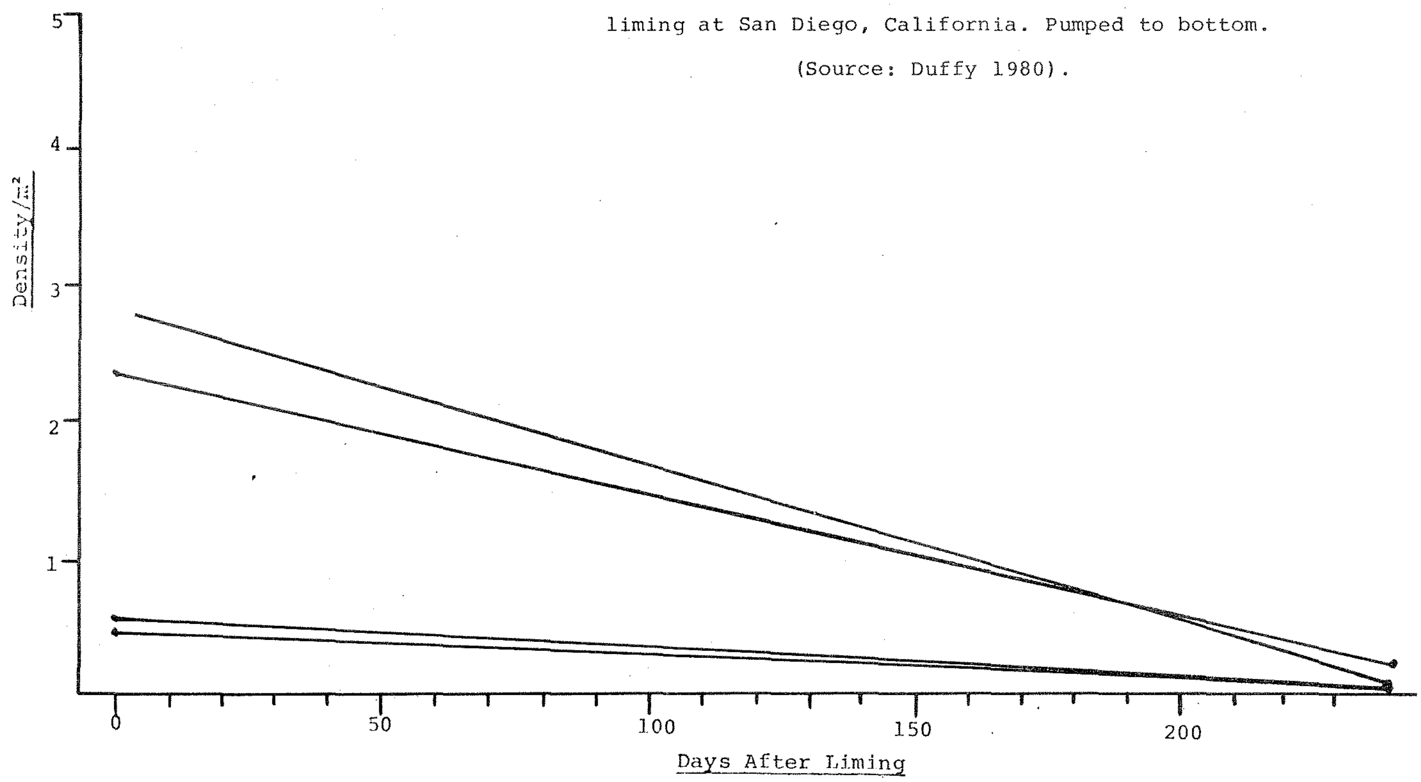
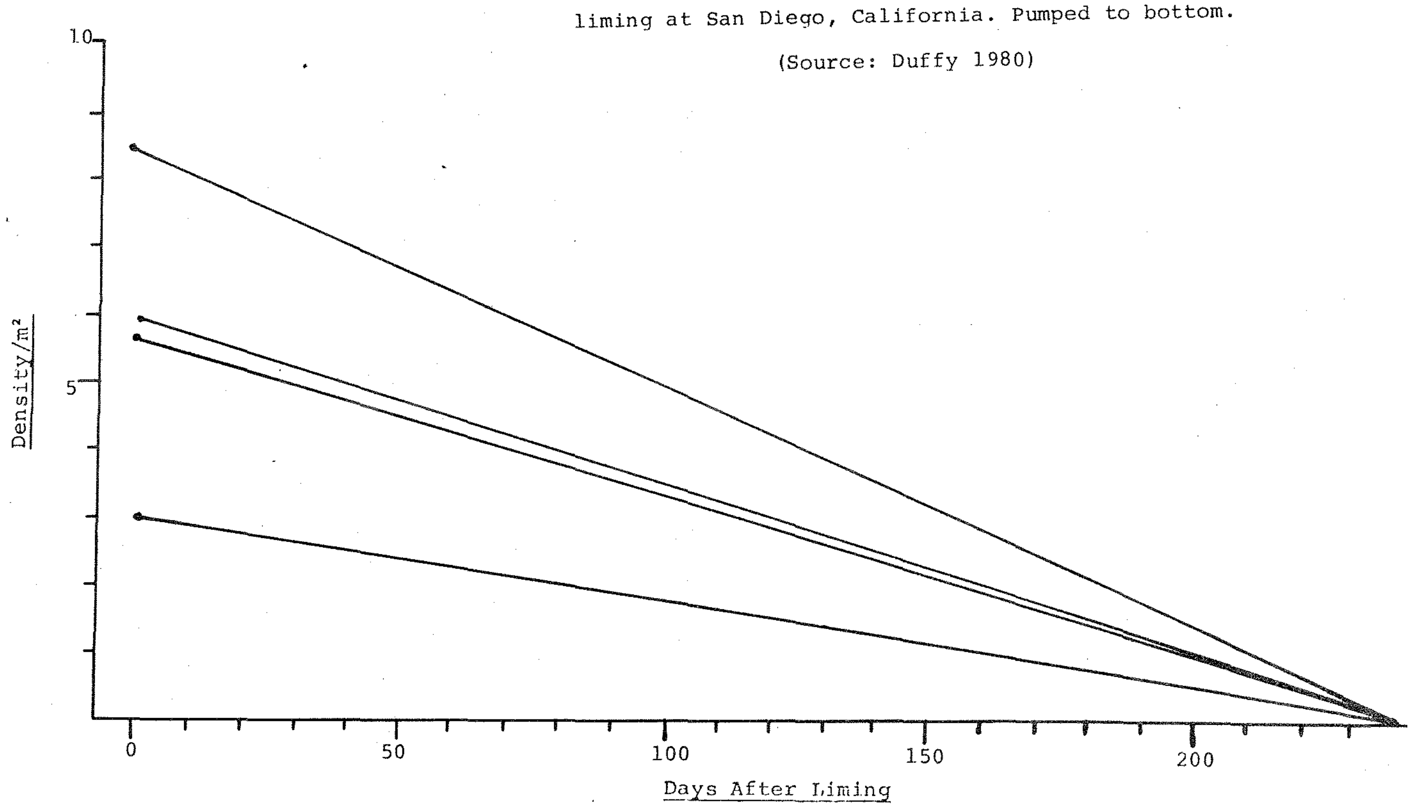


Figure 7b. Densities of Strongylocentrotus purpuratus before and after liming at San Diego, California. Pumped to bottom. (Source: Duffy 1980)



each separate survey, we assumed that the difference in urchin density between the pre-liming and the first post-liming surveys was entirely due to the application of quicklime. Then for all surveys in each category of Table 1, we calculated a mean percent reduction in density which we termed the "average kill rate."

Discussion

Table 1 shows that pumping the quicklime slurry through a hose to the bottom is by far the most effective technique of application. This is what one would expect, since the slurry reaches the bottom more quickly than with either of the other techniques. This means that the slurry is therefore hotter and more likely to cause the epidermal lesions which result in bacterial infection and death.

Also, Table 1 suggests no obvious difference between quicklime's effectiveness on the two species of urchin or in the offshore island and mainland habitats. The one anomalous kill rate of zero occurred at extremely low average urchin densities of $0.5/m^2$ and lower (Fig. 6c). It is possible that these few urchins were sheltered in rocks and protected from the lime's effects. It is also possible that kill rate estimates at these very low urchin densities are simply unreliable, because a small change in the numbers of urchins in the treatment area (due to migration, for example) will cause a relatively large change in the percent mortality.

EFFECTS ON OTHER ORGANISMS

Quicklime was originally used to control starfish in oyster beds (Loosanoff and Engle, 1942; Needler, 1940). In a series of laboratory experiments, North and Schaefer (1963) found that a wide variety of echinoderms were sensitive to quicklime. They also found that the abalone (*Haliotis* spp.), a large gastropod, was vulnerable to quicklime because it had no operculum to cover its aperture.

Field studies performed by the Kelco Company, the California Department of Fish and Game, and others have confirmed these results. Starfish and holothurians display obvious distress when limed, and immediately detach from the substrate (per. obs.; R. McPeak, Kelco Co., pers. comm.; P.K. Dayton, Scripps Institution of Oceanography, pers. comm.). Many other organisms, however, suffer no ill effects from liming. Duffy (1976) reports that lobsters (*Panulirus interruptus*) exposed in cages during a liming operation showed no effects

Table 1. Average mortality rates of two most abundant urchin species after different types of quickliming operations. Data from Duffy (1976), Parsons and Duffy (1977), Duffy and Hoban (1979), and Duffy (1980).

Species	Location	Method of lime dispersal		
		Surface	Gravity-fed to bottom	Pumped to bottom
S. franciscanus	San Clemente Island	0.56	0.78	-
	San Diego	0.70	0.81	0.97
S. purpuratus	San Clemente Island	0.00	0.73	-
	San Diego	0.57	0.77	0.99

during nine days of subsequent observation, nor are other crustaceans, fish, or gastropods with an operculum affected by lime. Kelco Company biologists have marked encrusting corals, bryozoans, sponges, and anemones and show that they survive even when exposed to two liming treatments.

Table 2 shows the average mortality experienced by several common species during the Department of Fish and Game liming operations. These data were collected on the pre- and post-liming surveys described in the section "California Fish and Game" previously. Comparison with the urchin mortality rates inn Table 1 shows that the sea cucumber (Stichopus sp.) and abalone (Haliotis spp.) were nearly as susceptible to lime as urchins, while all other species were much less so.

NOVA SCOTIA TECHNIQUES AND RECOMMENDATIONS

APPARATUS AND APPLICATION

Our liming apparatus was similar to that used by the California Department of Fish and Game (see "Pumped Dispersal at Bottom" - Table 2). The major difference was that the lime slurry passed through our pump, but not through Fish and Game's pump. There were three main components in our system (Fig. 8): 1) the mixing box, hung over the transom of the boat with the water inlets below the waterline; 2) the pump; and 3) the application hose. The mixing box was constructed of plywood. The pump was a 5 cm impeller-driven water pump powered by a 3 hp Briggs and Stratton motor. The hose was a 5 cm inner diameter PVC tubing and was 30 m long.

Lime (milled to top size of 40 mm) was shovelled into the mixing box at a rate of approximately 2 to 3 kg/min. It was there mixed into a slurry by water entering through the inlet holes. The inclined floor of the box directed the slurry to the 5 cm outlet in the bottom corner. The slurry was drawn from the mixing box to the pump, which forced it through the applicator hose to the diver who directed the flow onto the bottom. Because the lime passed through the pump, the larger pieces occasionally clogged the impeller.

During application, the boat was anchored and the diver worked to the limit of the hose, following disposable transects laid 10 m apart on the bottom. During rough weather, two anchors were used to prevent the boat from swinging. Positioning the boat allowed the diver to thoroughly cover an area before moving to another.

Table 2. Average mortality rates of species other than urchins present during quicklime operations. From Duffy (1976), Parsons and Duffy (1977), and Duffy and Hoban (1979; 1980).

Species	Method of lime dispersal		
	Surface	Gravity-fed to bottom	Pumped to bottom
Sea Cucumber (*Stichopus* sp.)	0.65	0.42	0.87
Spined Starfish (*Pisaster giganteus*)	0.27	0.29	0.72
Other starfish (*Henricia leviuscula*) (*Linkia columbiae*) (*Dermasterias imbricata*) (*Astrometis setulifera*) (*Pisaster brevispinnus*)	0.15	0.19	1.00*
Abalone (*Haliotis* spp.)	0.50	0.71	0.00*
Keyhole limpet (*Megathura crenulata*)	0.45	-	-

*Data from only one transect.

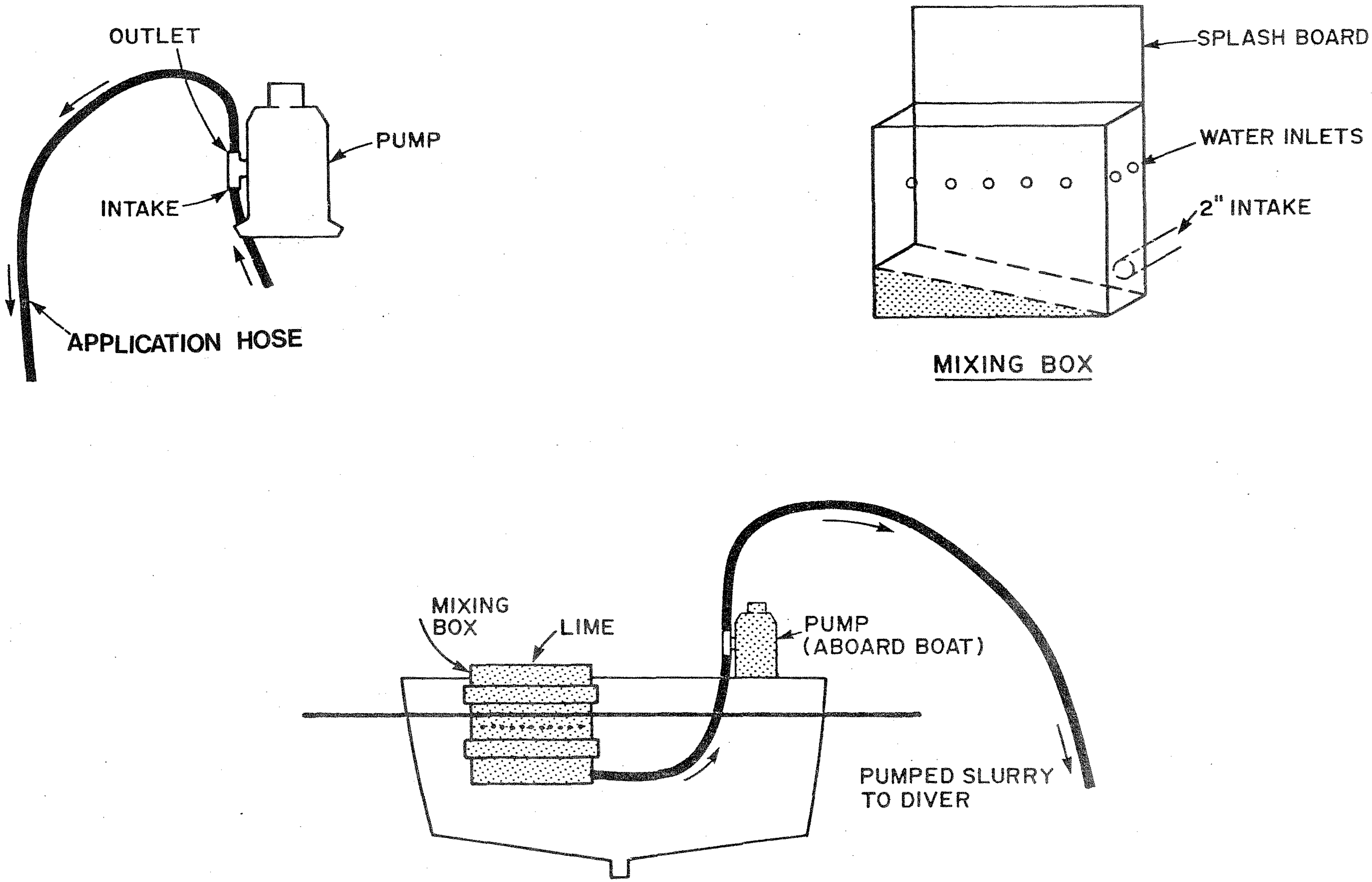


Figure 8. Liming apparatus utilized by the Welsford Research Group in Nova Scotia

Since we applied lime at different doses (see below), the rate at which the diver covered the bottom varied. At the low dose (0.33 kg/m^2), the diver treated about 6 to 7 m^2 per minute; at the higher dose (1.0 kg/m^2), he treated approximately 2 to 3 m^2 per minute. These rates varied, depending on diver experience, bottom topography, equipment malfunctions, and weather conditions. We found that diver experience and equipment malfunctions were the two most important factors to control in order to ensure a high application rate.

RECOMMENDATIONS

The equipment developed for this experiment performed acceptably, but certain improvements will make the liming operation more efficient. 1) A more uniform grade of lime (e.g., 15 mm) with fewer large chunks would react more completely and reduce wastage, since large chunks concentrate the lime on the bottom more than necessary. Less powder in the lime would reduce cloudiness in the water, improve diver visibility, and permit more efficient application. 2) Different length sections of hose would allow compensation for depth and reduce diver fatigue at shallower depths. The PVC hose was somewhat stiff and unwieldy. A corrugated, wire-reinforced hose would be more flexible and should be weighted to help the diver keep it near the bottom. A handle would also make the hose much easier to handle and would permit the diver to more accurately direct the flow of lime. 3) Clear sections of hose from the mixing box to the pump and at the pump outlet would allow the operator to quickly spot stoppages. In addition, there should be no right-angle bends in any of the connections. 4) The diver should have some means of controlling the flow rate. Two options are a diver-operated valve at the end of the hose or direct communication with the surface. Direct communication is preferable, because clogging could occur if the diver slowed the flow of lime while it was being pumped unabated from the surface. 5) Lime flow would be increased, and clogging reduced, by a larger self-priming pump with a flexible impeller (to permit passage of lime pieces), a throttle, higher horsepower, and larger intake and outlet. 6) A hopper for the mixing box that passed a steady flow of lime would release the operator from the necessity of constantly shovelling lime. 7) The rate of application could be increased by connecting two hoses to the pump outtake, each with a separate control valve. This would allow two divers to apply lime simultaneously. 8) The 6.7 m Boston Whaler used in this project easily accommodated the lime and liming equipment and could readily carry 800 kg of lime, or enough for about one day's liming.

LIMING EFFECTIVENESS IN NOVA SCOTIA

An experimental liming was performed in Nova Scotia to test its effectiveness in reducing urchin populations. The following sections describe and present the results of this experiment.

METHODS

Liming site and application

The liming site was in Terrence Bay, on the Atlantic coast of Nova Scotia between Halifax and St. Margarets Bay. The substrate was dominated by granite boulders interspersed with sand patches and sloped gradually to a depth of about 15 m, where boulders were replaced by sand and mud. There were no macroalgae in either the control or liming sites; they were both characteristic urchin-dominated barren grounds. The Appendix shows that the bottom fauna is predominantly urchins, with a few starfish (Asterias vulgaris). The liming and control areas were situated side by site, separated by a strip of sand about 30 m wide that limited urchin movement between the two areas.

Two doses of quicklime were tested. From March 10-25, 1981, we applied lime at the rate of 0.33 kg/m^2 to an area of approximatley 4000 m^2. During this period the water temperature was 5°C. On May 25 and 26, lime was applied to an area 400 m^2 at a rate of 1.02 kg/m^2. During this period the water temperature was 10°C.

Sampling

The sampling program was designed to test the null hypotheses that the densities of urchins and other large benthic organisms in the test area were not reduced by the application of quicklime. The two lime applications were treated as two separate experiments.

For the first liming, we sampled the test area and a nearby control area of equal size immediately before and one month after liming. Six 100 m long transects perpendicular to shore were laid in each area, beginning at the lower intertidal. For both the before and after sampling, animals from 45 quadrats of 0.25 m^2 were collected in each area. Quadrats were positioned along the transects by means of pre-selected random numbers. The quadrat frame was placed to the right of the line for the before sampling and to the left for the after sampling to prevent sampling the same spot twice. All samples were collected between the 0 m and 5 m marks on the transects to avoid the mud and sand substrate which occurred beyond this point. Samples, consisting of all urchins and other large benthic invertebrates in each quadrat, were counted, blotted, and weighed within several hours of collection.

The test and control areas for the second liming were 400 m^2 squares, 20 m on a side, and were situated in the first liming control area. Twenty-five quadrats, positioned along five transects with random numbers, were sampled in each of these areas three to four weeks after liming.

RESULTS

Observations

While mortality due to quicklime is delayed for days or weeks, depending on the dose and environmental conditions, there are immediate behavioral effects on many exposed organisms. Urchins fell off the rocks within minutes of being limed. Starfish and sea cucumbers displayed obvious distress. Starfish lifted and curled their arms, and some detached from the bottom, while sea cucumbers became bloated with water and "swam" above the bottom. Brittle stars were also irritated by the lime and withdrew their arms under the rocks.

Other organisms showed no response whatsoever to the lime. Lobsters and crabs were unaffected, even by direct contact with fresh lime. Fish (*Pseudopleuronectes americanus*, *Myoxocephalus* sp., *Lycodes* sp.) swam slowly through the lime or remained stationary and allowed themselves to be covered with no apparent effect. This corresponds to observations made during limings in California, where fish and crustaceans were unaffected.

Two weeks after the first liming (0.33 kg/m^2), some urchins' tube feet were shriveled and blackened, and the spines were lying flat rather than extended. There were many urchin tests that appeared to have been attacked by crabs. A few empty limpet (*Acmaea testudinalis*) shells, as well as one dead starfish (*Asterias vulgaris*) were observed. Brittle stars and mussels (*Modiolus modiolus*) appeared undamaged, and filamentous brown algae seemed more abundant in the shallow part of the limed area.

Quantitative changes in urchin populations

The Appendix presents the raw data, by individual quadrat, for all samples taken in both limed and control areas. All data sets were tested for normality (Sokal and Rohlf, 1969 - p. 122) and for disparity in variances; where appropriate, analyses were performed on the $\log_{10}(x+1)$ transformed data.

Table 3 shows that there is some heterogeneity among transect means of urchin weight and density in the areas used for the first liming (0.33 kg/m^2). T-tests on the untransformed data, however, reveal no significant differences between overall mean urchin density or weight in the two areas prior to liming. Because of its similar physical and biological characteristics, the control area is therefore an adequate reference against which to detect changes due to the first liming.

Table 4 shows the results of lime application at the rate of 0.33 kg/m^2. Urchin density in the limed area decreased by 40.6 $\pm$ 3% and in the control area by 11.2 $\pm$ 2%. The difference betwen these, 29.4 $\pm$ 5%, is the reduction attributable to quicklime. Similarly, the decrease in mean urchin biomass in the limed area relative to the control is 46% (+28%, -20%), similar to the decrease in density. A two-way analysis of variance on the untransformed urchin densities indicated this drop significant at the $p = 0.01$ level (Table 5). A similar analysis on the transformed data failed to demonstrate that the weight reduction was statistically significant (Table 6). This is not surprising, in view of the fact that the sampling program was designed with a level of replication sufficient to detect only a 50% drop in density or biomass.

Table 7 presents urchin density and weight after the second liming at 1.02 kg/m^2. The liming and control plots for this experiment were smaller subsets of the original control area for the first experiment and were not sampled as discrete units until after the second liming. Table 7 also shows that, compared to the average of the two control samplings, the second liming reduced urchin desnity by 73 $\pm$ 3% and urchin weight by 65 $\pm$ 10%. The before-liming estimates of density and weight are from the first experiment and are thus overall means for the entire area.

A two-way analysis of variance is not possible because of the unbalanced sampling design. We performed one-way analysis of variance on the transformed densities and an <u>a priori</u> comparison (Sokal and Rohlf, 1969 - p. 232) of the limed area and the two samplings of the control area. These showed that the reduction in urchin density after the second liming is significant at $p \ll 0.001$. Similar analyses on transformed urchin weight demonstrated that the reduction in biomass in the limed plot was significant at $p \ll 0.001$.

Quantitative changes in other organisms

Table 8 shows the densities, before and after liming, of the four most abundant large invertebrates in addition to

Table 3. Mean density and weight of urchins/1/4 m^2 quadrat along each of the sampling transects in the limed and control areas prior to liming.

		Transect						Area $\overline{X}$
		A	B	C	D	E	F	
Density:	Limed	11.50	15.62	14.28	9.87	13.83	16.12	13.51
	Control	16.28	11.25	14.12	9.14	10.86	9.37	11.82
Weight (g):	Limed	133.90	153.90	164.30	81.00	69.30	128.90	121.90
	Control	188.10	126.10	103.60	110.50	95.80	72.80	116.20

Table 4. Results of the first liming, at 0.33 kg/m^2. Densities and weights are of urchins/1/4 m^2 quadrat.

		Area	
		Limed	Control
Density:	Before	13.51	11.82
	After	8.03	10.50
Weight (g):	Before	121.90	116.20
	After	104.80	154.50

Table 5. ANOVA table for two-way analysis of variance on changes in urchin density after the first liming.

	df	SS	MS	F	P
Treatment (before vs. after)	1	579.60	579.60	18.873	0.001
Location (limed vs. control)	1	5.34	5.34	0.174	n.s.
Interaction (lime effect)	1	186.05	186.05	6.058	0.015
Error	176	5405.07	30.71		

Table 6. ANOVA table for two-way analysis of variance on the $\log_{10}(x+1)$ transformed changes in urchin weight after the first liming.

	df	SS	MS	F	P
Treatment (before vs. after)	1	0.11	0.11	0.748	n.s.
Location (limed vs. control)	1	0.13	0.13	0.565	n.s.
Interaction (lime effect)	1	0.15	0.15	0.652	n.s.
Error	176	41.52	0.23		

Table 7. Results of the second liming experiment, at 1.02 kg/m^2. Densities and weight are of urchins/1/4 m^2.

		Area	
		Limed	Control
Density:	Before		11.82
	After	2.96	8.60
Weight (g):	Before		154.50
	After	52.00	142.40

Table 8. Densities per 1/4 m^2 quadrat of the most abundant large invertebrates in addition to urchins. Limed and control plots differ for the first and second liming. L = limed; C = control.

	Asterias vulgaris		*Modiolus modiolus*		*Henricia sanguinolenta*		*Cancer irroratus*	
	L	C	L	C	L	C	L	C
Before	0.22	0.09	0.13	0.15	0.11	0.04	0.07	0.02
After first liming	0.15	0.20	0.11	0.11	0.02	0.07	0.02	0.02
After second liming	0.08	0.27	0.00	0.00	0.04	0.04	0.08	0.04

urchins. None of these was abundant enough for valid statistical analysis. The raw data, however, display no marked differences between limed and control areas that could be attributed to the effects of lime. At the dosages applied, therefore, lime appears to have no readily apparent effects on the abundance of large invertebrates other than urchins.

SUMMARY AND CONCLUSIONS

Quickliming has proven an effective urchin control measure in California, and the application technique used there proved readily adaptable to Nova Scotia. At a dose of 0.33 kg/m^2, we had poor results (29.4% kill), but at 1.02 kg/m^2, we achieved a kill rate of 73%, with 24% of the quadrats being empty of urchins. These dosages are higher than those used in California (0.22-0.44 kg/m^2).

The kill rate we obtained at the higher dosage is about the same effectiveness attained in California for *S. purpuratus* using a gravity-fed method of lime dispersal (Table 1). This urchin is in the same size range as *S. droebachiensis*. At this kill rate, Kelco Co. and the California Department of Fish and Game have successfully induced the reestablishment of kelp. They achieved this by judiciously applying lime at those times and places with the greatest potential for the settlement and survival of kelp.

While successful, our experiment did not achieve the 95+% kill rates reached in California. We attribute this to two causes: water temperature and lime particle size. North and Schaefer (1963) showed that urchin mortality after liming is related to temperature. This is because temperature controls the progress of the bacterial infections which ultimately kill the urchins (see Fig. 1). These infections proceed more slowly at the lower water temperatures in Nova Scotia. We therefore recommend that liming be carried out in late spring or summer and that treatment areas receive successive limings if extremely high kill rates are required. We also observed that the larger lime particles became caught in the urchins' spines and dissipated much of their reactivity in the water without coming into contact with the urchins' test. We suggest that the lime be milled to a maximum size of about 16 mm, rather than the "top 41 mm" used for this experiment. The lime supplier has indicated that they could readily supply a shipment of a smaller, more uniform size.

Adoption of the recommendations we proposed above, especially a smaller grade of lime, will most probably increase the kill rate from a single application to 80% or above. This may be the highest possible without successive applications. As stated above, this level of effectiveness is adequate for experimentation on the regeneration of algal communities.

We estimate that, at the 1 kg/m^2 dosage, one diver can apply 1000 kg of lime in one day. This assumes six hours of actual application at a rate of about 2.8 kg/minute. If the apparatus were modified to allow two divers to lime simultaneously, then about 2000 kg per day could be applied, and an acre could be treated in two days of liming. The actual rate will vary, of course, depending on weather and bottom topography. The costs of liming will vary, depending on the size of boat used and whether the work is performed by a private contractor, who must include overhead expenses in his charges, or by government personnel, who itemize only direct costs such as salaries. In any case, liming 4 hectares, for example, would require purchasing and constructing the pump, hoses, and mixing box, purchasing 40 tons of lime at $60/ton, and 20 full field days with three personnel to carry out the liming. Compared to any other available method, such as hammering, quickliming is the only feasible, cost-effective method for quickly clearing urchins from large areas.

ACKNOWLEDGEMENTS

We wish to thank R. McPeak of Kelco Co. and K. Wilson and J. Grant of the California Department of Fish and Game for generously sharing their time and information. Their first-hand liming experience and suggestions were invaluable. Dr. K. Tay of Environment Canada was instrumental in obtaining the necessary permits for the Nova Scotia field test. Dr. R. Miller of the Department of Fisheries and Oceans supervised the project and contributed many useful recommendations on both the field sampling and preliminary drafts of the final report.

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APPENDIX

Raw Quadrat Data

Sample number identifies transect line (letter or Roman numeral) and distance in meters along line from shallow end (number).

Before Liming

Control Area

Sample Number	Species	Number/¼m²	Wet Weight (g)
A-05	*S. droebachiensis*	20	418.0
	Crepidula fornicata	1	15.0
	Modiolus modiolus	1	115.9
A-09	*S. droebachiensis*	8	124.6
	Henricia sanguinolenta	1	0.5
A-18	*S. droebachiensis*	20	92.3
A-27	*S. droebachiensis*	8	260.5
	Echinarachnius parma	1	3.8
A-32	*S. droebachiensis*	22	105.3
A-41	*S. droebachiensis*	23	237.0
A-48	*S. droebachiensis*	13	79.0
B-01	*S. droebachiensis*	15	207.4
	*Homarus americanus**	1	1.5" carapace
	Modiolus modiolus	2	38.3
	Henricia sanguinolenta	1	0.7
B-19	*S. droebachiensis*	11	256.9
	Acmaea testudinalis	2	0.5
B-25	*S. droebachiensis*	4	55.7
B-26	*S. droebachiensis*	11	136.1
B-40	*S. droebachiensis*	11	47.1

* not removed

Sample Number	Species	Number/$\frac{1}{4}m^2$	Wet Weight (g)
B-42	1 anemone	not removed or measured	
	S. droebachiensis	11	133.0
B-47	*S. droebachiensis*	10	155.5
B-49	*S. droebachiensis*	17	17.4
C-11	*S. droebachiensis*	16	268.9
	Cancer irroratus	1	11.5
C-17	*S. droebachiensis*	17	201.0
	Modiolus modiolus	1	264.3
C-21	*S. droebachiensis*	13	91.0
C-28	*S. droebachiensis*	4	75.4
C-37	*S. droebachiensis*	4	8.1
C-39	*S. droebachiensis*	11	20.4
	Modiolus modiolus	1	234.2
C-40	*S. droebachiensis*	24	47.4
C-42	*S. droebachiensis*	24	116.4
D-08	*S. droebachiensis*	4	104.3
	Hiatella arctica	1	5.3
	Modiolus modiolus	1	71.7
D-13	*S. droebachiensis*	13	245.8
	Asterias vulgaris	1	3.5
D-19	*S. droebachiensis*	4	29.5
D-21	*S. droebachiensis*	11	79.9
D-29	*S. droebachiensis*	6	91.1
	Modiolus modiolus	1	31.4

Sample Number	Species	Number/¼m²	Wet Weight (g)
D-31	*S. droebachiensis*	11	159.2
	Echinarachnius parma	1	0.2
D-34	*S. droebachiensis*	15	64.0
E-06	*S. droebachiensis*	11	158.6
E-09	*S. droebachiensis*	7	119.9
	Acmaea testudinalis	1	1.3
E-18	*S. droebachiensis*	17	97.3
	Asterias vulgaris	1	1.0
E-22	*S. droebachiensis*	11	84.4
E-29	*S. droebachiensis*	8	57.3
E-32	*S. droebachiensis*	14	140.5
E-46	*S. droebachiensis*	8	12.4
F-05	*S. droebachiensis*	9	118.7
F-12	2 anenomes	not measured or removed	
	S. droebachiensis	6	82.9
F-19	*S. droebachiensis*	9	101.1
	Asterias vulgaris	1	8.0
F-27	*S. droebachiensis*	11	7.3
	Asterias vulgaris	1	0.1
F-32	*S. droebachiensis*	11	20.8
F-39	*S. droebachiensis*	8	41.6
F-41	*S. droebachiensis*	10	105.6
F-47	*S. droebachiensis*	11	104.4

Before Liming

Liming Site

Sample Number	Species	Number/¼m²	Wet Weight (g)
A-03	*S. droebachiensis*	21	244.3
	Asterias vulgaris	1	2.3
A-18	*S. droebachiensis*	11	166.2
	Buccinum undatum	1	24.8
	Mytilus edulis	1	2.5
A-19	*S. droebachiensis*	16	138.7
	Henricia sanguinolenta	2	1.4
	Modiolus modiolus	1	31.9
A-24	*S. droebachiensis*	9	182.7
	Modiolus modiolus	1	47.3
	Acmaea testudinalis	2	2.4
A-35	*S. droebachiensis*	12	19.0
A-37	*S. droebachiensis*	11	141.2
	Modiolus modiolus	1	10.2
	Asterias vulgaris	2	1.5
A-39	*S. droebachiensis*	5	75.9
A-42	*S. droebachiensis*	7	103.3
	Asterias vulgaris	2	0.8
B-01	*S. droebachiensis*	12	124.8

Sample Number	Species	Number/$\frac{1}{4}m^2$	Wet Weight (g)
B-08	*S. droebachiensis*	8	112.7
	Buccinum undatum	1	18.8
	Acmaea testudinalis	1	1.2
B-18	*S. droebachiensis*	23	288.9
	Modiolus modiolus	1	23.7
B-20	*S. droebachiensis*	15	252.6
B-23	*S. droebachiensis*	14	194.6
B-25	*S. droebachiensis*	21	235.1
B-26	*S. droebachiensis*	17	710.0
	Modiolus modiolus	1	41.7
	Henricia sanguinolenta	1	0.5
	Acanthodoris pilosa	1	0.6
B-48	*S. droebachiensis*	15	5.5
C-03	*S. droebachiensis*	9	22.0
	Littorina littorea	1	0.1
C-05	*S. droebachiensis*	16	301.7
C-22	*S. droebachiensis*	16	312.1
	Cancer irroratus	1	58.9
C-23	*S. droebachiensis*	10	146.9
	Asterias vulgaris	1	8.3
C-35	*S. droebachiensis*	17	310.4
C-39	*S. droebachiensis*	17	34.5

Sample Number	Species	Number/$\frac{1}{4}m^2$	Wet Weight (g)
C-40	S. droebachiensis	15	22.3
D-01	S. droebachiensis	4	91.8
	Modiolus modiolus	1	12.3
	Hiatella artica	1	2.0
D-03	Cancer irrorotus	1	43.7
	S. droebachiensis	13	95.3
D-19	S. droebachiensis	21	81.1
D-26	S. droebachiensis	13	73.2
	Asterias vulgaris	1	2.8
D-29	S. droebachiensis	17	111.2
D-42	S. droebachiensis	5	16.1
	Cancer irroratus	1	10.1
D-47	S. droebachiensis	2	2.1
	Buccinum undatum	1	27.2
	Asterias vulgaris	1	4.6
D-49	S. droebachiensis	4	96.4
	Asterias vulgaris	1	0.5
E-05	S. droebachiensis	12	58.2
E-09	S. droebachiensis	12	58.2
	Henricia sanguiolenta	1	0.6
E-11	S. droebachiensis	19	92.8
E-12	S. droebachiensis	12	134.8

Sample Number	Species	Number/$\frac{1}{4}m^2$	Wet Weight (g)
E-18	*S. droebachiensis*	20	50.4
E-47	*S. droebachiensis*	8	21.5
F-1	*S. droebachiensis*	27	272.6
F-4	*S. droebachiensis*	20	170.4
F-22	*S. droebachiensis*	19	101.1
F-28	*S. droebachiensis*	13	134.2
	Modiolus modiolus	1	17.3
	Asterias vulgaris	1	2.4
F-31	*S. droebachiensis*	8	138.5
F-42	*S. droebachiensis*	18	31.7
	Buccinum undatum	1	11.1
F-45	*S. droebachiensis*	13	151.9
	Henricia sanguiolenta	1	0.7
F-48	*S. droebachiensis*	11	31.2

First Liming

Control Site

Sample Number	Species	Number/¼m²	Wet Weight (g)
A-00	*S. droebachiensis*	31	569.3
	Acmaea testudinalis	1	0.8
A-07	*S. droebachiensis*	15	453.6
A-11	*S. droebachiensis*	11	314.4
A-18	*S. droebachiensis*	16	303.8
	Asterias vulgaris	1	0.1
A-19	*S. droebachiensis*	16	155.2
A-35	*S. droebachiensis*	16	136.8
A-46	*S. droebachiensis*	9	31.0
B-02	*S. droebachiensis*	16	542.6
B-09	*S. droebachiensis*	1	41.9
	Acmaea testudinalis	4	3.8
B-14	*S. droebachiensis*	1	54.6
	Henricia sanguinolenta	1	0.6
B-16	*S. droebachiensis*	5	64.7
B-28	*S. droebachiensis*	5	39.0
B-34	*S. droebachiensis*	19	164.5
B-39	*S. droebachiensis*	3	10.1
B-47	*S. droebachiensis*	9	15.8
	Pseudopleuronectes americanus	1	146.6
C-06	*S. droebachiensis*	17	299.3
	Asterias vulgaris	1	1.2
	Modiolus modiolus	1	243.2

Sample Number	Species	Number/$\frac{1}{4}$m^2	Wet Weight (g)
C-07	*S. droebachiensis*	23	313.6
C-26	*S. droebachiensis*	9	150.8
C-31	*S. droebachiensis* test	1	7.3
	Modiolus modiolus	1	18.1
C-45	*S. droebachiensis*	10	77.4
	Asterias vulgaris	2	12.6
	Psolus fabricii	1	41.2
C-47	*S. droebachiensis*	6	153.4
	Asterias vulgaris	1	0.2
	Modiolus modiolus	1	298.2
D-04	*S. droebachiensis*	15	309.5
D-07	*S. droebachiensis*	4	58.1
D-09	*S. droebachiensis*	18	177.9
	Asterias vulgaris	1	0.7
D-10	*S. droebachiensis*	13	265.9
D-16	*S. droebachiensis*	13	315.5
D-25	*S. droebachiensis*	22	108.9
D-31	*S. droebachiensis*	7	102.5
D-34	*S. droebachiensis*	17	57.1
E-02	*S. droebachiensis*	11	161.2
E-04	*S. droebachiensis*	17	306.4
	Modiolus modiolus	1	140.2
E-14	*S. droebachiensis*	5	87.5
E-15	*S. droebachiensis*	13	253.0
	Asterias vulgaris	1	0.1

Sample Number	Species	Number/¼m²	Wet Weight (g)
E-27	*S. droebachiensis*	2	17.1
E-41	*S. droebachiensis*	6	8.0
E-45	*S. droebachiensis*	3	75.5
	Cancer irroratus	1	5.4
	Buccinum undatum	1	6.8
E-48	*S. droebachiensis*	3	110.4
F-01	*S. droebachiensis*	14	191.7
F-07	*S. droebachiensis*	8	91.4
	Asterias vulgaris	1	0.9
	Henricia sanguinolenta	1	4.3
	Cancer irroratus	1	143.2
F-23	*S. droebachiensis*	5	31.7
	Henricia sanguinolenta	1	0.9
	Homarus americanus	1	8.0
F-26	*S. droebachiensis*	5	61.5
	Modiolus modiolus	1	77.6
	Homarus americanus	1	30.8
F-27	*S. droebachiensis*	5	19.2
F-36	*S. droebachiensis*	2	4.1
F-38	*S. droebachiensis*	4	5.0

First Liming

Liming Site

Sample Number	Species	Number/¼m²	Wet Weight (g)
A-00	*S. droebachiensis*	12	197.3
	Asterias vulgaris	1	0.6
	Acmaea testudinalis	1	0.1
	Cumcumaria frondosa	1	256.4
A-07	*S. droebachiensis*	5	73.6
	Modiolus modiolus	1	173.7
A-11	*S. droebachiensis*	9	136.3
A-18	*S. droebachiensis*	15	280.2
A-19	*S. droebachiensis*	11	296.9
A-35	*S. droebachiensis*	12	193.4
	Modiolus modiolus	1	301.7
A-45	*S. droebachiensis*	10	79.9
A-46	*S. droebachiensis*	10	81.6
A-47	*S. droebachiensis*	5	36.3
B-02	*S. droebachiensis*	7	76.3
	S. droebachiensis test	1	0.3
B-09	*S. droebachiensis*	16	133.9
	Acmaea testudinalis	1	0.1
B-14	*S. droebachiensis*	4	17.9
	Asterias vulgaris	1	0.3
	Modiolus modiolus	1	273.6

Sample Number	Species	Number/¼m²	Wet Weight (g)
B-16	*S. droebachiensis*	14	229.6
B-28	*S. droebachiensis*	6	29.7
B-34	*S. droebachiensis*	4	86.7
	Hiatella arctica	1	3.2
B-39	*S. droebachiensis*	5	76.3
B-47	*S. droebachiensis*	3	16.3
C-03	*S. droebachiensis*	9	116.8
	Asterias vulgaris	1	13.3
	Modiolus modiolus	1	45.6
C-16	*S. droebachiensis*	8	89.9
C-26	*S. droebachiensis*	9	107.6
C-27	*S. droebachiensis*	6	101.4
C-31	*S. droebachiensis*	10	42.3
C-45	*S. droebachiensis*	4	21.2
C-47	*S. droebachiensis*	5	31.4
	Modiolus modiolus	1	151.6
D-04	*S. droebachiensis*	4	6.9
D-07	*S. droebachiensis*	4	39.6
D-09	*S. droebachiensis*	7	102.3
D-10	*S. droebachiensis*	5	86.3
	Asterias vulgaris	1	14.2
D-16	*S. droebachiensis*	4	79.7
	Cancer irroratus	1	129.6
	Acmaea testudinalis	1	0.2

Sample Number	Species	Number/¼m²	Wet Weight (g)
D-25	S. droebachiensis	4	34.6
	Acmaea testudinalis	2	0.3
D-31	S. droebachiensis	10	17.4
D-34	S. droebachiensis	4	6.1
E-04	S. droebachiensis	10	106.4
E-14	S. droebachiensis	9	141.2
	Asterias vulgaris	1	2.6
	Henricia sanguinolenta	1	0.1
E-15	S. droebachiensis	10	291.6
E-16	S. droebachiensis	13	269.7
	Lycodes sp.	1	156.1
E-21	S. droebachiensis	3	4.9
E-41	S. droebachiensis	4	7.6
E-48	S. droebachiensis	2	17.6
F-01	S. droebachiensis	18	439.6
F-02	S. droebachiensis	7	161.3
	Asterias vulgaris	1	10.4
F-07	S. droebachiensis	12	189.5
F-23	S. droebachiensis	12	83.4
	Asterias vulgaris	1	0.8
	Buccinum undatum	1	59.6
F-26	S. droebachiensis	5	14.6
F-38	S. droebachiensis	9	32.1

Second Liming

Control Area

Sample Number	Species	Number/¼m²	Wet Weight (g)
I-01	*S. droebachiensis*	9	201.9
	Cancer irroratus	1	3.1
I-04	*S. droebachiensis*	8	93.6
I-08	*S. droebachiensis*	9	214.6
	Asterias vulgaris	1	0.2
I-09	*S. droebachiensis*	9	81.8
I-13	*S. droebachiensis*	6	93.3
	Asterias vulgaris	1	66.1
II-01	*Asterias vulgaris*	1	5.9
II-03	*S. droebachiensis*	3	45.8
	Asterias vulgaris	1	3.0
II-09	*S. droebachiensis*	17	321.7
II-10	-	-	-
II-16	-	-	-
III-01	*S. droebachiensis*	1	5.7
III-02	*S. droebachiensis*	10	181.9
III-05	*S. droebachiensis*	15	100.8
	Henricia sanguinolenta	1	0.6
III-07	*S. droebachiensis*	28	341.8
III-16	*S. droebachiensis*	8	165.0
	Asterias vulgaris	1	1.8

Sample Number	Species	Number/$\frac{1}{4}$m^2	Wet Weight (g)
IV-04	*S. droebachiensis*	12	253.2
IV-06	*S. droebachiensis*	15	127.6
IV-08	*S. droebachiensis*	10	322.4
IV-14	-	-	-
IV-16	*S. droebachiensis*	5	88.0
V-02	*S. droebachiensis*	12	227.7
V-06	*S. droebachiensis*	14	226.1
V-09	*S. droebachiensis*	7	192.5
	Asterias vulgaris	2	0.8
V-11	*S. droebachiensis*	3	39.4
V-16	*S. droebachiensis*	14	234.5

Second Liming

Limed Area

Sample Number	Species	Number/$\frac{1}{4}m^2$	Wet Weight (g)
I-02	-	-	-
I-06	*S. droebachiensis*	7	75.5
I-09	*S. droebachiensis*	2	8.4
I-11	*S. droebachiensis* test	1	5.6
I-16	*S. droebachiensis*	6	29.0
II-04	*S. droebachiensis*	5	131.8
II-06	*S. droebachiensis*	2	44.8
II-08	*S. droebachiensis*	1	2.4
II-14	*S. droebachiensis*	2	15.3
II-16	*S. droebachiensis*	5	33.0
III-01	*S. droebachiensis*	2	29.7
III-03	*S. droebachiensis*	12	252.5
III-09	-	-	-
III-10	*S. droebachiensis*	3	88.5
III-16	*S. droebachiensis*	2	4.7
IV-01	*S. droebachiensis*	8	182.2
	Henricia sanguinolenta	1	0.2
	Cancer irroratus	1	4.2
IV-02	*S. droebachiensis*	4	69.8
IV-05	-	-	-
IV-07	*S. droebachiensis*	2	47.0
	Asterias vulgaris	1	0.7

Sample Number	Species	Number/$\frac{1}{4}$m²	Wet Weight (g)
IV-16	*S. droebachiensis*	4	25.8
V-01	-	-	-
V-02	*S. droebachiensis*	2	96.9
V-05	*S. droebachiensis*	5	161.4
	Asterias vulgaris	1	17.5
	Cancer irroratus	1	83.1
V-07	-	-	-
V-16	-	-	-