# Mitigating Potential Impacts of Ferry Terminal Siting and Design on Eelgrass Habitat

Charles A. Simenstad
Wetland Ecosystem Team, School of Fisheries
University of Washington

Annette M. Olson
School of Marine Affairs
University of Washington

Ronald M. Thom
Marine Sciences Laboratories
Battelle Pacific Northwest Laboratories

*Winner of the 1997 Federal Highway Administration Environmental Excellence Award*

Sea Grant
Washington

# MITIGATING POTENTIAL IMPACTS OF FERRY TERMINAL SITING AND DESIGN ON EELGRASS HABITAT

Edited by

Charles A. Simenstad
Wetland Ecosystem Team, School of Fisheries
University of Washington, Box 357980
Seattle, Washington 98195

Ronald M. Thom
Marine Sciences Laboratories
Battelle Pacific Northwest Laboratories
Sequim, Washington 98382

Annette M. Olson
School for Marine Affairs
University of Washington, Box 355685
Seattle, Washington 98195-5685

**Washington State Transportation Center (TRAC)**
University of Washington, Box 354802
1107 NE 45th Street, Suite 535
Seattle, Washington 98105-4631

**Washington State Department of Transportation**
Technical Monitor
James A. Schafer
Senior Transportation Biologist

**Research Report**
Research Project T9903, Task 51
Eelgrass Phase II

Prepared March 1997 for

**Washington State Transportation Commission**
Department of Transportation
and in cooperation with
**U.S. Department of Transportation**
Federal Highway Administration

*1997 Federal Highway Administration*
*Environmental Excellence Award*

## DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented therein. The contents do not necessarily reflect the official views or policies of the Washington State Transportation Commission, Department of Transportation, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

A Washington Sea Grant Program publication

This report is published in part by Grant #NA76RG0119, Project A/PC-5, from the National Oceanic and Atmospheric Administration to Washington Sea Grant Program, University of Washington. The views expressed herein are those of the author(s) and do not necessarily reflect the views of NOAA or any of its subagencies.

 Contact Washington Sea Grant Program, Communications, 3716 Brooklyn Avenue N.E., Seattle, WA 98105-6716, phone 206-543-6600, fax 206-685-0380, email: seagrant@u.washington.edu

Washington Sea Grant Program web site: http://www.wsg.washington.edu

## TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF TABLES

## EXECUTIVE SUMMARY

The objectives of this study are to understand effects of ferry terminals and ferry operations on eelgrass (*Zostera marina* L.) meadows in Puget Sound and to design appropriate measures to avoid, minimize, and compensate for associated impacts. Dramatic increases in population and ferry traffic in western Washington have resulted in the need to expand existing terminals. Our studies have shown that eelgrass meadows near ferry terminals are affected by light reduction and other initial and long-term disturbances associated with terminal construction and maintenance, propeller wash, and bioturbation by macroinvertebrates (i.e., sea stars and Dungeness crab). Experimental work on light showed that below about 3M $m^{-2}$ $d^{-1}$ photosynthetically active radiation (PAR) for one to two weeks resulted in death of the plants. Long-term growth and PAR monitoring, as well as short-term measurements in eelgrass meadows, corroborated this value. Technological measures to mitigate impacts showed that concrete blocks with clear plastic centers, reflective material placed under terminals, and artificial lighting could all enhance light under the terminals. Restoration of damaged meadows adjacent to the terminals is proposed as a viable alternative for mitigating impacts from terminal expansion.

# INTRODUCTION TO STUDIES

by

Charles A. Simenstad
School of Fisheries
Box 357980
University of Washington
Seattle, Washington 98195-7980

Ronald M. Thom
Marine Science Laboratory
Battelle Pacific Northwest Laboratories
1529 West Sequim Bay Road
Sequim, Washington 98382

and

Annette M. Olson
School for Marine Affairs
Box 355685
University of Washington
Seattle, Washington 98195-5685

## BACKGROUND

Demand for increased ferry service and growth projected in regional transportation plans in Washington State mandate that the Washington State Department of Transportation (WSDOT) consider expanding existing dock structures over the waters of Puget Sound. However, because many of these terminals are over or proximate to intertidal and shallow subtidal eelgrass (*Zostera marina* L.) habitats, there is concern that expansion of terminals could impact the diverse ecological functions of these eelgrass communities. Docks over water are believed to affect eelgrass primarily by limiting light ("shading"), but associated ferry operations may also disturb the eelgrass habitat directly (e.g., through scouring by propeller wash) or indirectly (e.g., through resuspension of bottom sediments and subsequent light limitation due to turbidity). Our research challenge was to evaluate the configuration and arrangement of docks and associated ferry activities that create "significant" light reduction and promote other disturbances of eelgrass, and to evaluate alternative designs that would prevent or compensate for the impacts.

*Zostera marina* is a rooted flowering plant that in Puget Sound grows in sand to mud substrates between mean lower low water (MLLW) and approximately -6.1 m (-20 ft) MLLW. It forms densely vegetated "beds" or "meadows" and constitutes one of the most structurally complex of lower littoral and sublittoral estuarine/marine habitats. Eelgrass beds are well known to support important fisheries and wildlife resources, including juvenile salmon (*Oncorhynchus* spp.), Dungeness crab (*Cancer magister*), Pacific herring (*Clupea harengus pallasi*), and many types of waterbirds.

Eelgrass requires an underwater light environment sufficient to maintain growth and reproduction, and reduction or alteration of this light environment can result in reduced growth rates and plant loss. Reduction in light energy created by the placement of a structure over water is generally thought to be the primary cause of loss of seagrasses. The depth and distribution of eelgrass is undoubtedly controlled to a great degree by available photosynthetically active radiation (PAR; Olson and Doyle 1995, Zimmerman *et al.* 1994). Zimmerman *et al.* (1991) hypothesized that periodic episodes of light attenuation, as occurs when boats moor or pass over seagrasses, can affect eelgrass survival. This variability has been undersampled in previous investigations of the light requirements of eelgrass, as discussed in Kenworthy and Haunert (1991) and Morris and Tomasko (1993).

Concerns about the impacts of dock structures and ferry operations on eelgrass habitat structure, function, and support of fisheries resources has prompted natural resource agencies to require that widening of ferry docks or construction of new facilities impose minimal or no impact on the eelgrass resource. These concerns are representative of many coastal zone management policies regarding the effects of docks and boat activity on eelgrass in a variety of marine and estuarine environments in diverse locations. For example, Burdick and Short (1995) showed that eelgrass density and canopy structure were impacted directly under and directly adjacent to boat docks in Waquoit Bay and Nantucket Harbor, Massachusetts. Pentilla and Doty (1990) concluded after a survey of several boat docks in Washington State marine waters that shading structures can eliminate the existing macroflora under and adjacent to them. Scars in seagrass meadows created by boat moorings (Williams 1988, Walker *et al.* 1989) and propellers (Loflin 1993, Ehringer 1993) are commonly observed, especially in very shallow areas such as in Florida.

To address the critical need for further information, WSDOTsponsored an applied research project conducted by the University of Washington's School of Fisheries (UW/SOF) Wetland Ecosystem Team (WET) and School of Marine Affairs (UW/SMA), and Battelle Pacific Northwest Laboratories' Marine Sciences Laboratory (PNL/MSL), to develop a quantitative understanding of how docks affect eelgrass habitats and how to minimize (i.e., mitigate) this effect.

## OBJECTIVES

Our objectives in this study were to develop a causal and quantitative understanding of how ferry terminals and ferry operations impact eelgrass habitats in Puget Sound and to investigate potential measures to minimize these impacts. An indirect objective was to interpret the consequences of eelgrass habitat alterations and mitigation to fish, shellfish, and other living resources that use eelgrass. We documented the distribution and relative density of eelgrass at three terminals in Puget Sound. In addition, we conducted investigations of light under and near the terminals to document the effect of the terminal on light and to define the light regime under which eelgrass persists. The investigations also included experiments on the light requirements for eelgrass in the region. In addition, we developed the use of a spatially-explicit computer (computer-assisted design, CAD) model to define cumulative shading levels and patterns around the Clinton ferry terminal.

Finally, we examined the use of various methods for enhancing light under the terminals as an *in situ* mitigation method. In the discussion, we present a conceptual model of the effects of terminals and ferry operation on eelgrass. On the basis of the studies, we describe how modifications in one terminal design may mitigate or avoid many of these impacts.

As pointed out above, investigations of light requirements for seagrasses have been extensive. Much of this previous work has quantified either photosynthetic rate of leaf sections relative to instantaneous irradiance (photosynthetically active radiation, PAR), or short-term growth relative to the integrated daily PAR. Our experiments specifically investigated integrated daily PAR required to maintain long-term (seasonal to annual) growth of eelgrass. This information was required to assess the long-term impacts of light reduction and to help design terminal expansions to limit the effects of shading on eelgrass growth.

## APPROACH AND WORK PLAN

Field studies were conducted at three ferry terminals in north-central Puget Sound, Washington: (1) Clinton, (2) Port Townsend, and (3) Edmonds, Washington (Figure 1). These terminals were chosen because they are scheduled for expansion in the near future and because they occur in areas containing eelgrass. The terminals extend from land seaward over intertidal and shallow subtidal habitats to a depth of about -15 m MLLW. The terminals vary in width from 30 m at Clinton and Edmonds to 50 m at Port Townsend. Ferries dock essentially straight in at the seaward end of the terminal at Edmonds and Port Townsend, and at an angle to the long axis of the terminal at Clinton. Propeller wash is evident at a minimum of 30 m from the landward end of the boats during arrivals and departures. Ferries depart or arrive at approximately 20- to 45-minute intervals at all terminals during the day, with the most frequent arrivals and departures at Clinton and Edmonds. Ferry activity is much reduced at night. Although studies were conducted at all sites, because of pending dock expansion plans and permit applications, much of our more detailed investigations and analyses focused on the Clinton ferry terminal, and most of the examples described herein are from that site.

Our principal research objectives included the following:

1. Correlate *in situ* light transects with a sampling of eelgrass distribution, coverage, density, biomass and epiphyte biomass.
2. Link light availability to growth and survival of Puget Sound eelgrass by conducting a series of mesocosm experiments at the PNL/MSL facility.
3. Quantify spatial and temporal variation in the light environment by deploying continuously recording *in situ* light intensity meters at the Clinton ferry terminal.
4. Develop a three-dimensional computer model of the Clinton terminal that permits us to track the shadow of the terminal as it crosses eelgrass habitat in different seasons.

Six tasks, and associated subtasks, were defined to assess theimpacts of docks on eelgrass distribution and to recommend mitigation alternatives:

- Task 1—Review existing literature and data on light requirements of eelgrass
- Task 2—Implement a field monitoring program

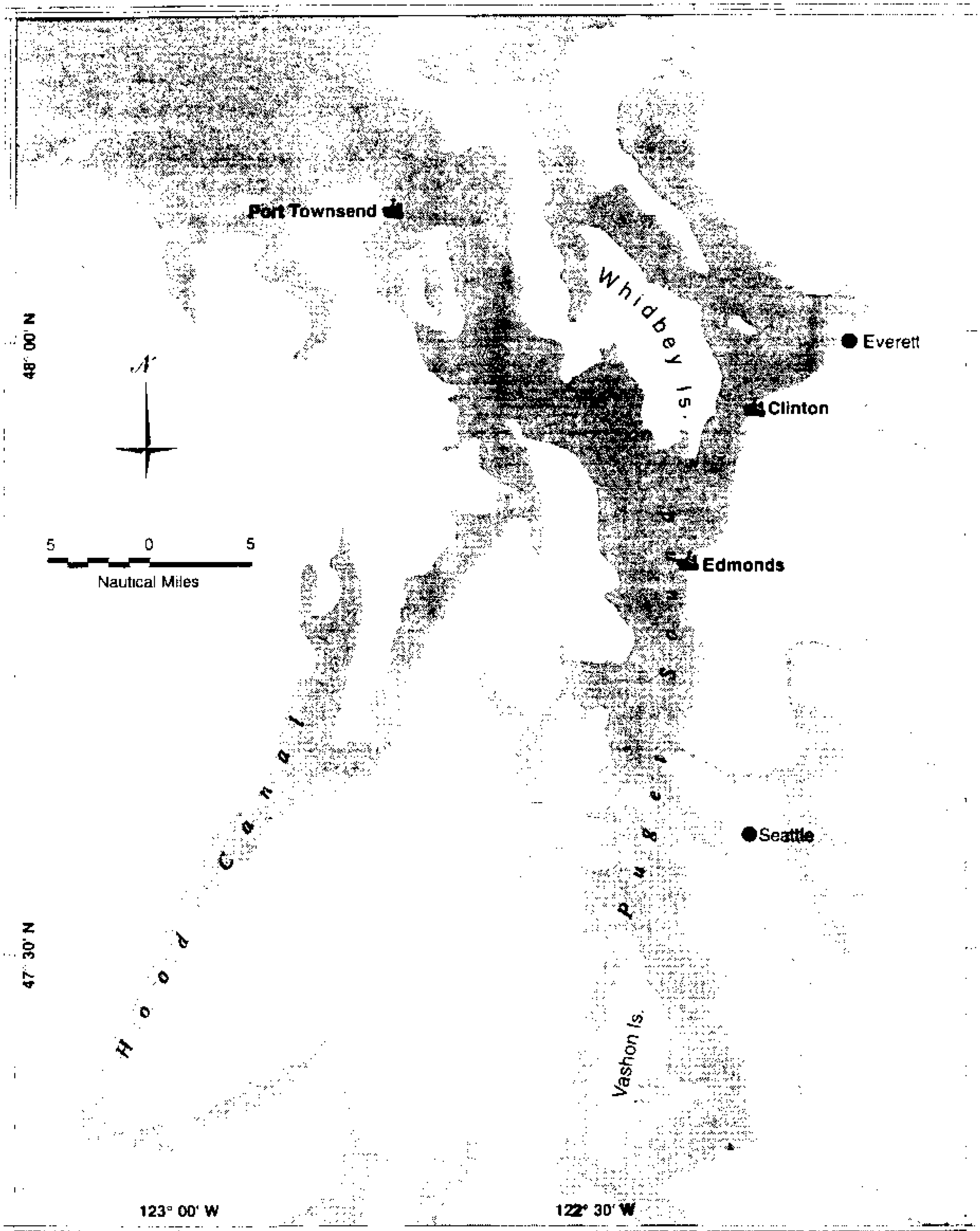


Figure 1. Location of three eelgrass study sites associated with Washington Department of Transportation ferry terminals

- Task 3—Evaluate the feasibility of using artificial lighting and selected physical structures to reduce the shading effect of docks
    - ♦ Subtask 3.1—field test the use of artificial lighting and physical structures
    - ♦ Subtask 3.2—study the photosynthesis and growth response of eelgrass to artificial lighting
    - ♦ Subtask 3.3—evaluation of the effects of various grating types or other physical structures to reduce shading
- Task 4—Identify mitigation alternatives
    - ♦ Subtask 4.1—inventory of potential eelgrass mitigation sites
    - ♦ Subtask 4.2—inventory of overwater structures
- Task 5—Perform data filing, quality assurance, and initial summary analysis
- Task 6—Manage study and communicate information

This research was accomplished in two phases: Phase I, conducted between May 1994 and June 1995, included Tasks 1, 2, 3 (in part) and 4 (in part); Phase II included the remaining tasks and was completed in December 1996. This report summarizes the results of both research phases.

Evaluating ecological interactions between environmental conditions and biotic responses of a complex habitat such as eelgrass requires a tightly coupled, interdisciplinary research effort. We assembled a diverse team of UW/SOF-WET, UW-SMA, and PNL/MSL estuarine/coastal scientists to address these tasks. The team and their relevant expertise was composed of the following:

<u>University of Washington</u>

- ♦ *School of Fisheries*
    - * Charles A. Simenstad, Senior Fishery Biologist; estuarine/coastal marine ecology, food web structure, wetland restoration
    - * Jeffery R. Cordell, Fishery Biologist; estuarine/coastal marine ecology, benthic and epibenthic invertebrate taxonomy and ecology
    - * James Norris, Fishery Consultant; seagrass videography, fisheries
- ♦ *School of Marine Affairs*
    - * Annette M. Olson, Assistant Professor; community ecology, coastal management, conservation biology
    - * Sandy Wyllie-Echeverria, Research Analyst; seagrass autecology, ethnobotany, videography

<u>Battelle Marine Sciences Laboratories</u>

- * Ronald M. Thom, Senior Research Scientist; estuarine/coastal marine ecology, marine plant/algal physiology, wetland restoration
- * David Shreffler, Fishery Biologist; fisheries, wetland restoration

The primary investigators responsible for the different subtasks are indicated as authors in following report sections that describe the results of the component research tasks.

# REVIEW EXISTING LITERATURE AND DATA ON LIGHT REQUIREMENTS OF EELGRASS

by

Annette M. Olson
School for Marine Affairs
Box 355685
University of Washington
Seattle, Washington 98195-5685

and

Ronald M. Thom
Marine Science Laboratories
Battelle Pacific Northwest Laboratories
1529 West Sequim Bay Road
Sequim, Washington 98382

## INTRODUCTION

The design, construction, and operation of dock facilities (as well as other shoreline structures) potentially affect the extent and quality of eelgrass habitats through direct shading, physical disturbance, and sedimentation. A major initial objective of our Phase I research was to review the scientific literature on the light requirements of eelgrass and evaluate alternative models for managing the impacts of altered light environments due to docks and comparable shoreline structures, as well as anthropogenic activities (e.g., turbulence generated from ferry docking and departures), that indirectly affect light incidence in water. We evaluated all relevant information on *Z. marina*; however, we also utilized information on other *Zostera* spp. and other seagrasses if applicable.

To provide the context of these prior scientific literature results on eelgrass growth, light requirements, and the *in situ* light environment to eelgrass communities near WSDOT ferry terminals in Puget Sound, we also monitored long-term eelgrass growth *in situ* and measured short-term (seasonal) growth relative to both ambient and manipulated light levels using experimental chambers (mesocosms).

## METHODS

### Literature Survey

Using electronic bibliographic databases, we searched for literature on the light requirements of eelgrass, concentrating on U.S. studies but including Europe and Asia (no references on Asian populations were located). We also surveyed policy documents on the management of light regimes or overwater structures.

## Long-term Growth Monitoring and Chamber Experiments

*Long-term in situ Growth Monitoring*

In order to determine seasonal patterns in eelgrass growth, as well as understand the relationship between PAR and growth, eelgrass growth rate was measured at a site approximately -1 m MLLW in a meadow located near the PNL/MSL, Sequim, Washington. Growth was measured using the shoot marking technique developed by Kentula and McIntire (1986), which consists of punching a small hole through all leaves at a point just above the sheath. The marked plants were delineated by a thin wire quadrat ($0.1 m^2$ in area) that was anchored to the substrata. In general, all plants within three quadrats were marked. After approximately two weeks, the plants within the quadrats were removed to the laboratory. The growth of the leaves relative to the mark in the oldest (senescent) leaf was cut from the plant, dried, and weighed. The number of plants in each quadrat for which growth was measured ranged from 18 to 155. Growth rate was measured 25 times between June 1991 and April 1996. *In situ* PAR was recorded during most of the growth experiments and converted to integrated daily average PAR for each growth period.

*Photosynthesis-Irradiance Experiments*

Experiments were conducted to evaluate the relationship between net primary productivity rate (NPP, as oxygen flux) and irradiance (PAR) in short-term incubations of leaf sections held in bottles. For each experiment, two or three 10-cm long leaf sections were cut from healthy leaves and placed in a 1-L canning jar. The jar was filled with ambient sea water from near the PNL/MSL, and the initial dissolved oxygen was measured with a YSI oxygen meter and probe. The jar was then incubated in shallow (outdoor) water tables held at ambient sea temperature. Five replicate jars containing eelgrass were run along with five jars with water only as a control for plankton metabolism. Two to five runs, each run consisting of the ten jars, were made each day that the experiments were conducted. Instantaneous PAR was monitored during the 2-hr incubations, and mean PAR was graphed against mean NPP. The experiments were conducted in summer 1991 and winter and spring 1993, during which over 80 runs were made.

*Growth Chamber Experiments*

We also experimentally evaluated irradiance requirements by manipulating light levels in flowing seawater tanks at PNL/MSL. Three 2.1-m long x 0.5-m wide x 0.5-m deep tanks were divided into four sections. A screen was placed over three sections in each tank to reduce the PAR reaching the plants. Two 15-cm diameter flower pots, each containing three shoots in sediment, were placed under each of the four light treatments (three with screen and one with no screen). At 7-d to 21-d intervals (depending on growth rate), all shoots were trimmed to be 30 cm long. The material trimmed from the end of the shoots was dried and weighed. Although some loss of material off the ends of the leaves probably occurred, we observed this to be minimal since the plants were in a relatively quiet environment not subject to wave action or other erosive forces. This "leaf trim" method provided a convenient assay of growth differences among treatments without severe damage or loss of plants. Before removing the eelgrass growth, epiphytic growth was removed by gentle scraping. The epiphytes were dried and weighed. The experiments ran from 24 November 1994 to 19 November 1995. Plants were replaced in February 1995 because most had died in the lower light treatments. The tanks were held at ambient sea temperature by flowing seawater.

PAR reaching the plants was monitored periodically to quantify the difference in irradiance among the treatments. Ambient PAR was monitored continuously. PAR in each treatment was predicted on the basis of a regression relationship that was developed between continuous ambient light and periodic data on light in each treatment.

## RESULTS

### Literature Survey

The complete report (authored by Olson, Doyle and Visconty) on the results and synthesis of the literature survey is included as Appendix A. The following is a summary of these findings.

We found that the bulk of research has focused on physiological-, individual-, and population-level responses to changes in light regime; the effect of light on the structure, persistence, and functioning of eelgrass beds has rarely been directly studied. Furthermore, we found few published studies on the light requirements of eelgrass in the Pacific Northwest; most studies we surveyed have been conducted in the Atlantic and in California, where physical conditions differ substantially from those in Puget Sound.

#### *Seagrass Management Authority and Implementation*

In the United States, regulation of direct disturbance to seagrasses (as well as planning for conservation of seagrass habitats) occurs under the Clean Water Act, Coastal Zone Management Act, and other federal, state, and local mandates. Management of direct disturbance may also include the issuance of guidelines for dock design and restrictions on moorage and vessel operation in seagrass habitats. In Washington State, management standards for seagrasses focus exclusively on direct physical alteration and/or destruction of seagrass habitats.

Management of the light environment for submerged aquatic vegetation (SAV, including seagrasses and freshwater macrophytes) has been proposed or implemented in several Atlantic Coast jurisdictions. In Washington State, however, mechanisms for management of the light environment do not exist, and the light requirements of seagrasses are not reflected in water quality or other management standards. Furthermore, specific standards that regulate the shading impacts of docks and other shoreline structures on seagrasses appear to be lacking in the U.S., and field studies that document shading impacts are rare.

#### *Approaches to Managing the Light Environment of Seagrasses*

The light requirements of seagrasses are not simple to define because the light received by a leaf does not translate directly into a "healthy," persistent seagrass bed. Instead, a complex set of adaptations determines a plant's carbon balance—a measure of how the plant uses light and allocates photosynthetic products—and thus its potential for survival, growth, and reproduction. Describing the light environment is also complex. Plants are able to use only certain spectra of the available light, and the quantity and quality of the light environment varies in time and space. We found two main approaches to defining the light requirements and describing the light environment of seagrasses in a management context: (1) a "seagrass depth limits" model, and (2) a "carbon balance" model.

*Seagrass Depth Limits and Mean Light Attenuation*

The seagrass depth limits model assumes that, if seagrasses are present, the available light must be sufficient. Seagrasses themselves are viewed as "integrators" of the light environment. Seagrass depth limits are correlated with mean light attenuation in the water column to infer the minimum light needed to support seagrass populations (Appendix A, Table 1). Those taking the "depth limits" approach also assume that plant distribution reflects average light conditions. The average light attenuation in the water column (or the proportion of surface irradiance reaching the leaves) is thus used as an indicator of the quality of the light environment.

The seagrass depth limits model has been applied to management of seagrasses in several Atlantic and Gulf Coast jurisdictions (Kenworthy and Haunert 1991, Batiuk *et al.* 1992, Morris and Tomasko 1993, Short *et al.* 1993, Dixon and Leverone 1995), most notably in Chesapeake Bay. By defining light requirements in terms of light attenuation, one can predict the change in the deep edge of seagrass distribution associated with different levels of light attenuation and, thus, determine the aerial extent of gain or loss of seagrass habitat associated with a given change in attenuation. This permits managers to set restoration goals in terms of increased area of benthos or depth extensions to be gained and to determine the reduction in attenuation needed to attain those goals (Batiuk *et al.* 1992, pp. 20, 21, 29).

Changes in water quality necessary to achieve the desired reduction in light attenuation may be guided by water transparency or pollution reduction standards or both. Water transparency standards based on seagrass light requirements have been proposed in Florida (Morris and Tomasko 1993, Appendix II). Development of pollution-reduction standards requires the additional step of determining how different classes of pollutants contribute to light attenuation and thus limit light availability at a given depth (e.g., Batiuk *et al.* 1992, Morris and Tomasko 1993).

*Whole-plant Carbon Balance and Variable Saturating Irradiance*

The alternative "carbon balance" model incorporates more biological complexity to predict plant carbon balance in a given light environment. This approach assumes that if available light is sufficient to produce a positive net carbon balance, plants will grow and persist in that light environment. Carbon balance is determined experimentally in laboratory studies of photosynthetic response to light. Those taking an alternative, "carbon balance" approach note that variation in the light environment may be more important for plant distributions than average conditions. Two measures of light availability have been proposed to describe the quality of the light environment under this model (Appendix A, Table 1): the daily integrated irradiance (DII, in moles of photons per meter squared per day) and the daily period of irradiance-saturated photosynthesis ($H_{sat}$, in hours).

Strengths and limitations of the carbon balance model derive from the premise that if available light is sufficient to produce a positive net carbon balance, plants will grow and persist in that light environment. The principle advantage of this approach is the direct experimental link it makes between light availability and plant performance (photosynthesis), making its definition of minimum light requirements more general than those of the depth limits approach. Secondarily, temporal variation in light availability is taken into account explicitly, because measurement of DII or $H_{sat}$ requires frequent or continuous *in situ* light monitoring.

The carbon balance model has had limited application to management, despite its technical sophistication. The approach appears to have influenced the design of monitoring programs by calling attention to the problem of variability in the light environment (e.g., Kenworthy and Haunert 1991, Morris and Tomasko 1993, Dixon and Leverone 1995). In addition, it has been used to validate the depth limits approach (e.g., Dennison 1987, Dixon and Leverone 1995). However, we do not know of any program that has attempted to manage the light environment of seagrasses by implementing water quality or other management standards based on carbon balance.

However, several factors may make it difficult to translate the carbon balance model into management practices. First, the approach does not make any direct link between light availability and plant distribution—a major concern of managers. The carbon balance approach assumes that plants with positive carbon balance should grow and persist. However, if factors other than light remove plant tissue (*e.g.*, disturbance, herbivory, epiphytes, or disease), then plants may not persist even where *in situ* light is predicted by the model to be sufficient. Furthermore, to establish the minimum light levels needed for positive carbon balance requires more technical expertise and equipment than those needed to apply the depth limits approach.

Other factors that limit the application of the carbon balance approach to management involve the difficulty of using carbon balance-based criteria to monitor changes in the light regime. Continuous *in situ* monitoring is needed to determine DII or $H_{sat}$ for a given region or site, and thus the spatial scale of monitoring is limited by cost and logistics. The carbon balance approach may be more applicable to managing the light environment around stationary structures, such as docks, where variability in light attenuation is more predictable and where the spatial extent of required monitoring is limited.

*Applications to Monitoring and Management of the Light Environment of Eelgrass Near Docks in Puget Sound*

Two main factors limit the extent to which existing approaches can be applied to managing the light environment of eelgrass near docks in Puget Sound. First, the impacts of docks on the light environment differ from those of degraded water quality. Second, Puget Sound differs fundamentally from other systems for which management approaches have been developed. Consequently, new applications must be devised to solve management problems posed by the design, construction and maintenance, and operation of ferry terminals and other overwater structures in Puget Sound.

To date, most efforts to manage the light environment of seagrasses have attempted to mitigate or reverse the effects of water quality degradation. The scientific approaches to management (see Olson *et al.*, and Thom and Wyllie-Echeverria, below) have thus been developed in the context of water quality monitoring and regulation. However, the impacts of docks and their use on Puget Sound populations of eelgrass present somewhat different scientific and management problems and opportunities than associated with water quality. For example, because light attenuation varies over space and time, water quality impacts on specific eelgrass populations are difficult to predict. In contrast, shading by over-water structures is highly predictable and related to architectural details of their design (Burdick and Short 1995, Fresh *et al.* 1995, Olson *et al.* 1996, Witherspoon and Rawlings 1994). Somewhat less predictable is shading due to construction and maintenance equipment, parked and operating ferries, and the plume of suspended sediments and bubbles cast off by docking and departing vessels. In addition, light attenuation due to pollution in the water column varies at large spatial scales relative to the size of eelgrass beds, whereas shading due to dock design is site-specific and small in spatial scale.

Finally, strategies for water quality management (water clarity and/or pollution reduction standards) differ from options for mitigating the shading effects of docks. Design options to mitigate shading effects include optimizing dock orientation, width, height over the water, and distance of slips from shore; installing gratings, transparent surfaces, reflective materials, or artificial lighting; and reducing the numbers of pilings (Burdick and Short 1995, Fresh *et al.* 1995, Witherspoon and Rawlings 1995; Thom *et al.* 1995). Careful scheduling of construction and maintenance can minimize the impacts of temporary equipment. Because the impacts of docks are small in spatial scale, relatively predictable, and susceptible to site-specific avoidance and minimization, we suggest that methods such as the "carbon balance" model are feasible to apply to mitigation.

Differences between Puget Sound and other U.S. estuaries also affect the choice of approaches to managing the light environment near docks. The Puget Sound environment is distinctly different from other areas where comprehensive research has been conducted on light requirements of eelgrass: It differs in its bathymetry, and in salinity, temperature, nutrient, and tidal regimes. Because so little research has been conducted on the light requirements of Pacific Northwest populations of eelgrass, the effects of these differences for eelgrass abundance and distribution cannot be stated with certainty. However, it is likely that short-term photosynthetic response is significantly affected by the macro-tidal regime because both water column depth and currents vary significantly over the mixed semi-diurnal tidal cycle. Additionally, the extreme tidal variation makes application of the depth limits approach inappropriate for defining light requirements of eelgrass in terms of mean light attenuation (or percentage of surface irradiance).[1] Consequently, we conclude that the carbon balance model is most appropriate for defining the light requirements of eelgrass and for monitoring changes in the light environment.

**Long-term Growth Monitoring and Chamber Experiments**

The short-term NPP incubations showed that photosynthesis appeared to be saturated at a PAR of about 300 to 400 $\mu M\ m^{-2}s^{-1}$ (Figure 2) in all seasons. Peak NPP was greatest in winter, intermediate in spring, and distinctly lower in summer.

---

[1] The depth limits approach assumes that variation in water depth is negligible, making it possible to correlate the attenuation coefficient with the lower distributional limit of eelgrass in order to define its habitat requirements. Because tidal extremes are so great in Puget Sound, the water depth term (*z*) in the Beers-Lambert equation cannot be assumed to be constant, and thus light attenuation (*k*) does not serve as a good proxy for the depth penetration of seagrasses.

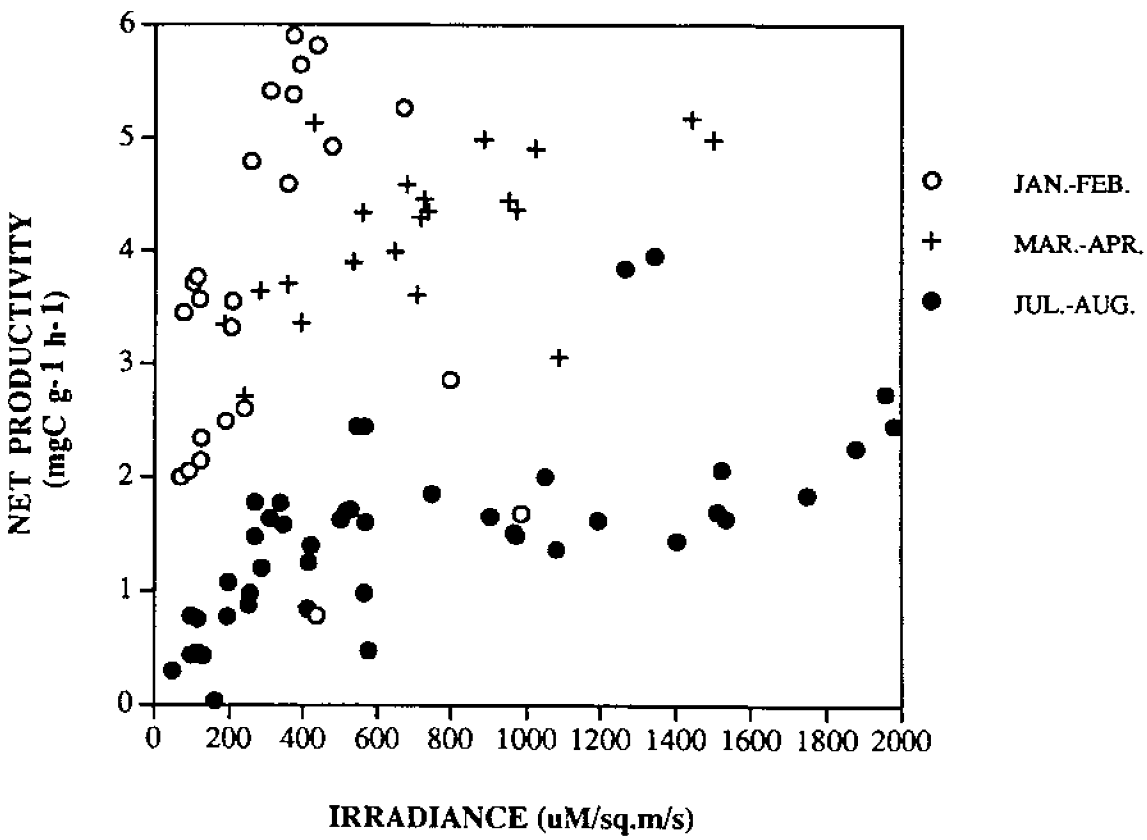


Figure 2. Net productivity of eelgrass leaf sections versus irradiance; each point represents a mean of five measurements.

The *in situ* growth rate of eelgrass at PNL/MSL showed seasonal patterns, with slowest rates in mid-winter, maximum rates in late Spring, and intermediate rates in summer and autumn (Figure 3). The growth rate appeared to peak at an average PAR of about 3 to 5 M $m^{-2}d^{-1}$ (Figure 4). However, very low PAR in late winter-early Spring of 1996 corresponded with growth rates comparable to rates at much higher PAR. PAR monitoring between May 1995 and July 1996 at PNL/MSL showed the dynamic nature of variability in PAR among seasons (Figure 5). In contrast, the consistently low PAR between mid-December and mid-April is striking.

Experiments conducted 2 June 1995 indicated that the shading in the chambers affected photosynthetic rate (Figure 6). The lowest rates occurred under the greatest shade. There was little difference in photosynthetic rates between the least shaded and unshaded treatments; both had relatively high average instantaneous PAR levels during the experiment.

The results from experiments in the growth chambers can be divided into four relatively distinct groups: (a) a period of low light, low temperature and low growth in winter (December-February); (b) a period of highest growth rate and rapidly increasing light and temperature in spring (March-May); (c) a summer period (June-July) of highest light and temperature but a growth rate somewhat less than that in spring; and, (d) an autumn period (September-November) with intermediate light and temperature and a growth rate between those of winter and summer (Figure 7A-7C).

The shade material effectively reduced PAR enough to affect growth rate in most periods (Figure 7B-7C). PAR in the most shaded treatment was about 13 percent of that in the unshaded treatment at high levels of natural irradiance. In December 1994 through February 1995, growth of eelgrass was very low in most treatments and essentially ceased in the most shaded treatments. Growth was very low in autumn 1995 in the lowest light treatment. In comparing the light (Figure 7B) with the growth rates in Figure 7C, it appears that during winter and autumn if PAR is below about 3 M $m^{-2}$ $d^{-1}$ for approximately one week, growth would either cease or be very low. Because of the much greater ambient PAR in Spring and summer, cessation of growth did not occur in the chambers even at the lowest light treatment. However, reduced light affected growth in this treatment even during the periods of greatest PAR.

A scatter plot of growth versus irradiance for all treatments combined suggests that light becomes limiting at about 4 to 5 M $m^{-2}d^{-1}$ (Figure 8). Below about 1 M $m^{-2}d^{-1}$, no growth occurs. The data in Figures 4, 6 and 7B suggest that maintenance of growth during winter and autumn would require about 3 to 4 M $m^{-2}d^{-1}$.

Epiphyte growth was also affected by variations in PAR in the chambers (Figure 9). A period of very low growth in winter was followed by a period of increased growth in Spring, a period of low growth in summer, and then a period of most rapid growth in late summer and autumn. Although highly variable, growth appeared to decrease below about 7 to 8 M $m^{-2}d^{-1}$ (Figure 10). There appeared to be a slight positive relationship between eelgrass growth and epiphyte growth (Figure 11), with a major peak in epiphyte growth at intermediate eelgrass growth rate. This increase corresponds with the autumn peak in epiphyte growth, which is a period of intermediate eelgrass growth.

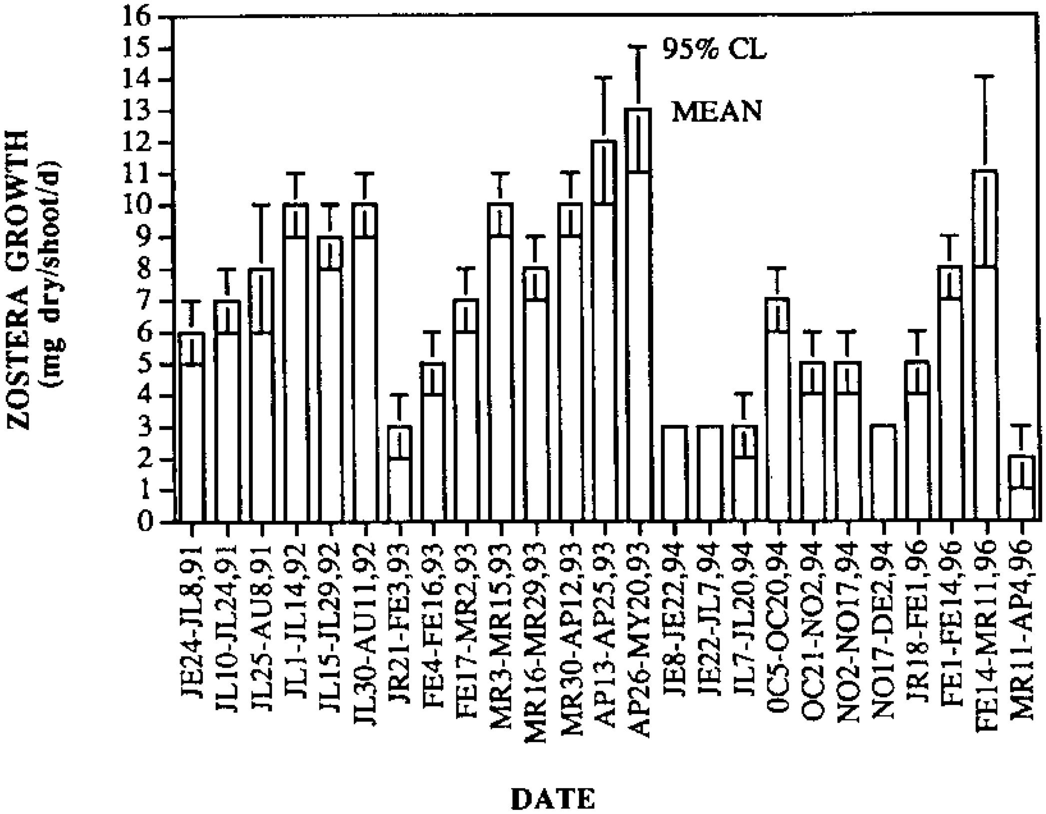


Figure 3. *In situ* growth rate of eelgrass at PNL/MSL between summer 1991 and spring 1996.

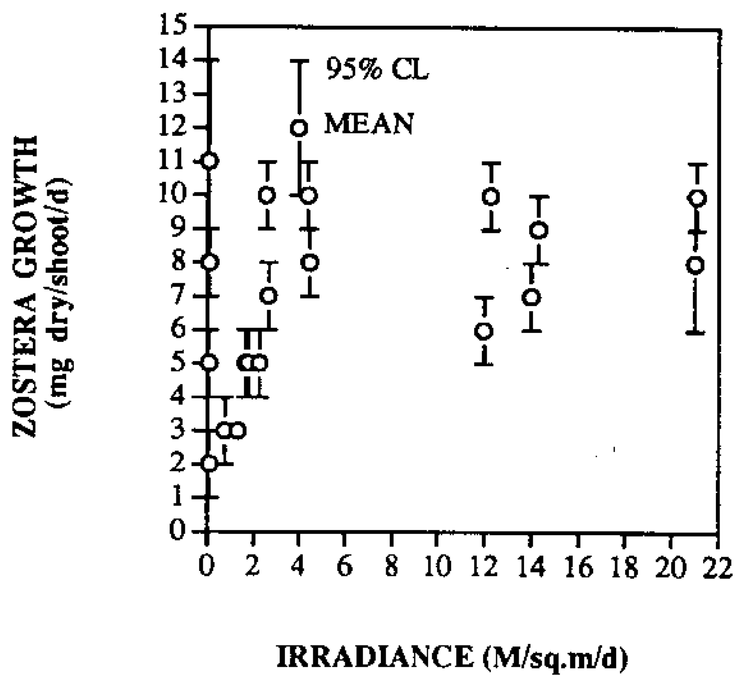


Figure 4. Integrated daily irradiance versus *in situ* growth of eelgrass at PNL/MSL.

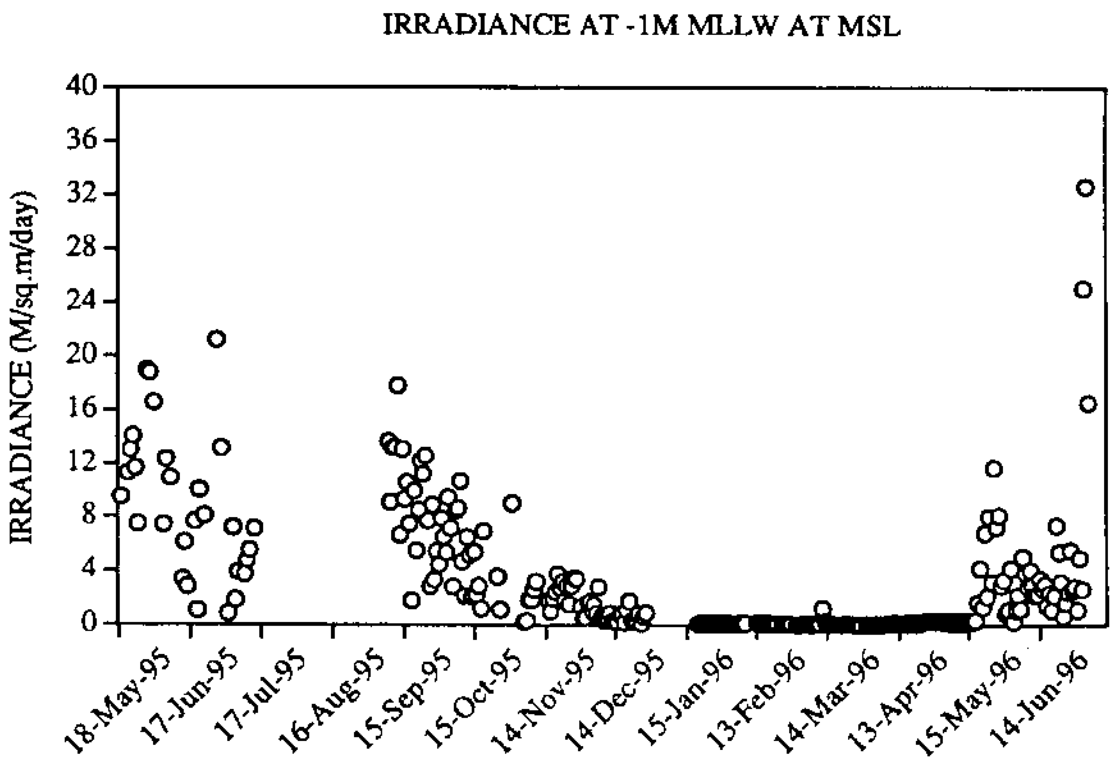


Figure 5. *In situ* PAR at -1 m MLLW at PNL/MSL.

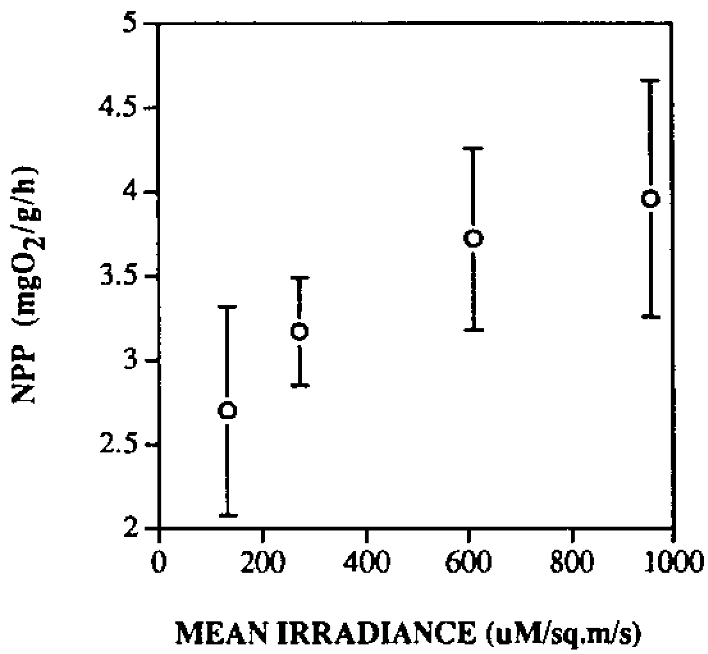


Figure 6. Net productivity of eelgrass leaf sections versus irradiance in the eelgrass growth chambers.

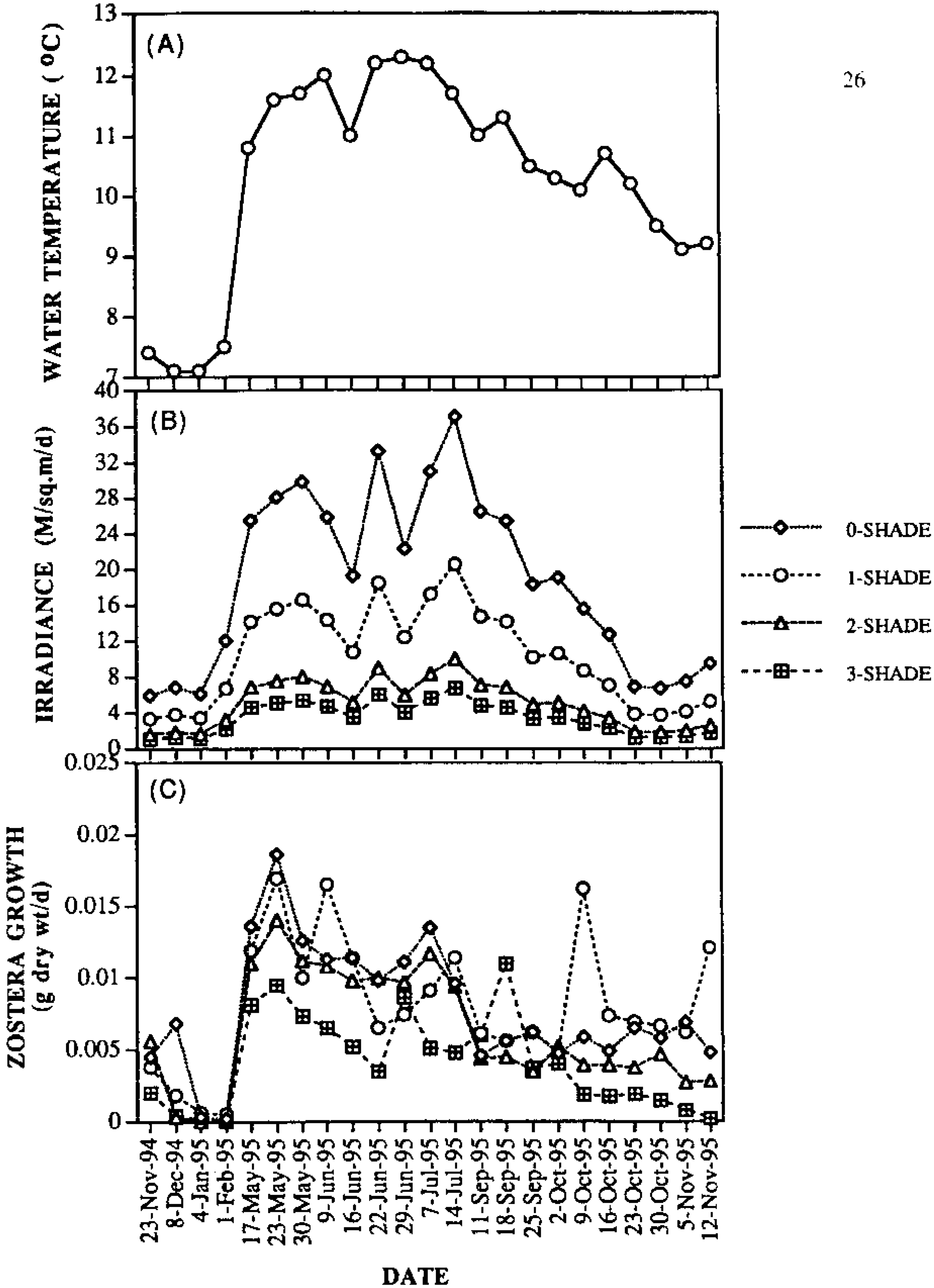


Figure 7. Eelgrass growth chamber results: (A) water temperature; (B) irradiance; and (C) growth. 0-shade corresponds to light shading and 3-shade corresponds to heavy shading.

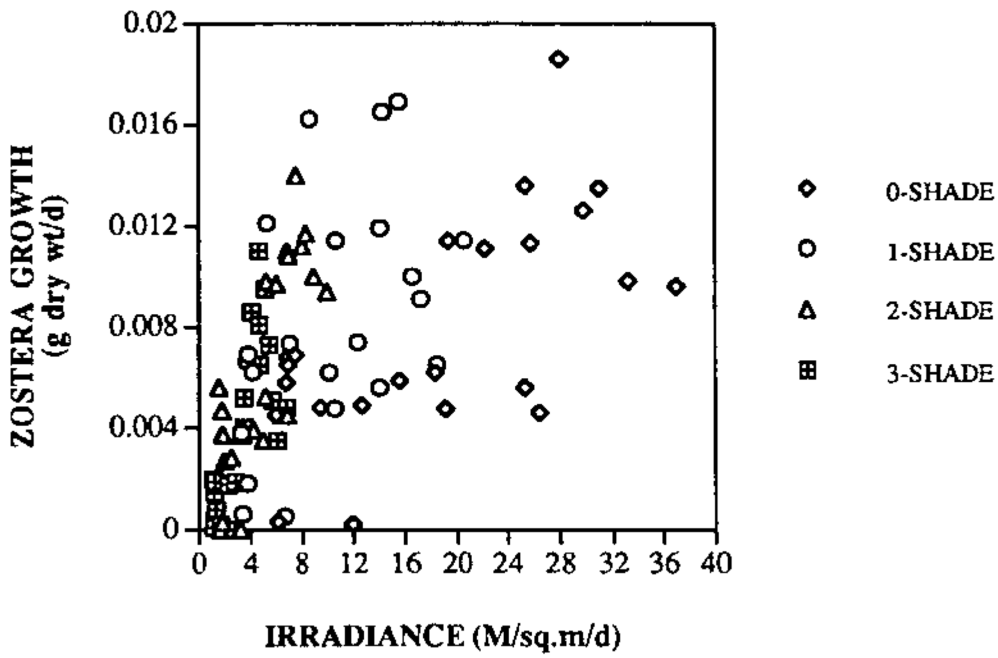


Figure 8. Eelgrass growth versus irradiance in growth chambers.

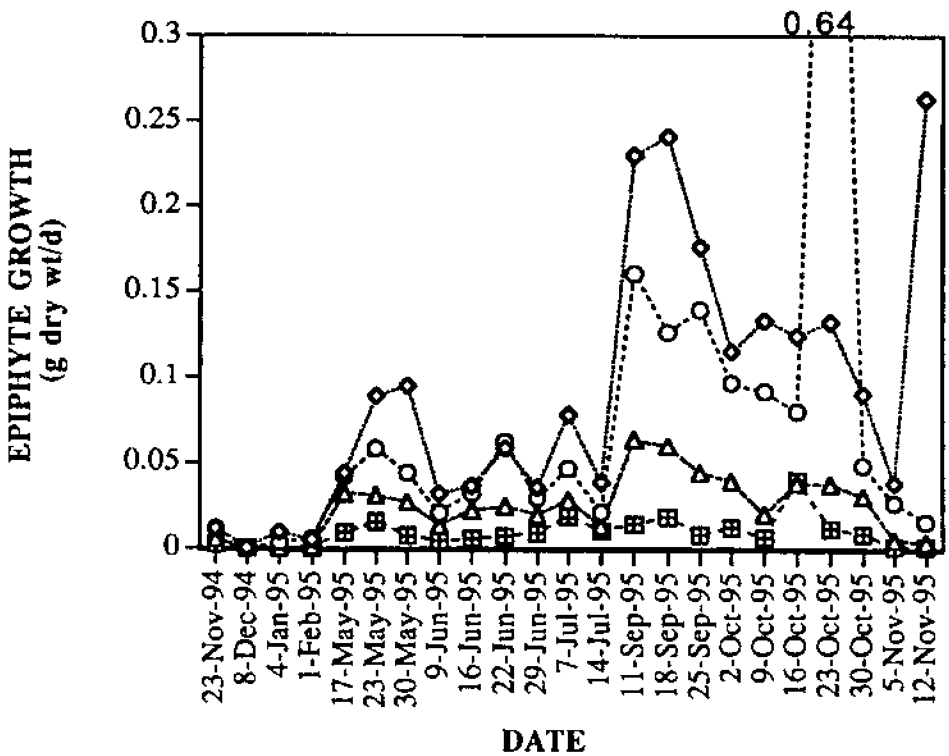


Figure 9. Epiphyte biomass growth in growth chambers.

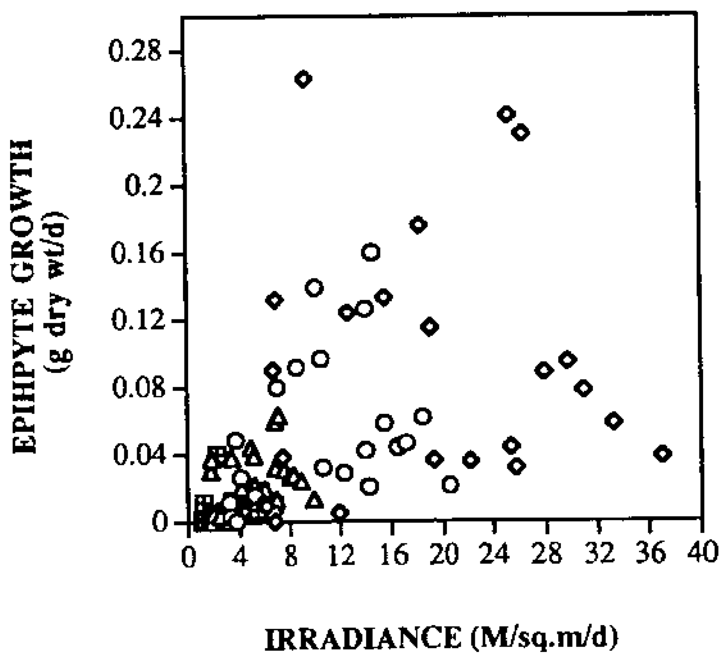


Figure 10. Epiphyte growth in chambers versus irradiance.

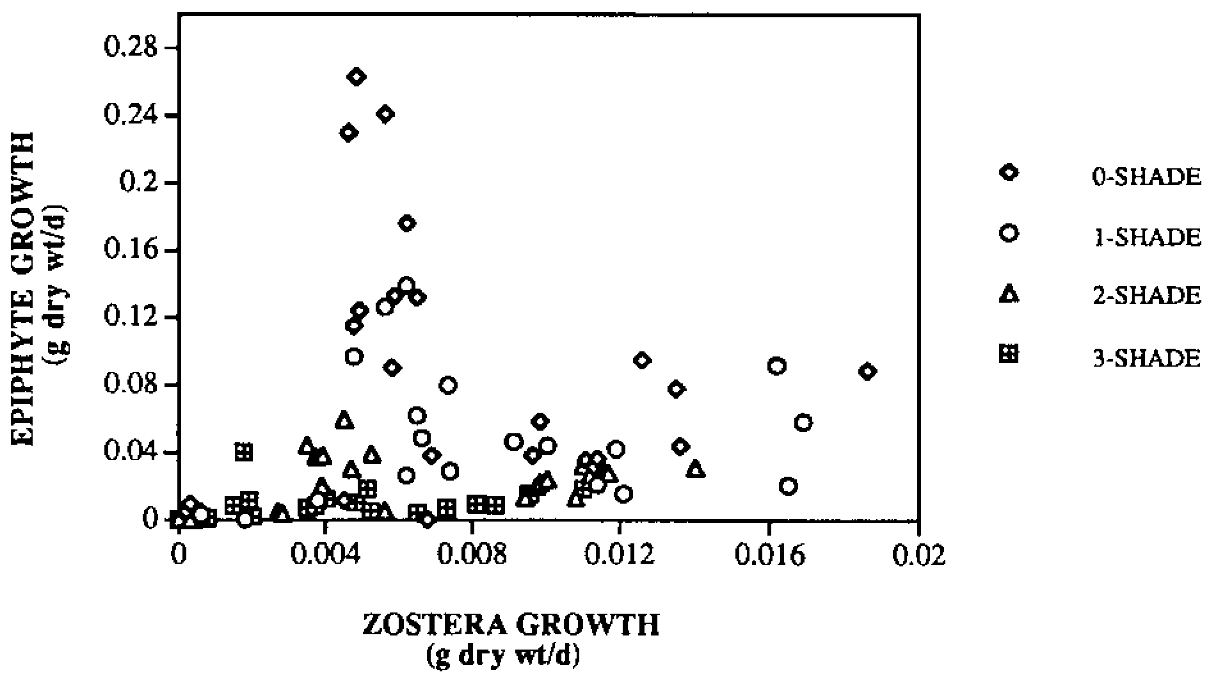


Figure 11. Eelgrass growth versus epiphyte growth in chambers.

## DISCUSSION

The long-term growth monitoring in the field and in the chambers indicates a strong seasonal growth pattern that is tied to irradiance. A period of low but measurable growth occurs in winter and is followed by dramatic increases in growth rate between February and May. Growth rate is intermediate in summer and declines in autumn. The chamber experiments indicated that, at least during a period of low growth, if PAR goes below about 3 M $m^{-2}d^{-1}$ for about a week the plants will die. Severe reduction of *in situ* growth rate was seen below about 4 to 5 M $m^{-2}d^{-1}$ in the long-term monitoring, especially in the treatment receiving the lowest light. Hence, these two independent data sets suggest that when integrated irradiance falls below about 3 to 5 M $m^{-2}d^{-1}$, growth will be limited and the plants may die if this level of irradiance persists for an extended period. In comparison, the field data on PAR from the Clinton Terminal indicated an instantaneous threshold of 150 $\mu$M $m^{-2}s^{-1}$. This value would be equivalent to about 5.4 M $m^{-2}d^{-1}$ over a 10-hr day, which is remarkably close to the estimates provided by the other two data sets.

Maintenance of eelgrass may be dependent not only on light in winter but even more on light conditions in spring through fall. The fact that plants ceased to grow during Fall in the lowest light treatment, coupled with the observation that light is consistently very low in winter to early spring, suggests that light conditions during spring through fall may be important in controlling long-term survival of plants. That is, the plants may build carbon reserves in their rhizome during the higher light period for use during the period of very low light (Kraemer and Alberte 1993). Hence, shading of plants may be more important in summer than winter in terms of long-term maintenance. The importance of winter light conditions cannot be fully discounted, however, since it appears that eelgrass is well adapted for utilizing very low light to support growth.

The short-term incubations conducted in three seasons indicated that eelgrass has a varying capacity for NPP throughout the year. Plants in winter showed NPP rates of up to six times higher than those in the summer. Although increased respiration under warmer summer conditions probably partially explains the lower NPP (as oxygen flux), some of the difference may be due to altered plant biomass allocation. In Puget Sound populations, leaves in winter are typically smaller and somewhat thicker than leaves in summer (Phillips 1984). This condition may result in more chlorophyll per unit biomass. Hence, plants would respond more quickly to increases in PAR in winter than in summer when chlorophyll concentration is less. Olesen and Sand-Jensen (1993) found that biomass allocation from rhizomes to leaves increased with reduced light availability (as occurs in winter). In addition, leaf weight normalized to area declined at low light. In combination, the altered biomass allocation and the lower leaf weight caused sustained leaf elongation for several weeks, despite severe shading and loss of plant weight. These results indicate that eelgrass possesses a strategy for maintaining growth under less that optimal light conditions, which would help sustain growth near or under terminals.

# DISTRIBUTION AND ABUNDANCE OF EELGRASS AND ASSOCIATED EPIPHYTES

by

Charles A. Simenstad, Jeffery R. Cordell
Wetland Ecosystem Team
School of Fisheries
Box 357980
University of Washington
Seattle, Washington 98195-7980

Ronald M. Thom
Marine Science Laboratories
Battelle Pacific Northwest Laboratories
1529 West Sequim Bay Road
Sequim, Washington 98382

Sandy Wyllie-Escheverria
School for Marine Affairs
Box 355685
University of Washington
Seattle, Washington 98195-5685

James Norris
School of Fisheries
Box 357980
University of Washington
Seattle, Washington 98195-7980

and

Annette M. Olson
School for Marine Affairs
Box 355685
University of Washington
Seattle, Washington 98195-5685

## INTRODUCTION

The descriptive, field-based portion of the research program was designed to map the distribution and relative coverage and density of the eelgrass habitat near the ferry terminals and to interpret the probable limiting factors on eelgrass within that area. We inferred limiting factors from systematic sampling of irradiance and selected eelgrass habitat parameters, including growth rate, epiphyte loads, patch size and dynamics, and shoot density under and immediately adjacent to existing docks and in adjacent control eelgrass beds. *In situ* monitoring of the light environment was conducted to correlate eelgrass distribution with light availability (following the "depth limits" model identified in the literature survey) and to describe the impact of the dock structure (and possibly of the propeller wash turbidity plume) on light availability.

## METHODS

### Eelgrass Habitat Mapping and Sampling

In the area surrounding each ferry terminal, eelgrass was mapped with underwater videography in association with a Global Positioning System (GPS). An underwater video camera was towed behind a boat along 26 transects at the Clinton Ferry Terminal, 45 transects at Port Townsend, and 14 transects at Edmonds. The transects traversed the entire meadow within at least 200 m on either side of each terminal. Eelgrass distribution, cover, and density sampling were also extended under the dock with conventional diver (see below) and walking transects.

The video images were analyzed visually to characterize three cover classes of eelgrass (no eelgrass, 1 to 50 percent cover, 51 to 100 percent cover), and these data were transferred to a Geographic Information System (GIS) to produce plots of the cover of eelgrass near the terminals. Spyglass Transform™ (ver. 3.1, Spyglass Inc.) was used to generate surface plots of eelgrass boundaries and densities. The fill matrix method was kernal smoothing, and images of the matrices were generated with Spyglass's "Interpolate Image" option. This method of spatially interpolating eelgrass distribution from the non-uniform (e.g., non-grid) data collection is prone to some error where there is not a continuous gradient, and will in this case predict eelgrass occurrence at low coverage even though there is an abrupt "edge" to the eelgrass distribution.

Raster images of the matrices were then exported as PICT files and then imported and registered in MapInfo™. When available, we added additional GIS layers for other geographically referenced features, such as the terminal structures, roads, shorelines, topography, and bathymetry; however, WSDOT could only provide CAD/GIS data for the ferry terminals at Clinton and Edmonds, and only shorelines, topography, and bathymetry at Clinton.

In summer 1994, eelgrass densities, percentage of cover, and biomass and epiphyte loads were quantified at fixed points during SCUBA surveys along approximately 150-m long transects at each terminal. Three transects were established, each aligned parallel to shore and perpendicular to the axis of the ferry terminal, and including a mid-section under the terminal, in the inner, middle, and outer portions of the eelgrass habitat; only one transect (outer portion) was placed on the south side of the Edmonds terminal because of a lack of eelgrass inshore of this point. Surveys were made at Port Townsend on 29 and 30 July 1994, at Edmonds on 31 July and 1 August 1994, and at Clinton on 2 and 6 August 1994.

At 5-m intervals along the transect, divers placed a 0.25-$m^2$ quadrat and recorded shoot density, depth, and time. Depths were later corrected to MLLW by reference to tidal plots for each day. Divers also noted disturbances of the eelgrass associated with the docks (e.g., sedimentation, scouring, biological disturbance). Five eelgrass shoots were collected from predetermined positions within each quadrat and placed in plastic bags for shoot and epiphyte biomass analysis. The samples were held on ice in the field and later frozen until analyzed. In the laboratory, the epiphytes were carefully removed by scraping, then they were dried and weighed. The shoots were also dried and weighed.

Divers recorded macrofauna and flora easily observed during all of the surveys at the terminals, as well as during reconnaissance dives made the transects were established. While these data are qualitative observations of the species that were common in the meadows during the survey periods, they provide very good insight into the general differences between species found in the meadows and under the terminals. Differences among the terminals in species observed were also documented.

### Bottom Currents and Propeller Wash

We specifically observed propeller wash and bottom currents during ferry operations at the Clinton Terminal. The extent of the plume from the wash was drawn on maps that showed the terminal and surrounding areas. The maps also contained the outline of the eelgrass meadow. Observations on nine arrivals and departures were made on 3 October 1994. On 8 August 1995, bottom currents were measured with a hand-held current meter (Global Water™) at a point south of the terminal at a depth where eelgrass normally would occur but was absent. This point was approximately 50 m from the end of the docked vessel and well within the extent of the plume. In addition, PAR was measured at this same point.

## RESULTS

### Eelgrass Distribution and Relative Coverage

As has been documented for certain large dock and overwater structures in Puget Sound (Fresh *et al.* 1995) and elsewhere (Appendix A), docks produce a common proximal effect on eelgrass distribution and coverage. This is illustrated by general discontinuities in eelgrass distribution and/or density around each of the docks, although the patterns and potential sources of impacts appear to vary among the three docks. (1) The Clinton Terminal illustrates complete disruption under and around the dock of the relatively continuous eelgrass habitat along that shoreline along southeastern Whidbey Island (Figure 12). (2) The continuity of eelgrass is maintained, but apparently under lower plant coverage/density, under the outer margins of the Edmonds Terminal, and extensive disturbance is suggested immediately offshore the pier (Figure 13). (3) Eelgrass distribution and coverage/density is relatively patchy around much of the Port Townsend Terminal (Figure 14) .

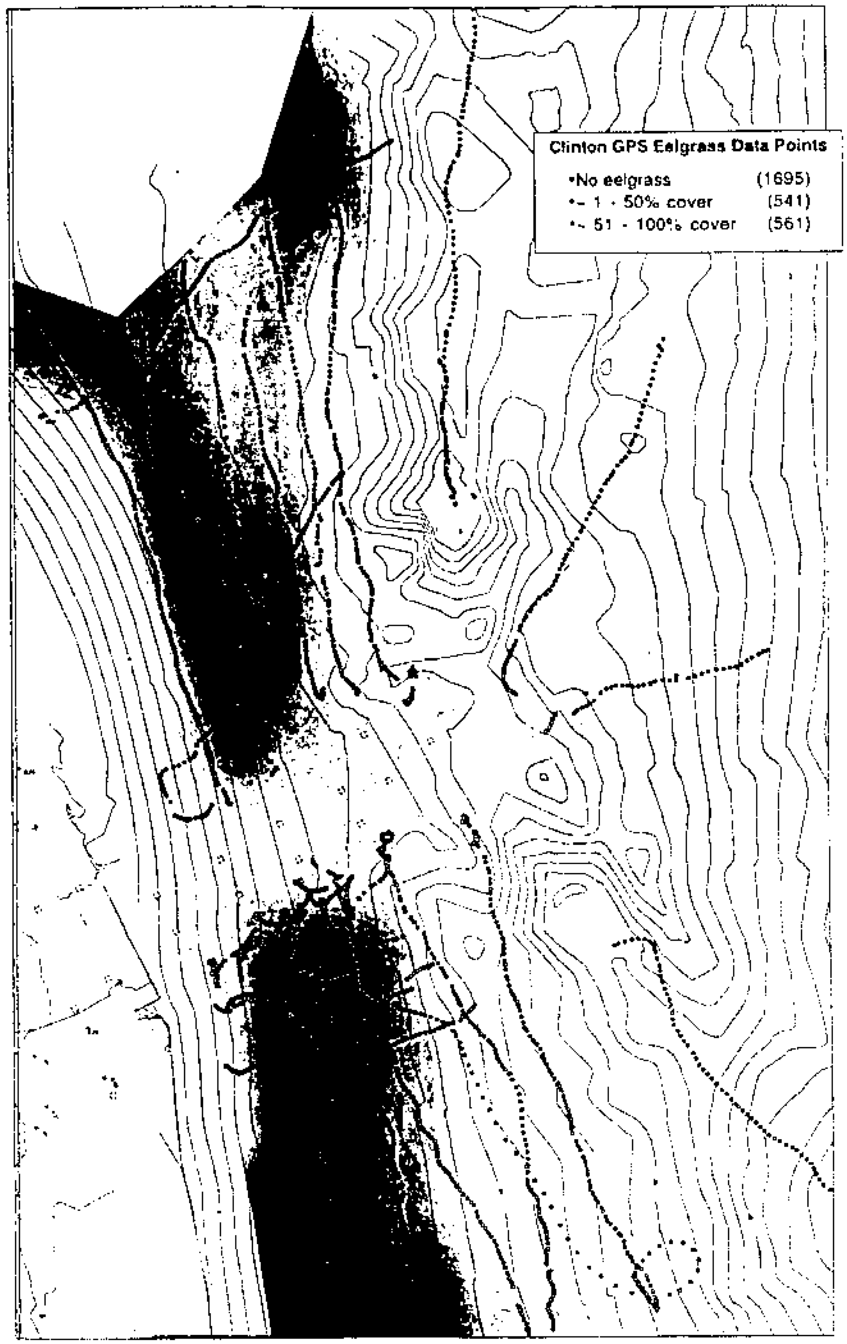


Figure 12. Eelgrass distribution and relative coverage near the Clinton Ferry Terminal; bathymetry contours are in ft MLLW and ferry dock and shoreline features are displayed in grey tone. Note that eelgrass actually does not appear under this terminal, although eelgrass may appear to extend under the dock as an artifact of the computer-aided contouring algorithm.

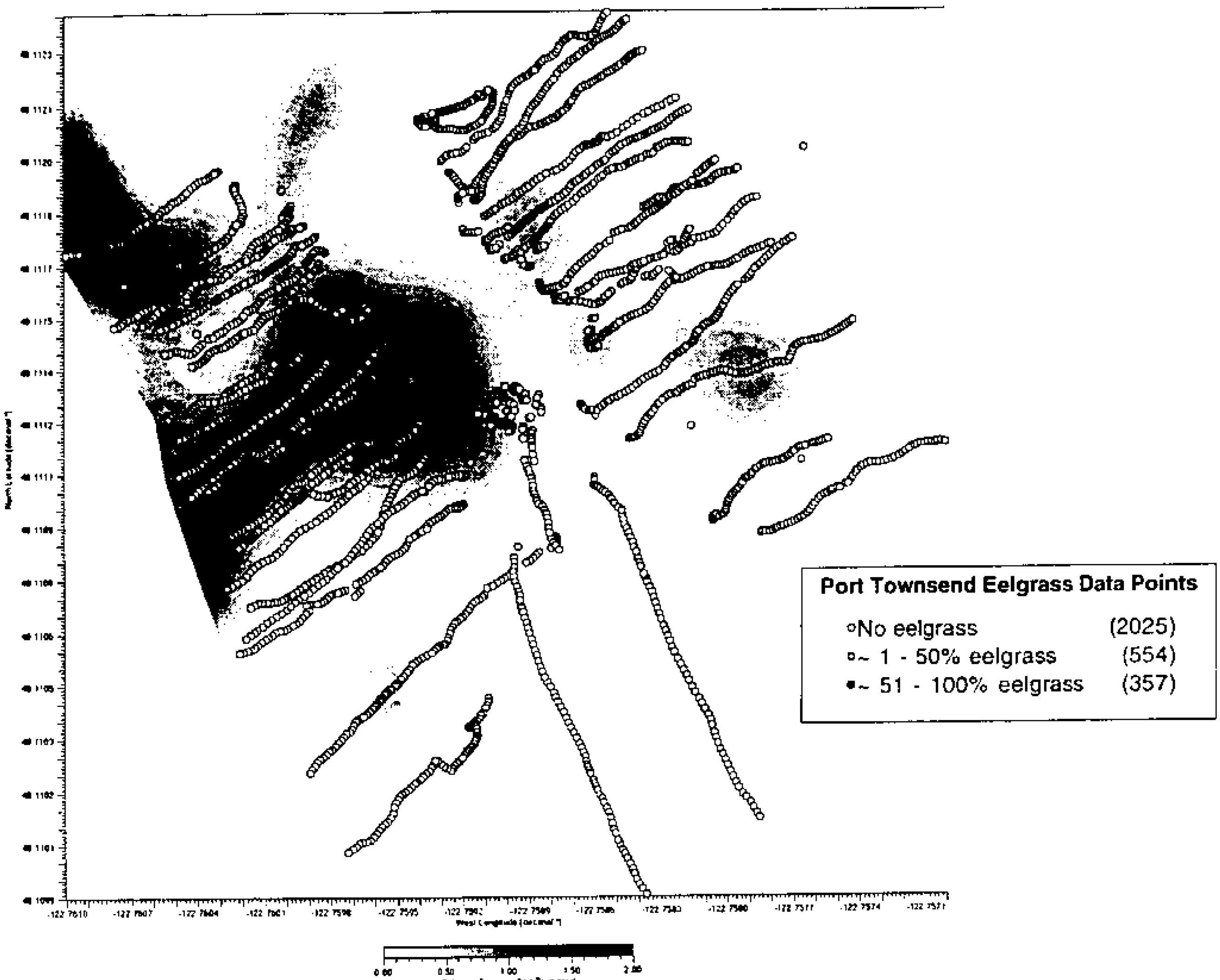


Figure 13. Eelgrass distribution and relative coverage near the Edmonds Ferry Terminal; no GIS bathymetry, or shoreline topography was available for this site.


Figure 14. Eelgrass distribution and relative coverage near the Port Townsend Ferry Terminal; GIS data for ferry terminal structures, bathymetry and shoreline features were not available for this site. Note that eelgrass actually not continuous under this Terminal; the appearance of eelgrass extending under the the dock is an artifact of the computer-aided contouring algorithm.

Examination of the eelgrass habitat boundaries relative to the terminals indicated that eelgrass does not occur in areas where light is probably inadequate to support growth (see the following section on light environment and eelgrass shading). In general, there is a 5- to 10-m area immediately adjacent to the terminals where eelgrass predictably should occur but occurs sporadically or not at all. The patterns of eelgrass distribution and coverage also suggest that several factors other than shading affect the eelgrass habitats at the terminals. At a distance from the dock, most of the eelgrass distribution can be explained by high and low tidal elevation (depth) limits, although there are some areas near active ferry slips that indicate potential disturbance (e.g., scouring or turbidity plumes) effects and some gaps in otherwise dense eelgrass beds that also indicate localized disturbance effects (e.g., a deposited tire, pipe, or outboard boat propeller scar).

The pooled frequency distribution of eelgrass shoot density in the eelgrass habitat (i.e., within the depth range of 0 to -5 m MLLW, and excluding samples directly under the terminals) near the three ferry terminals ranged from 1 to 200 shoots 0.25 $m^{-2}$, but in general densities averaged between 10 and 20 shoots 0.25 $m^{-2}$ (Figure 15A); mean shoot density within the eelgrass habitat over all sites was approximately 19 shoots 0.25 $m^{-2}$, or 76 shoots $m^{-2}$. When all transect samples were included, approximately 52 percent of the quadrats contained no eelgrass (Figure 15B).

Eelgrass was found over the depth range of 0 to -9 m MLLW (Figure 16), but the greatest densities were generally found in the shallower depths surveyed (0.5 to -5.2 m MLLW); no eelgrass occurred at -9 m. The lower depth limit of eelgrass differed among the three sites. Clinton had the shallowest and Edmonds had the deepest depth limits; the depth limit at Port Townsend was more similar to Edmonds. Maximum shoot densities occurred at Clinton, with values commonly above 50 shoots 0.25 $m^{-2}$. Most of the zero values within the eelgrass depth range were from samples under the terminals; we encountered only one quadrat under a terminal (southeast corner of Port Townsend terminal, Figure 13) that contained eelgrass. Note that computer-automated eelgrass density contouring predicts eelgrass contigous at low coverage under the Terminal, which was not the case.

Eelgrass biomass ranged from less than 1 to more than 100 g dry wt 0.25 $m^{-2}$, and the greatest biomass values were recorded at the shallowest sites at Clinton (Figure 17). There was no apparent gradient in biomass relative to depth between about -1 m MLLW and the maximum lower depth limit of eelgrass.

Total epiphyte biomass showed considerable variability at all sites over the depth range sampled (Figure 18). Only at Clinton was there a clear indication of decreasing epiphyte biomass with increased depth, where the highest epiphyte biomass occurred in the shallower ("high") transects, but there was no discernable relationship to the proximity to the terminal (Figure 19).

**Eelgrass Density-Biomass and Epiphyte Load Relationships**

Among-site differences in eelgrass plant morphology were indicated by density-biomass relationships (Figure 20). The eelgrass habitat at Port Townsend contained plants with the greatest ratio of biomass to shoot density, indicating that the largest plants occurred at this site. Conversely, eelgrass at Edmonds generally consisted of the smallest

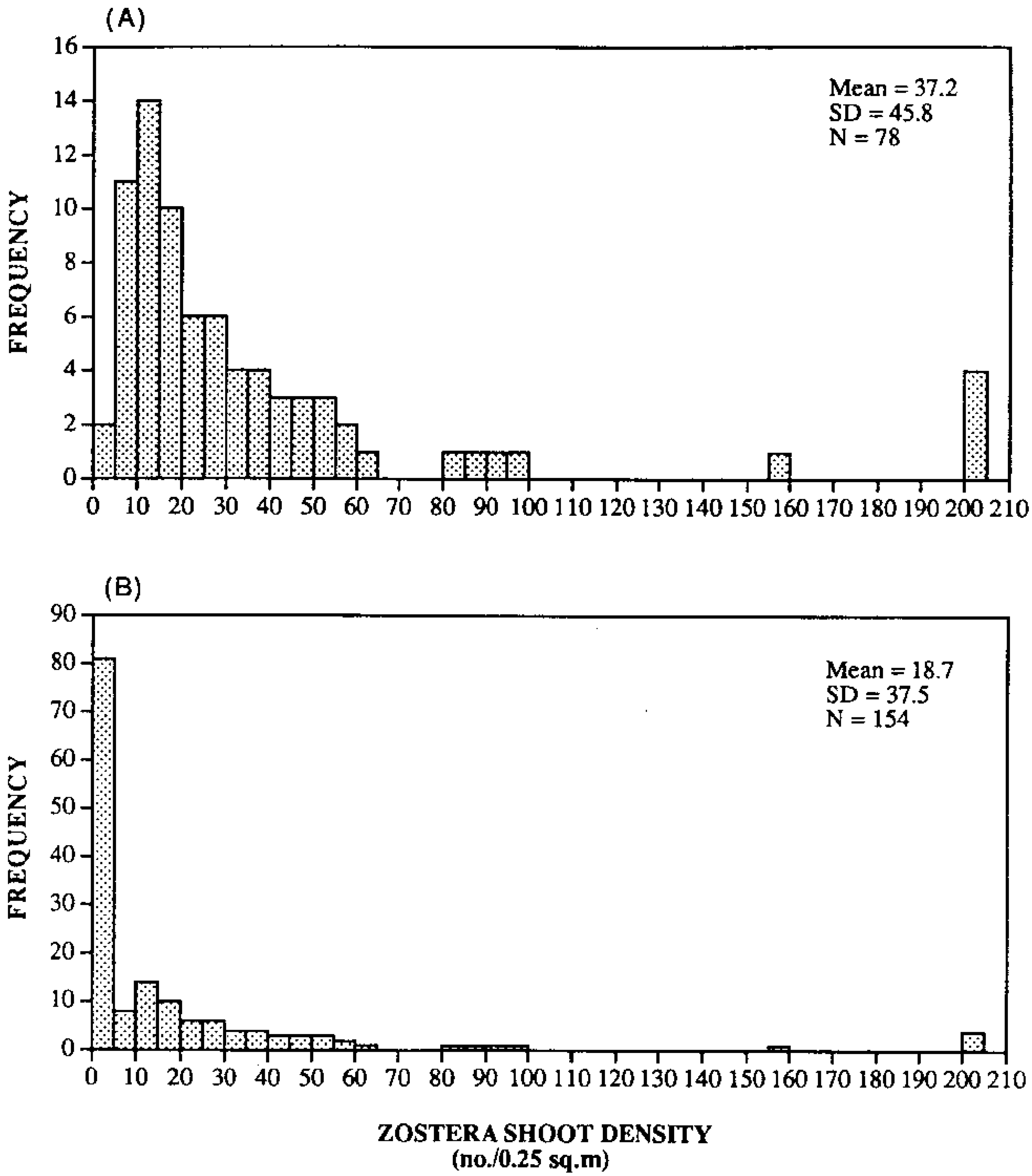


Figure 15. Frequency distribution of eelgrass shoot density: (A) only quadrats with non-zero densities; (B) all quadrat samples.

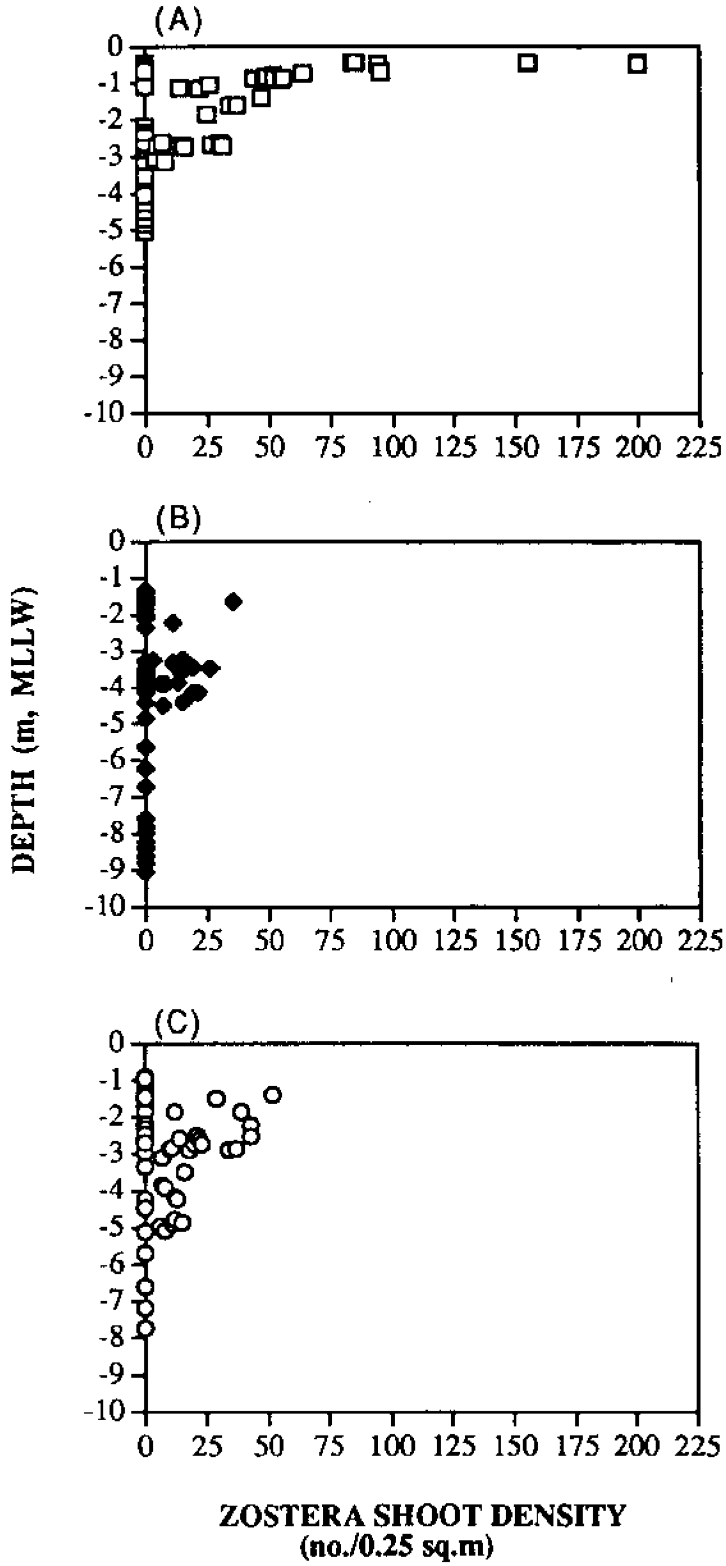


Figure 16. Eelgrass shoot density versus depth at (A) Clinton, (B) Port Townsend and (C) Edmonds.

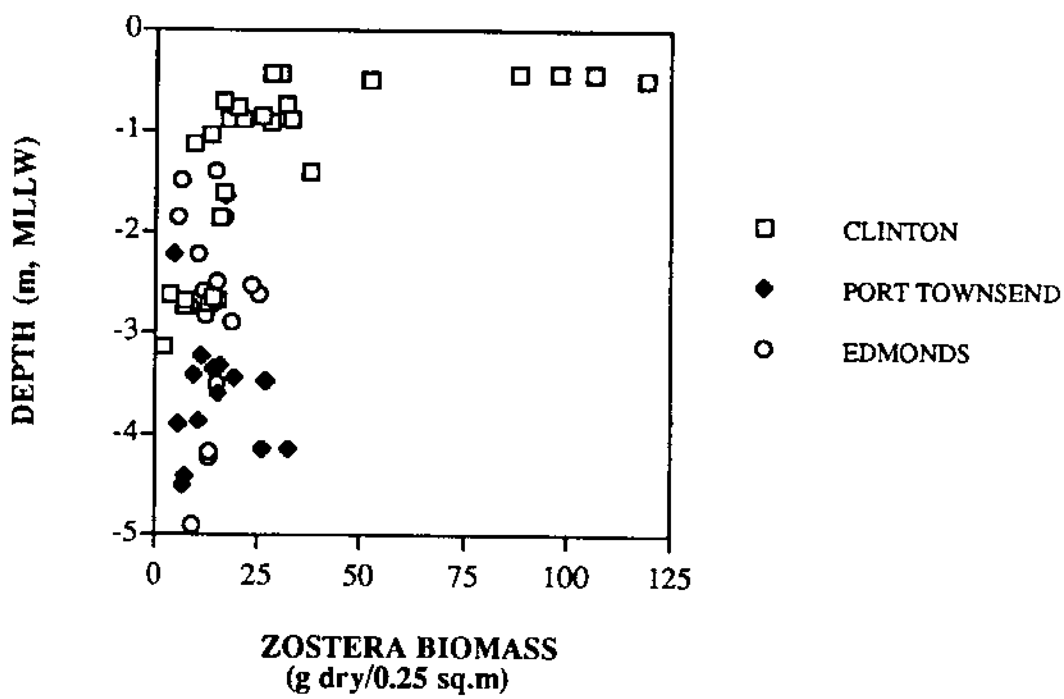


Figure 17. Eelgrass shoot biomass versus depth at the three sites.

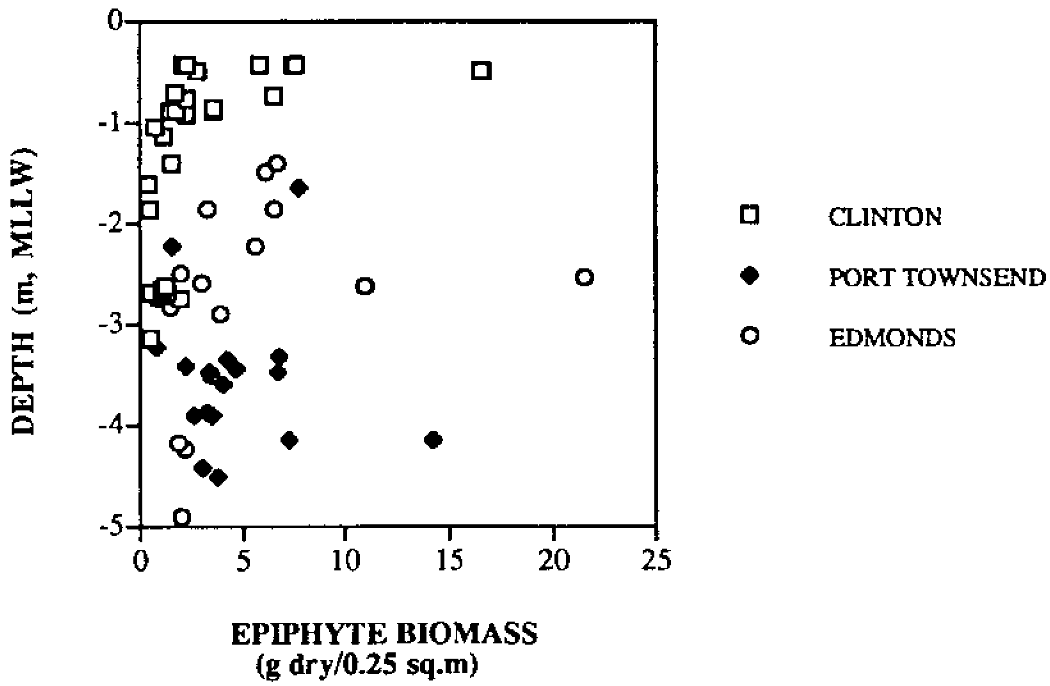


Figure 18. Eelgrass epiphyte biomass versus depth at the three sites.

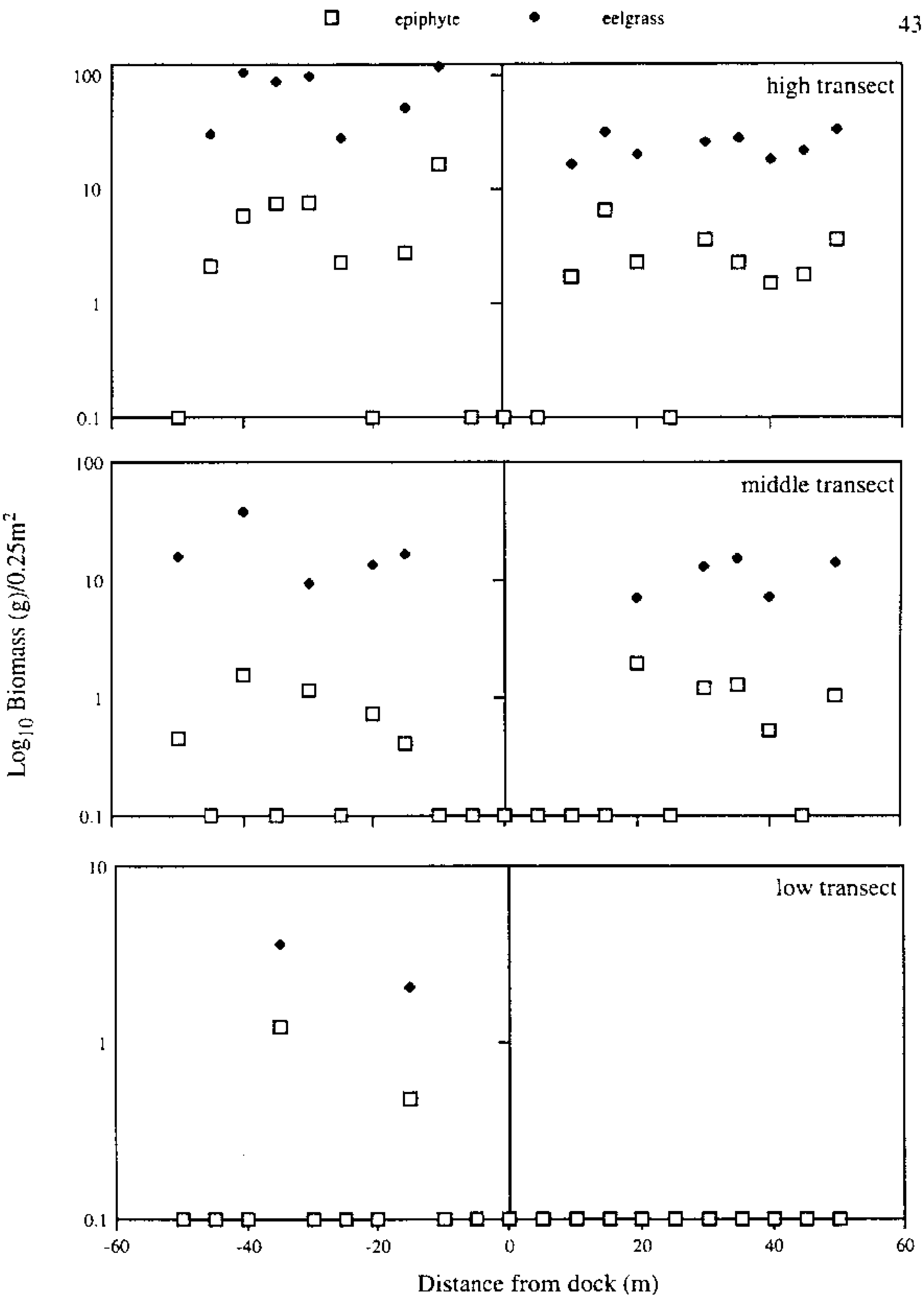


Figure 19. Biomass (g dry wt 0.25 m$^{-2}$) of eelgrass and associated epiphytes along three transects at Clinton Ferry Terminal; measurements of zero were assigned a value of 0.1.

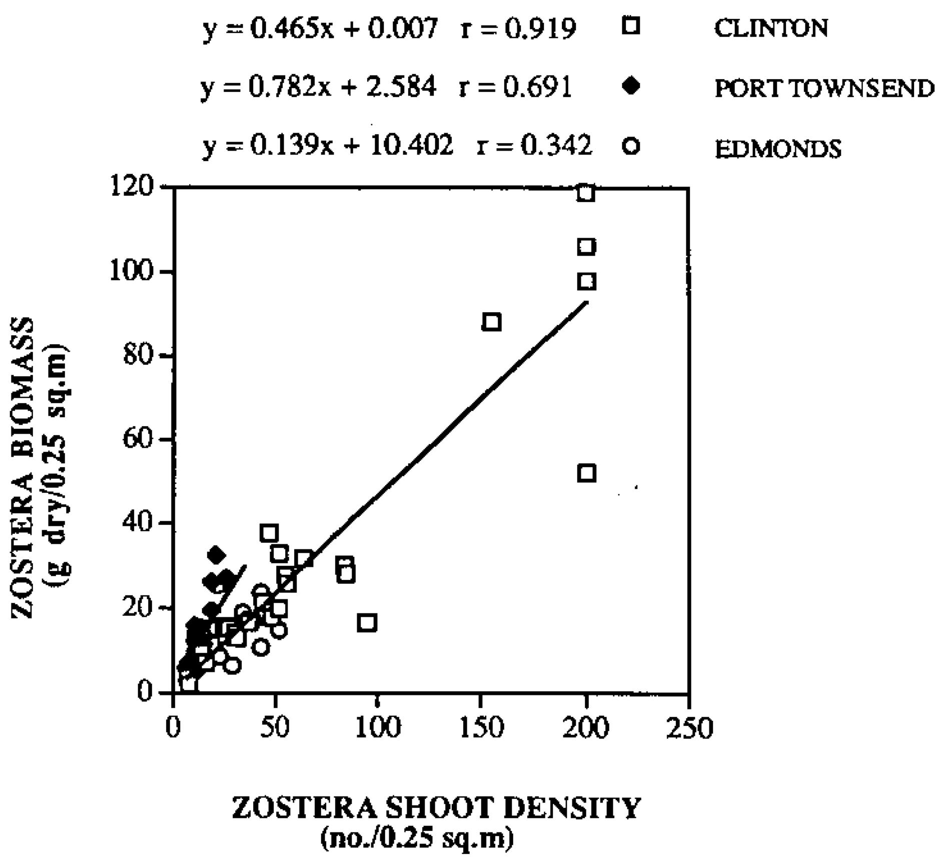


Figure 20. Relationship between shoot density and shoot biomass.

plants, as indicated by the relatively low ratio. The ratio of epiphyte biomass to shoot density was greatest at Port Townsend and Edmonds (Figure 21). This indicates that there was a greater biomass of epiphytes per shoot at these sites than at Clinton. There was considerable variability among the mean ratio of epiphyte biomass to eelgrass shoot biomass at the three ferry terminal study transects (Fig. 22), which ranged from ~0 (negligible epiphyte biomass) to over 0.6 (epiphyte biomass = 60 percent of eelgrass biomass per unit area). Highest epiphyte loading occurred at Clinton, coincident with the higher eelgrass shoot density at that site; epiphyte loading was much more variable at Port Townsend and Edmonds. The distribution of this relative epiphyte load ratio showed high variability and no identifiable patterns relative to proximity to the docks, as indicated by the three transects at the Clinton Terminal (Figure 23).

### Bottom Currents and Propeller Wash

Continuous monitoring of bottom currents at the Clinton site showed that current speeds were increased rapidly during ferry arrivals and departures. The observations indicated that the duration and level of increase were highly variable and were dependent partially on the rate of approach or departure of the ferry. Examples of the data indicated that current speeds were increased from 1 to 2.5 m $s^{-1}$ over background, and that acceleration of bottom currents to these rates occurred within 5 to 20 s (Table 1).

Table 1. Bottom current speeds within the plume of the propeller wash in the edge of the eelgrass zone (8 August 1995).

| Time | Maximum Baseline Current (m $s^{-1}$) | Maximum Current in Wash (m $s^{-1}$) |
|---|---|---|
| 14:40 | 0.5 | 1.5 |
| 14:50 | 0.5 | 3.0 |
| 15:05 | 1.5 | 3.5 |

### Plants and Animals Observed at the Terminals

Observations made during the diving surveys revealed 11 macrophyte, 21 macroinvertebrate, and 24 fish taxa associated with the eelgrass meadows and terminal sites (Table 2). All sites contained a similar total number of taxa (Port Townsend = 34, Edmonds = 35, Clinton = 34). The numbers of invertebrate species and fish species were lower under the terminals than in the eelgrass meadow. Benthic plant taxa were, however, either absent or severely limited in distribution under the terminals. Port Townsend, the newest terminal, did have a small patch of eelgrass under the southern edge at the seaward end of the terminal.

Observations also revealed that Dungeness crab (*Cancer magister*) and the sunflower seastar (*Pycnopodia helianthoides*) were having an impact on the eelgrass meadows directly associated with the terminals. At Clinton, and to a lesser extent at the other terminals, seastars (all species) were foraging on barnacles and mussels attached to pilings.

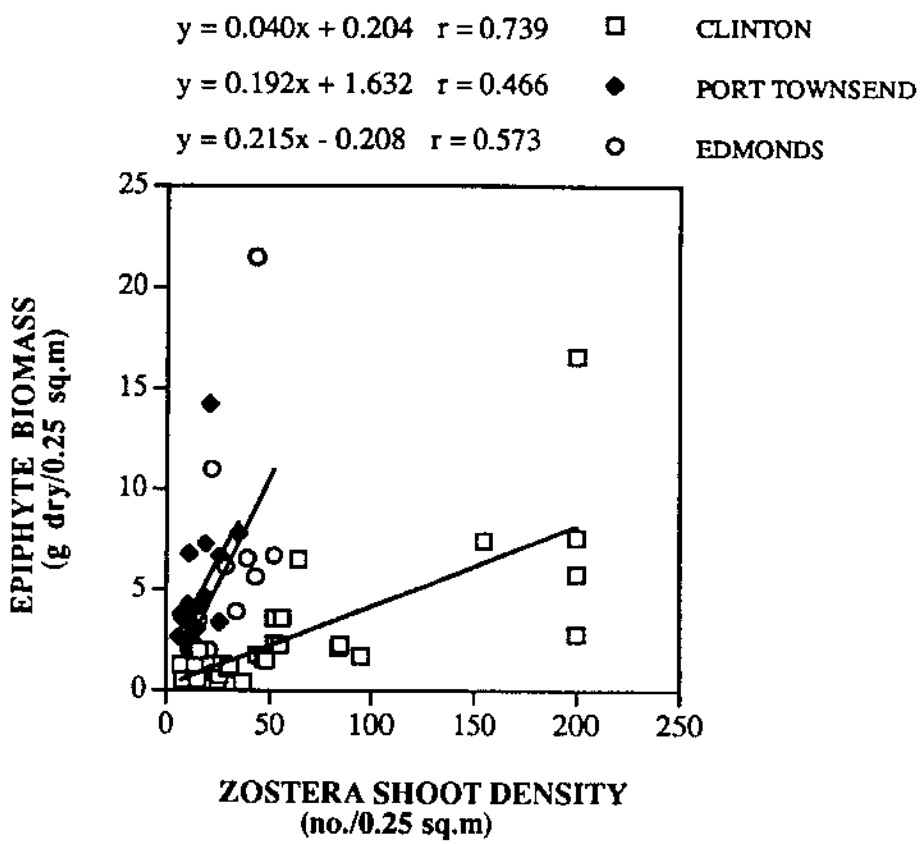


Figure 21. Relationship between shoot density and epiphyte biomass.

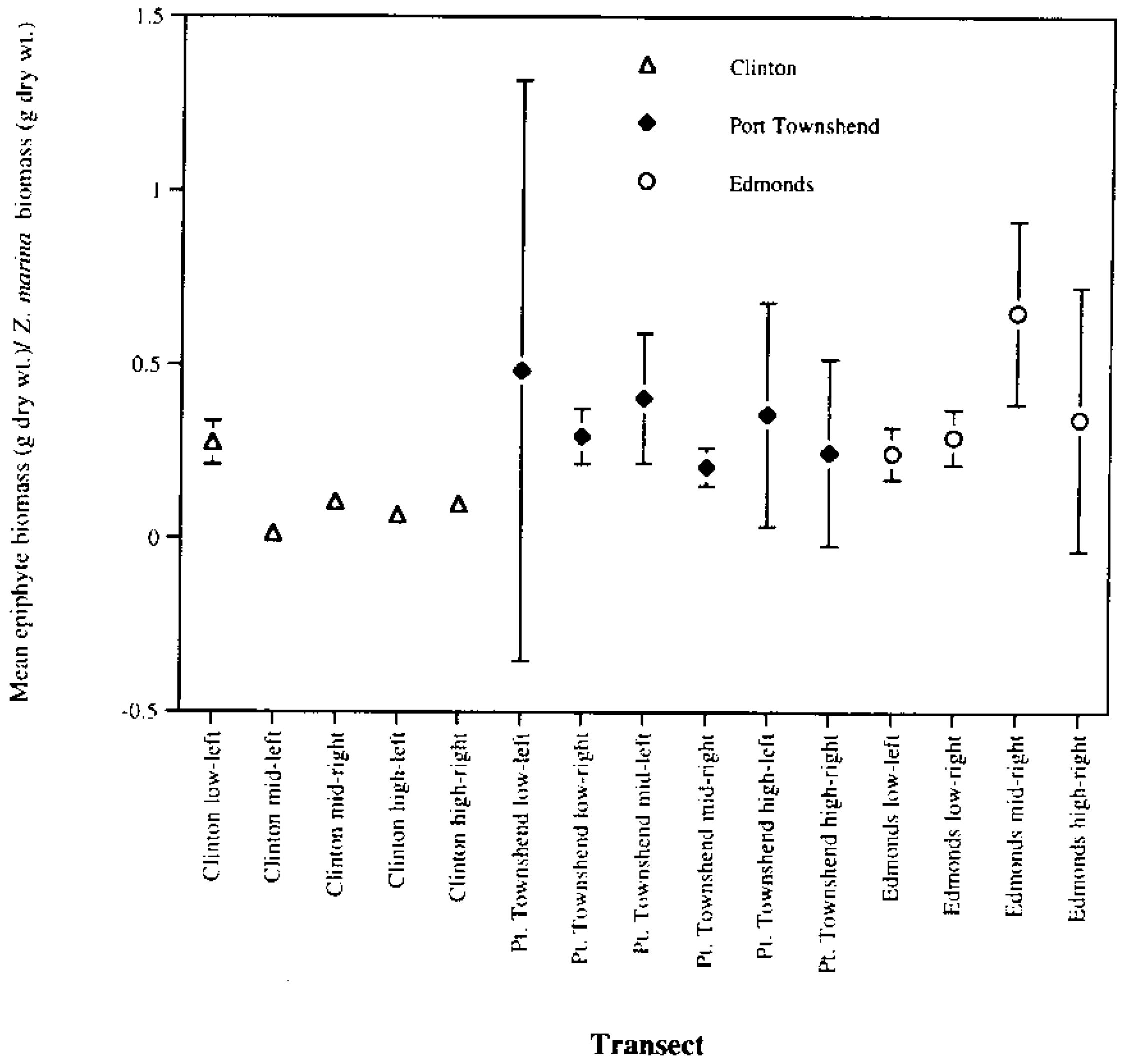


Figure 22. Mean proportion of epiphyte biomass to eelgrass biomass along transects on either side of ferry terminals at Clinton, Port Townsend, and Edmonds, Washington.

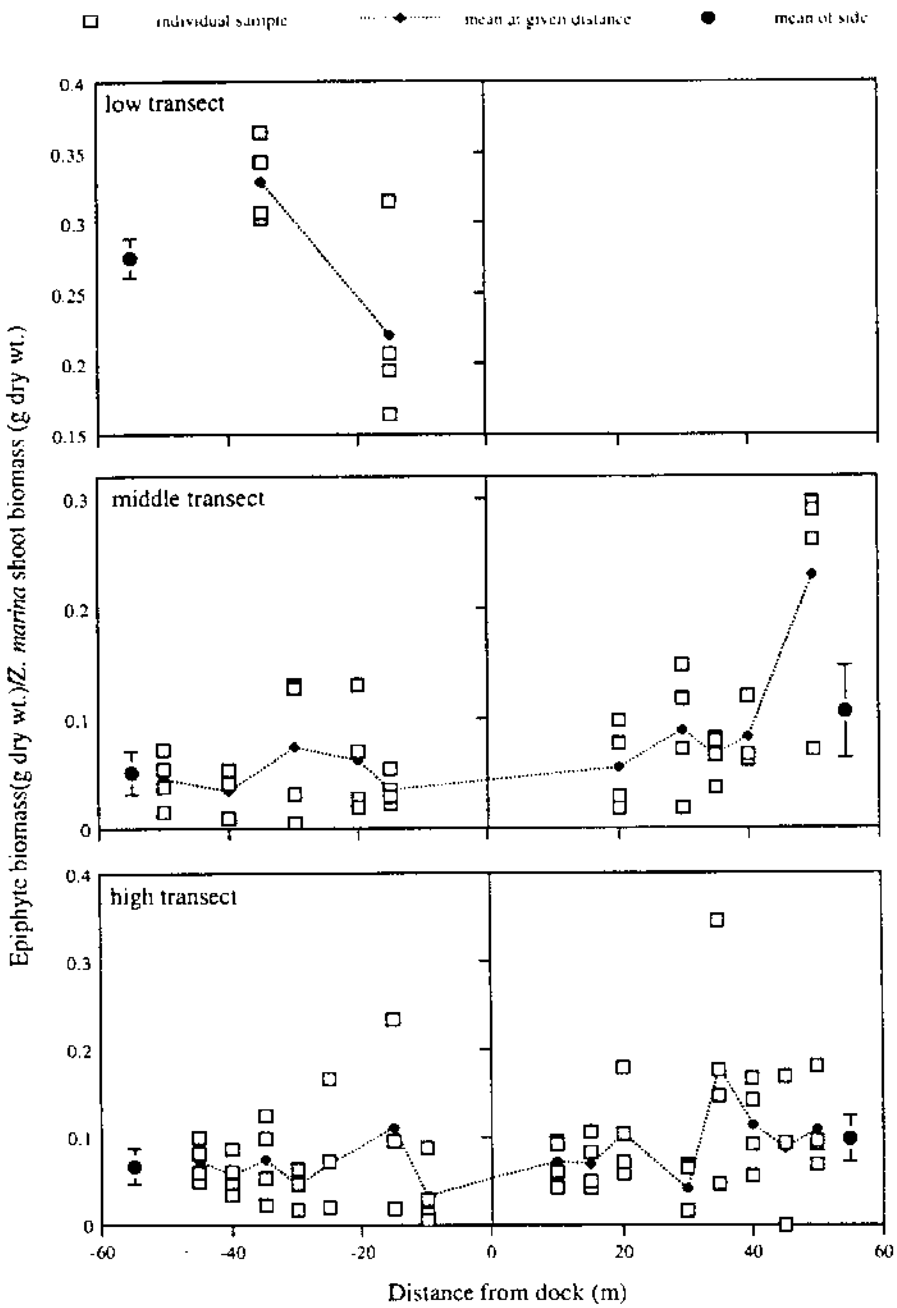


Figure 23. Ratio of epiphyte to eelgrass biomass along three transects at the Clinton Ferry Terminal; vertical lines represent 95 percent confidence intervals.

Table 2. Invertebrates, macrophytic vegetation, and vertebrates observed during SCUBA diving surveys in eelgrass habitats and ferry terminals at Port Townsend, Edmonds, and Clinton Ferry terminals.

| | | IN OR ADJACENT TO EELGRASS | | | UNDER FERRY DOCK | | |
|---|---|---|---|---|---|---|---|
| COMMON NAME | SCIENTIFIC NAME | PORT TOWNSEND | EDMONDS | CLINTON | PORT TOWNSEND | EDMONDS | CLINTON |
| ***Invertebrates*** | | | | | | | |
| barnacle | *Balanus spp.* | | | | • | • | • |
| Dungeness crab | *Cancer magister* | • | • | • | • | | • |
| red rock crab | *Cancer productus* | • | • | • | • | | • |
| heart cockle | *Clinocardium nuttallii* | | | • | • | | • |
| leather star | *Dermasterias imbricata* | | | • | | | |
| nudibranch | *Dirona aurantia* | • | • | • | | | |
| brooding anemone | *Epiactus prolifera* | • | • | • | | | |
| snail (chink shell) | *Lacuna spp.* | • | • | • | | | |
| nudibranch | *Melibe leonina* | | | • | | | |
| plumose anemone | *Metridium senile* | • | | | • | | • |
| bay mussel | *Mytilus spp.* | | | | • | • | • |
| spiny star | *Orthasterias koehleri* | • | | | | | |
| coon-striped shrimp | *Pandalus danae* | • | | • | • | | • |
| sea cucumber | *Parastichopus californicus* | • | | | | | |
| purple star | *Pisaster ochraceus* | • | | • | • | • | • |
| moon snail | *Polinices lewisii* | | • | | | | |
| sea pen | *Ptilosarcus gurneyi* | • | | | | | |
| kelp crab | *Pugettia producta* | | | • | | • | • |
| sunflower star | *Pycnopodia helianthodes* | | | • | • | | • |
| helmet crab | *Telmessus cheiragonus* | • | | • | | | |
| horse clam | *Tresus capax* | • | • | • | • | • | • |
| ***Vegetation*** | | | | | | | |
| fauchea | *Fauchea sp.* | • | • | | | | |
| turkish towel | *Gigartina exasperata* | • | | | | | |
| gracilaria | *Gracilaria pacifica* | • | • | • | | | |
| sugar wrack | *Laminaria saccharina* | | | • | • | | |
| bull kelp | *Nereocystis luetkeana* | | • | | • | | |
| porphyra | *Porphyra perforata* | | • | | | | |
| sargassum | *Sargassum muticum* | | • | | | | |
| Smithora | *Smithora naiadum* | • | | | | | |
| sea lettuce | *Ulva spp.* | • | • | • | | | |
| diatoms | *unidentified species* | • | • | • | | | |
| eelgrass | *Zostera marina* | • | • | • | • | | |
| ***Vertebrates*** | | | | | | | |
| Pacific sandlance | *Ammodytes hexapterus* | • | • | | • | | |
| penpoint gunnel | *Apodichthys flavidus* | | | • | | | |
| tubesnout | *Aulorhynchus flavidus* | | | • | | | |
| sanddab | *Citharichthys spp.* | • | • | • | | • | • |
| shiner perch | *Cymatogaster aggregata* | • | • | • | | • | • |
| striped perch | *Embiotocca lateralis* | | • | • | | • | • |
| buffalo sculpin | *Enophrys bison* | • | | | | | |
| spiny lumpsucker | *Eumicrotremus orbis* | • | | | | | |
| kelp greenling | *Hexagrammos decagrammus* | | | • | | | |
| butter sole | *Isopsetta isolepis* | | • | | | | |
| salmon | *Oncorhynchus spp.* | • | | | | | |
| lingcod | *Ophiodon elongatus* | | | | | • | |
| crescent gunnel | *Pholis laeta* | | | • | | | • |
| saddleback gunnel | *Pholis ornata* | | | • | | | • |
| starry flounder | *Platichthys stellatus* | | • | | | | |
| C-O sole | *Pleuronichthys coenosus* | | | | | • | |
| sand sole | *Psettichthys melanostictus* | | • | | • | | |
| pile perch | *Rhacochilus vacca* | | • | • | | • | • |
| cabezon | *Scorpaenichthys marmoratus* | | • | | | • | |
| copper rockfish | *Sebastes caurinus* | | | • | | • | |
| quillback rockfish | *Sebastes maliger* | | | | | • | |
| tiger rockfish | *Sebastes nigrocinctus* | | | | | • | |
| sculpins | *various unidentified species* | • | • | • | • | • | • |
| flatfish | *various unidentified species* | • | • | • | • | • | • |

This foraging activity resulted in piles of mussel shell and barnacle plates under the terminals. In addition, piles of infaunal bivalve (e.g., butter clams) shell were dense near the terminals. The divers observed seastar densities as great as 15 $m^{-2}$, and hundreds of small (yearling, 1+ yr) Dungeness crabs near the terminals. Seastars were observed actively foraging for bivalves at the edge of the meadows. Crabs were noted to burrow in areas at the edge of the meadow, as well as in open spaces within the meadow.

A large lingcod was observed under the Edmonds terminal, which is adjacent to the Edmonds Marine Park, which provides considerable sheltered substrate for large fish like lingcod. This individual was observed to actively feed on organic material stirred up from the bottom during ferry sailings and dockings.

## DISCUSSION

### Physical Disturbance

Shading by ferry terminals is undoubtedly a major factor in causing a loss of eelgrass near the terminals, the evidence for which appears in the following chapter. However, propeller wash, bioturbation, and other physical disturbances may also be contributing to the loss. The irradiance measurements clearly showed that light reaches very low levels under the terminals. However, lack of eelgrass in a 5 to 10 m wide band around the terminal suggests that other factors are active. Terminals like Clinton and Edmonds (from the mid-1950s) were constructed by hydraulically inserting wood piles into the sediment. This process eliminates eelgrass and likely drastically modifies sediment conditions such as organic content and redox profile. Eelgrass, which primarily spreads by rhizome growth in the region, may take decades to recover from this type of disturbance. Annual maintenance of wood terminals is required, and these activities (e.g., barge grounding and anchoring, propeller scars from tugs and work boats) may also disturb eelgrass. Although we know little about the rate at which eelgrass can recolonize disturbed areas in Puget Sound, recolonization rates especially in deeper subtidal areas, are probably slow because of the low proportion of the population (i.e., 6 percent, Phillips 1984) that flowers annually.

### Biological Disturbance

Around terminals in Puget Sound, we suspect that bioturbation and other damage caused by enhanced seastar and crab densities (at a minimum) may be responsible for retarded recruitment of eelgrass in formerly disturbed areas. The 'reef effect' of the terminal and its pilings enhances habitat for seastars and Dungeness crab. Dungeness crab larvae are known to settle in shell piles. The shell offers shelter from predation, as well as enhanced food resources for the young crab (Dumbauld *et al.* 1993). Enhanced crab abundances under the terminals may be due to the availability of prime habitat for settlement of crab larvae. During eelgrass surveys, the divers noted seastars foraging extensively not only on piling communities but also on bivalves at the edge of the eelgrass habitat adjacent to the dock. We have observed that crab and seastar foraging activity disrupts eelgrass and could retard recruitment of eelgrass. In addition, Dungeness crab bury in sediments as a predator defense mechanism. This burrowing activity may also disrupt newly recruiting eelgrass seedlings. Where crab population density is great, such as at Clinton, burrowing may be a significant factor inhibiting recruitment of eelgrass. Large-scale disturbance of seagrass meadows by animal foraging or burrowing has been reported elsewhere (e.g., Camp *et al.* 1973, Orth 1975, Heinsohn *et al.* 1977, Williams 1988, Baldwin and Lovvorn 1994).

**Erosive Disturbances**

Erosion of eelgrass by propeller wash likely explains some loss of eelgrass. We measured current speeds of up to 3.5 m $s^{-1}$ at a point approximately 50 m from the propeller. Although little data exist on current speeds that erode eelgrass, Phillips noted that eelgrass generally does not occur in high current areas in Puget Sound. He did find eelgrass growing in areas with tidal currents of up to about 2 m $s^{-1}$. Fonseca *et al.* (1983) have noted eelgrass existing in areas with tidal current of up to 1.5 m $s^{-1}$. However, we found that propellers accelerate current from 0.5 to 3.5 m $s^{-1}$ within a few seconds, much faster than the acceleration associated with tides. We suspect that this acceleration can erode established eelgrass and disrupt seeds and seedlings. We also suspect, on the basis of studies by Fonseca and others, that the meadow has a great capacity to buffer accelerated current speeds at some distance beyond where threshold erosion velocities develop (Fonseca *et al.* 1982; Fonseca and Fisher 1986; Worcester 1995).

# LIGHT ENVIRONMENT AND EELGRASS SHADING AROUND THREE WSDOT FERRY TERMINALS

by

Annette M. Olson, Sasha Visconty
School for Marine Affairs
Box 355685
University of Washington
Seattle, Washington 98195-5685

Boykin Witherspoon III, Kevin Sweeny
Department of Landscape Architecture
Box 355734
University of Washington
Seattle, Washington 98195-5734

Ronald M. Thom and David K. Shreffler
Marine Science Laboratories
Battelle Pacific Northwest Laboratories
1529 West Sequim Bay Road
Sequim, Washington 98382

## INTRODUCTION

Both proponents and regulators of shoreline development projects require good scientific information, in a usable format, to ensure that the project design and regulatory processes can be predictable and efficient, as well as effective in protecting aquatic resources. In the typical permit process, scientific information is used to develop standards for assessing impacts on aquatic resources (impact criteria, e.g., Courtemanch *et al.* 1989) and to define permit conditions, including design, monitoring, and evaluation criteria for mitigation[2]. However, inadequate scientific or technical information, or institutional impediments may limit the application of science in project design and regulatory decisions.

In Washington State, for example, shading by overwater structures potentially affects the extent and quality of eelgrass[3] habitats because light availability limits the growth and

[2] The "mitigation sequence" involves avoidance and minimization of, as well as compensation for, impacts (Fresh 1994). Because large-scale transplantation of eelgrass is in its infancy in the Pacific Northwest (Thom 1990), it is important to avoid or minimize impacts of docks and other shoreline structures on eelgrass beds, to the fullest extent possible.

[3] Both the native eelgrass (*Zostera marina* L.) and the non-native Japanese eelgrass (*Zostera japonica* Aschers. & Graebn.) occur in Puget Sound. *Zostera marina* occurs from +1.8 to -6.6 m MLLW and *Z. japonica*, from +1.0 to +2.4 m MLLW (Phillips 1984). In this report, we focus on the light requirements of the native eelgrass, which, because of its subtidal distribution, larger size, and perennial habit is more likely to experience light limitation than *Z. japonica*. [See Phillips (1984) and

distribution of eelgrass (Zimmerman *et al.* 1989, Dennison et al. 1993, Bulthuis 1994). Thus, mitigation of shading impacts is an important concern for transportation and natural resource management in the Puget Sound region. However, quantitative impact criteria are not presently available (Wyllie-Echeverria *et al.* 1994, Fresh 1994, Pawlak and Olson 1995, Fresh *et al.* 1995). Consequently, mitigation requirements are based on qualitative assessments (B. Williams, WDFW, *pers. comm.*). A quantitative model that links the shade cast by docks with *in situ* light availability and eelgrass productivity and persistence is needed to define the intensity and aerial extent of shading impacts.

In this component of our research, we developed a new approach to modeling the shading impacts of overwater structures on eelgrass and related it to the light environment that we documented in the eelgrass habitat and near the ferry terminal structures. Ultimately, an important goal will be to understand how the shade cast by docks affects the functioning of eelgrass beds as habitat for fish and wildlife. New research will be required to establish several of the causal links in the model. For example, the importance of the persistence and spatial structure (e.g., shoot density, patch size, and spacing) of eelgrass beds in supporting habitat functions has not been studied in our region (Simenstad 1994). We also know little about how individual plant performance (e.g., photosynthetic and respiration rates, root to shoot ratios, seed production) contribute to eelgrass bed persistence and structure. Furthermore, only limited information is available for our region to link *in situ* light availability with plant performance (Olson *et al.* 1996, Thom and Shreffler 1996; Bulthuis, pers. comm.).

This research was specifically designed to address the technical and scientific bases for describing the shade produced by docks and quantifying its effect on the *in situ* light environment. Our approach was to use our empirical *in situ* measurements of the light environment in eelgrass habitats and around ferry terminal structures, in combination with the development of a physical model of light shading using three-dimensional computer-assisted drafting (CAD) and geographic information system (GIS) technology, to evaluate light impacts at Clinton. We further evaluated the power of the model to predict underwater light availability by using data from continuously recording *in situ* light meters.

## METHODS

### Eelgrass Habitat and Ferry Terminal Light Environment

To show the effect of terminal structures on photosynthetically active radiation (PAR) in the eelgrass habitat, a 4π PAR sensor attached to a digital data logger (Licor model LI-1000) was used to measure PAR at 1-m intervals along a transect moving from 30 m south of the Clinton terminal, under the terminal, and then to 30 m north of the terminal.

Diel changes in PAR were monitored on the same days as the eelgrass surveys described in the previous section. One sensor was placed near the mid-depth transect, well away from the terminal, so as to not be shaded by the terminal. A second sensor was attached to the terminal to record ambient (in air) PAR. Recordings were made at 5-minute intervals throughout the day. To measure spatial variation in PAR within the meadow, a

Nomme and Harrison (1991a and b) for comparisons of the biology and ecology of the two species in the Puget Sound region.]

sensor was placed at each eelgrass sampling point along the mid-depth transect, and the mean of 5 to 10 PAR readings collected over a 1-minute interval was recorded.

## Shade Model Development

### *Light Irradiance Measurements to Document Shading*

Light incidence measurements were made over two diel (day-night) cycles at the three ferry terminals during the period of eelgrass field sampling in summer 1994. In addition, the Clinton terminal was selected for a more detailed, higher (temporal) resolution sampling of the local light environment. On 8 June 1995, three Inset HOBO® continuous-recording *in situ* light intensity meters were deployed at three locations: (1) on the roof of the equipment shed (in air/no shade), (2) at approximately -5.5 m (MLLW) and approximately 30 m south of the main deck of the terminal (submerged/no shade), and (3) at approximately -5.5 m (MLLW) underneath the north edge of the dock (submerged/in shade). The submerged stations were located near the lower depth limit of eelgrass at the site, thus recording the minimum light levels reaching the eelgrass beds. A HOBO® continuous recording *in situ* temperature meter was also installed at the submerged/no shade station.

### *Shade Modelling*

To better understand how shade affects eelgrass health, we wanted to address two questions: (1) How do overwater structures affect the light environment? and (2) How does the light environment affect eelgrass health and abundance? To begin answering these questions, we constructed a computer model to link dock architecture with the fate of eelgrass. The goals of the model were to provide a predictive tool in assessing shading impacts and to synthesize our current understanding of light requirements of eelgrass.

We constructed a three-dimensional model of of the ferry dock at Clinton, Washington, using the computer-assisted design (CAD) software FormZ©. This model was built from dock dimensions, bathymetry, piling configurations, and other relevant information provided by WSDOT (Figure 24). Once the computer model had been generated, we used FormZ© to render shadows cast by the dock by entering the latitude, longitude, date and time of the desired image into the computer. The resulting picture represents a snapshot of the shade cast by the dock at a specific location, date, and time. For the Clinton ferry terminal, we rendered shadows cast by the dock on both solstices (December 21 and June 21) and on the vernal equinox (March 21). We generated a series of shadow renderings at half-hour intervals between 10 AM and 2 PM, resulting in nine shadow images for each date.[4]

Each image was captured as a temporary file and saved in a format compatible with Macintosh graphics software applications[5]. We then imported the converted files into the geographic information system (GIS) Map II© for Macintosh. The purpose of this step was

---

[4] This is the standard period for monitoring in *situ light* for eelgrass (Zimmerman *et al.* 1994).

[5] Because FormZ© was used on a PC platform, and the graphics software we used to combine the images runs only on a Macintosh platform, we converted the files from PC to Macintosh through the graphics program Adobe Photoshop©.

to combine the nine picture images into a shadow map and to generate the sum of these shadows. Rather than simply layering images, Map II© allows maps to be combined while retaining all relevant information on each pixel in the legend. This feature allowed us to simplify the seasonal shadow maps by combining all nine images into one map that represented a daily light budget (Figure 25).

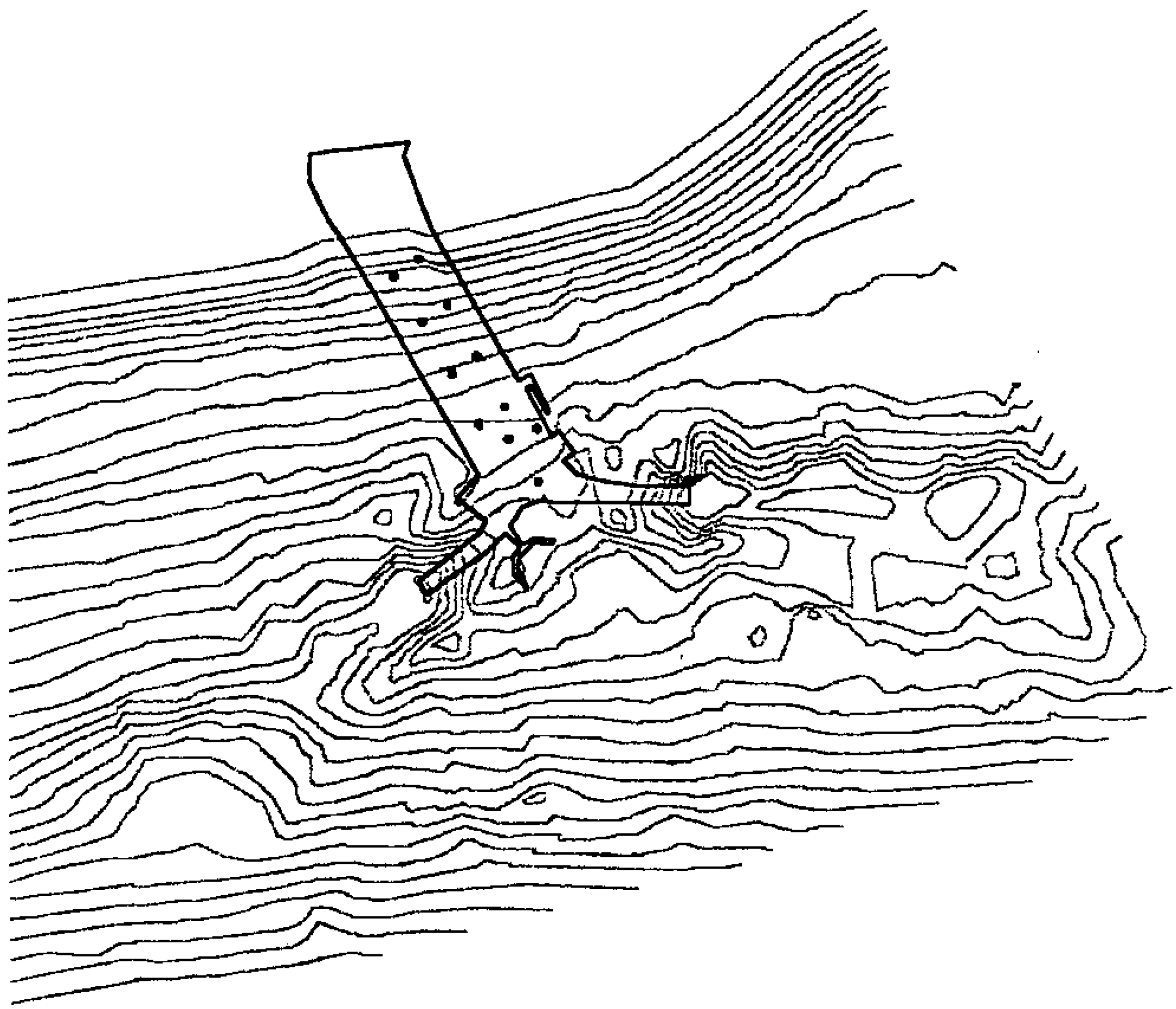

Figure 24. "Wireframe" diagram of Clinton Ferry Terminal used in CAD shading model.

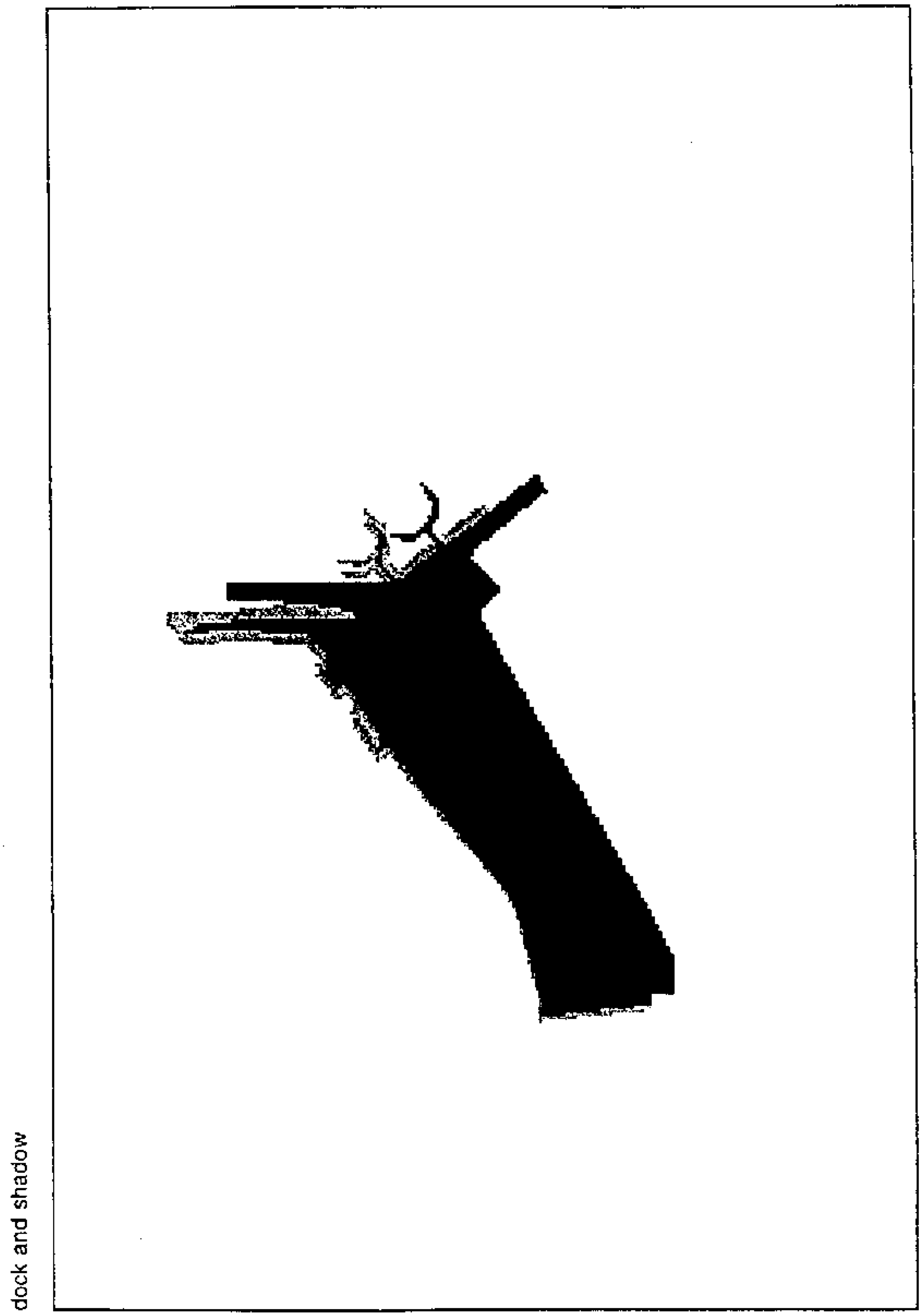


Figure 25. Combination of two MAPII© plots of shading around Clinton Ferry Terminal.

Because only two maps could be combined at a time, we generated a series of temporary files as we combined each image sequentially. For example, we combined a map of a 10:00 shadow with a 10:30 shadow and saved it as a temporary file. This map was then combined with an 11:00 map, and saved as a temporary file, and so forth. After all nine maps are combined, the resulting map portrayed a range of 300 to 500 gradations of shade in different shadow combinations. This map was simplified by manually recoding and combining shadows based on the length of time each pixel is covered by shade each day. We simplified the final map into six shade classes representing predictions of the shade model.

The resulting "shade gradation" map was then combined with a map of eelgrass distribution and relative coverage derived from video surveys (Wyllie-Echeverria *et al.* 1994; see previous section). If necessary, we could also combine the shade map with contour lines to better judge the location of the shadows. The result is a picture and legend representing the total area of eelgrass predicted to be covered by shade from the dock on a given date, such as seasonal variations in solar angle and incidence in March, June, and December (Figure 26A-C).

*Model Validation*

We further evaluated the ability of the computer-generated model to predict shade cast by overwater structures through the use of *in situ* light meters. These submersible HOBO™ light intensity meters were placed at strategic lcoations underwater at the Clinton terminal. We tested the ability of the model to predict shade cast by the Clinton terminal during March and April 1996; in the following section, we specifically describe the April results. The submersible HOBO® data loggers were mounted on a stand that held them approximately 0.5 m above the benthos and in four locations on the bottom that the model predicted to be in shade 0 percent, 37.5 percent, 62.5 percent, and 100 percent of the period from 10:00 to 14:00 hr. The data loggers were programmed to take a light reading (measured in Langleys $ft^{-2}$) at 12-min intervals for 15 d. The resulting 1800 readings by HOBO® were downloaded into a spreadsheet and analyzed. On the basis of these analyses, we generated several graphs to illustrate the results of the field data, including daily mean light intensity, integrated irradiance, and hours of saturating irradiance. We then compared these data with the predicted results from the computer-rendered shadows.

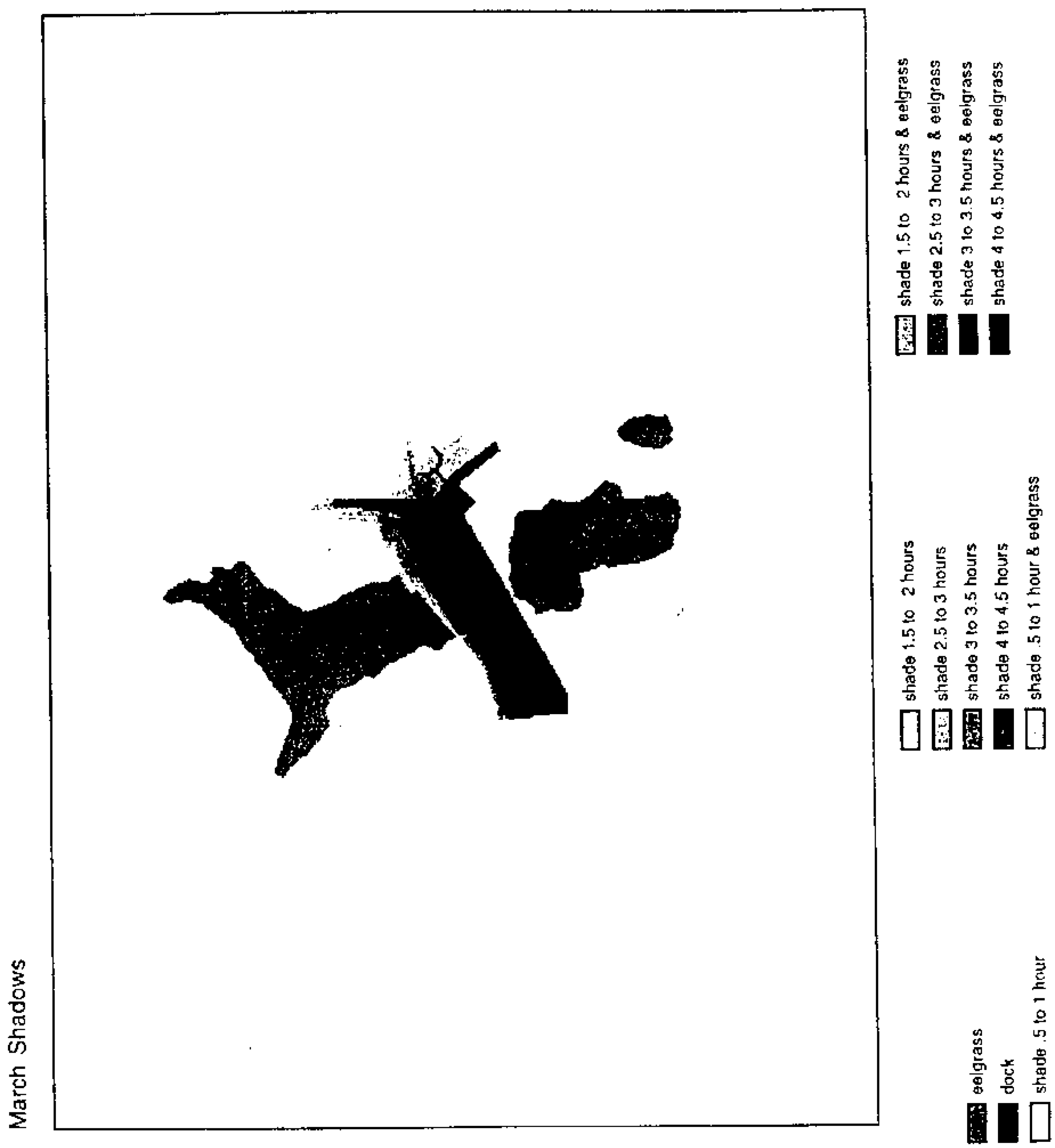


Figure 26A. Finished shadow gradient maps for shading gradients at the Clinton Ferry Terminal in March.


Figure 26B. Finished shadow gradient maps for shading gradients at the Clinton Ferry Terminal in June.

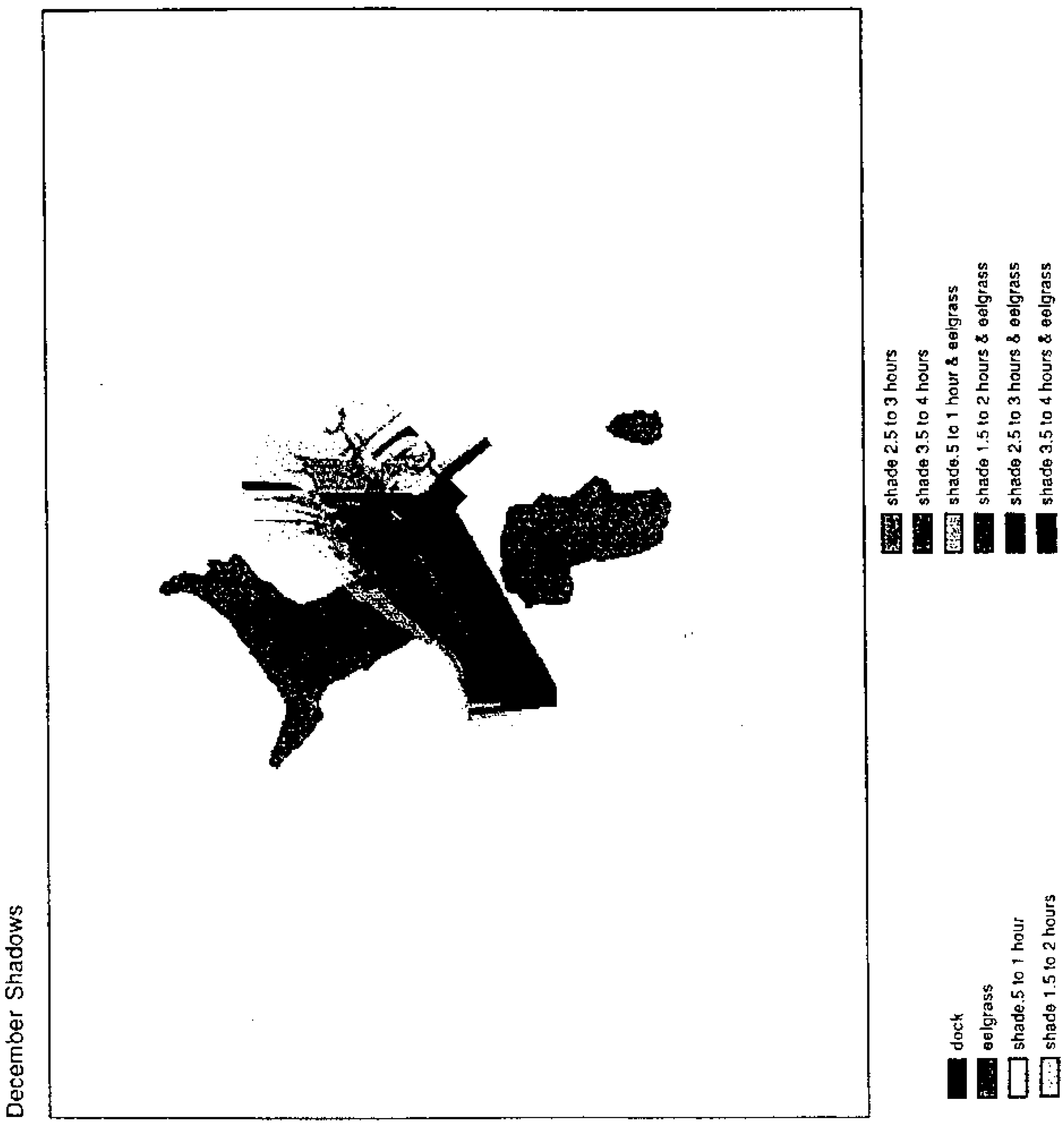


Figure 26C. Finished shadow gradient maps for shading gradients at the Clinton Ferry Terminal in December.

# RESULTS

## Irradiance (PAR) in Eelgrass Habitats

The diel sampling of PAR at a fixed point approximately in the middle of the depth distribution of eelgrass at the sites indicated the effect of tide level and ambient PAR. Maximum PAR recorded at this point in the meadows decreased with depth (Figure 27). Maximum PAR at 3 m deep was over 500 μM $m^{-2}s^{-1}$, whereas maximum PAR never exceeded 150 μM $m^{-2}s^{-1}$ at 6 m deep. In contrast, PAR was rarely below 100 μM $m^{-2}s^{-1}$ when the sensor was at depths shallower than 5 m. The degree of variability in PAR decreased with depth, with PAR ranging between 125 and 550 μM $m^{-2}s^{-1}$ at -3 m, and between 30 and 125 μM $m^{-2}s^{-1}$ at -6.5 m. At a depth of about 5 m and above, most of the PAR measurements were above the linear regression line. Although the relationship between surface (in air) PAR and PAR in the middle of the meadows (Figure 28) is positive, the high variability is likely due to tidal fluctuations, sun angle and particulate in the water column. Mean in-air and on-bottom PAR for the period of measurement was 2254 (SD = 700) and 238 μM $m^{-2}s^{-1}$ (SD = 126), respectively.

Data on in-air PAR taken mid-day in summer showed that PAR was reduced substantially under the terminal deck (Figure 29). Irradiance values on the order of 100 μM $m^{-2}s^{-1}$ were recorded approximately 5 m under the south edge of the terminal and reached a similar value at about 2 m under the north edge of the terminal. Irradiance increased rapidly moving away from the terminal edges and reached near background levels with 5 m from the edges of the terminals.

Measurements of PAR on the bottom showed that ferry propeller wash resulted in substantial reductions in PAR (Figure 30) at a point 50 m from the propeller. PAR was reduced by 10 to 70 percent during plume events relative to background (non-plume) conditions. The events occurred approximately every 18 to 20 minutes during mid-day, and PAR remained detectably reduced for 1 to 5 minutes.

## Predicted Shading Versus Eelgrass Distribution

### *Daily Mean Light Intensity*

In April 1996, average light intensity (based on all light readings taken with the Hobo® sensors over each of the 14 days sampled, including nighttime readings) was consistent with model predictions (Fig. 31). For example, the monitor in the unshaded location recorded the highest light intensities, while the three shaded sensors recorded proportionately lower light intensities. Note that these values include night readings, making comparisons among the stations very conservative.

### *Integrated Irradiance*

Integrated irradiance is the total light available for plant photosynthesis as photon flux density, which is the total number of photons striking an area per unit time. Integrated irradiance is derived from the sum of the instantaneous light readings (converted to PAR) multiplied by the duration of exposure.

Figure 32A illustrates the ability of the model to characterize the light environment during a period (10:00-14:00 hr) for which the data was generated. As the model

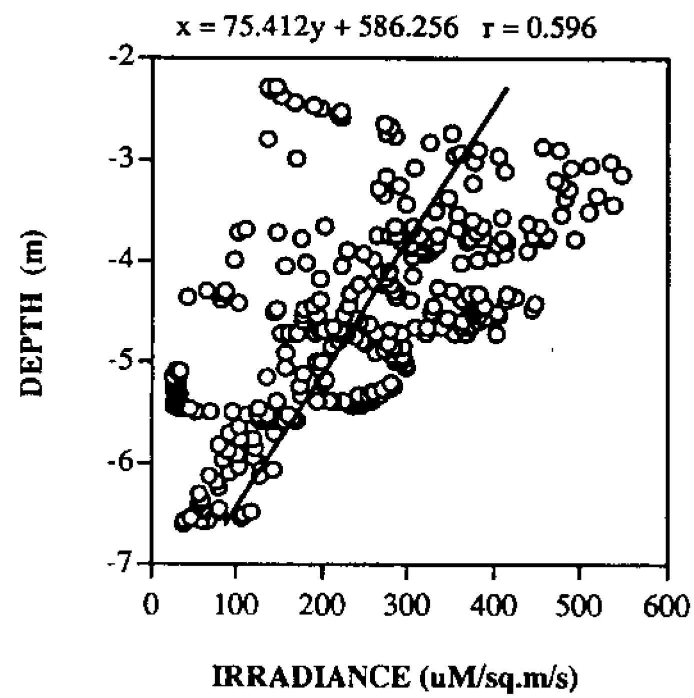


Figure 27. Irradiance versus depth from all daily measurements pooled from the three ferry terminal sites, and associated linear regression line.

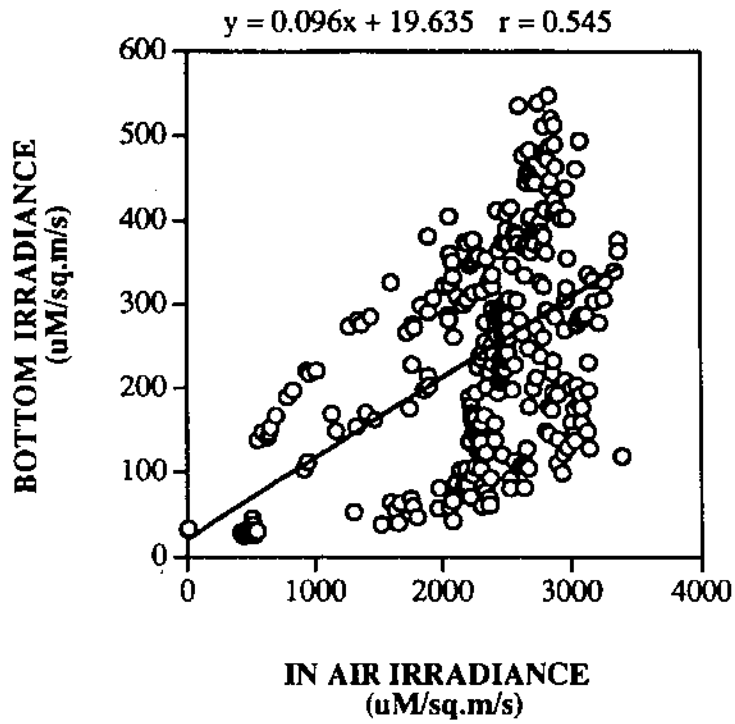


Figure 28. In-air irradiance versus bottom irradiance at all depths pooled from the three ferry terminal sites.

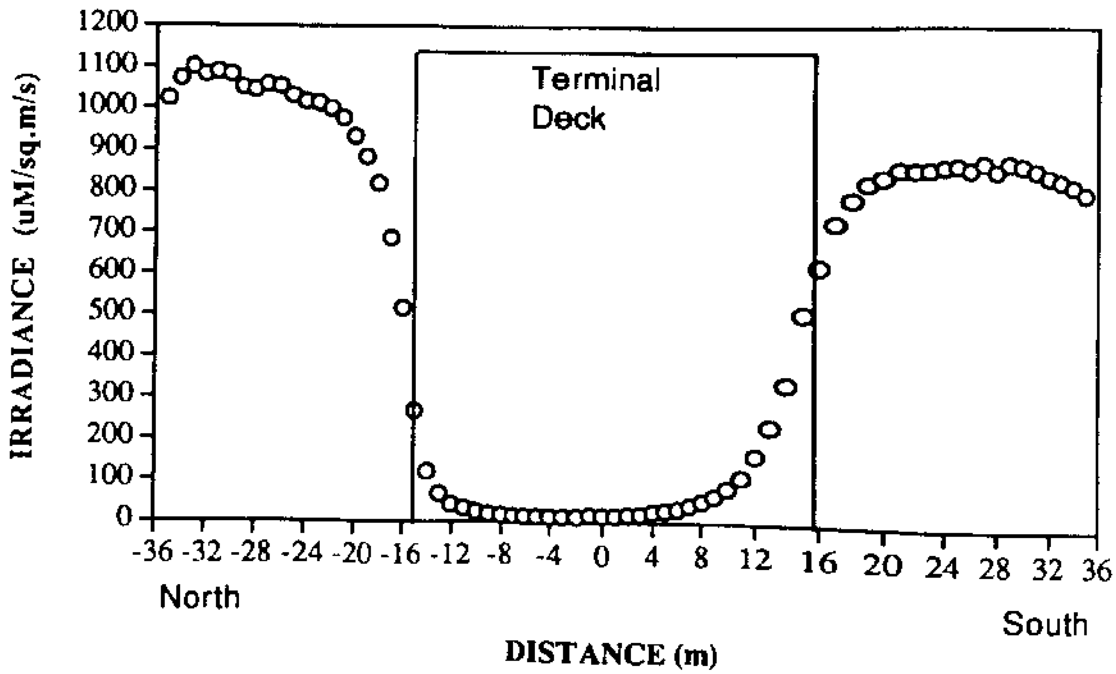


Figure 29. In-air irradiance along a transect passing under the Clinton Ferry Terminal.

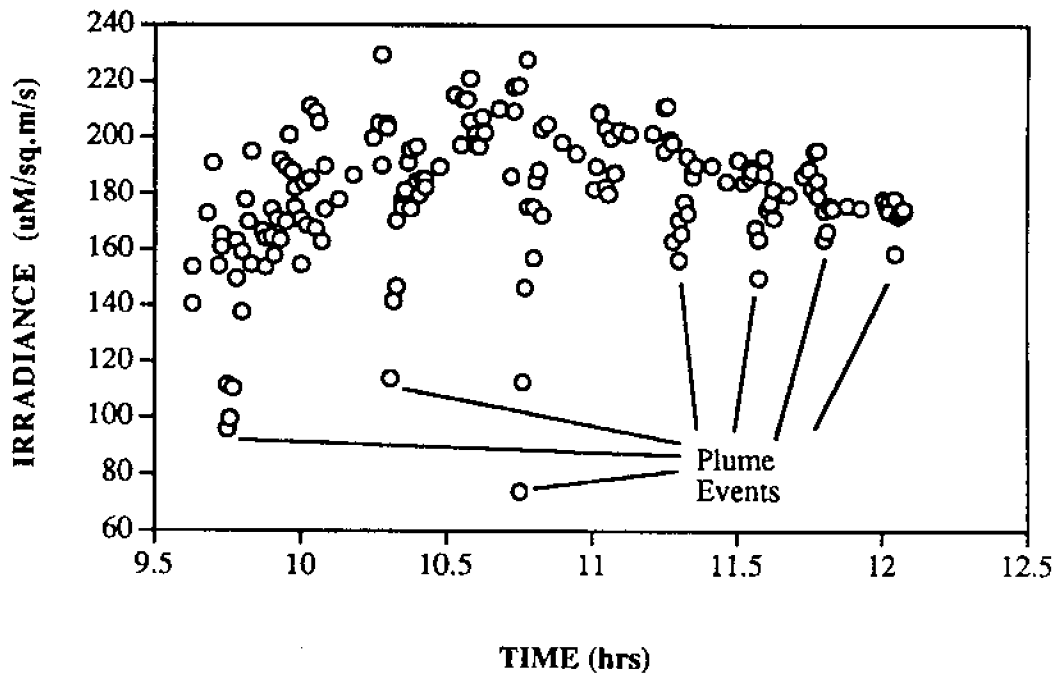


Figure 30. Irradiance during ferry departures and dockings at Clinton Ferry Terminal; plume events indicate the time when a visible plume from the ferry wake was over the sensor.

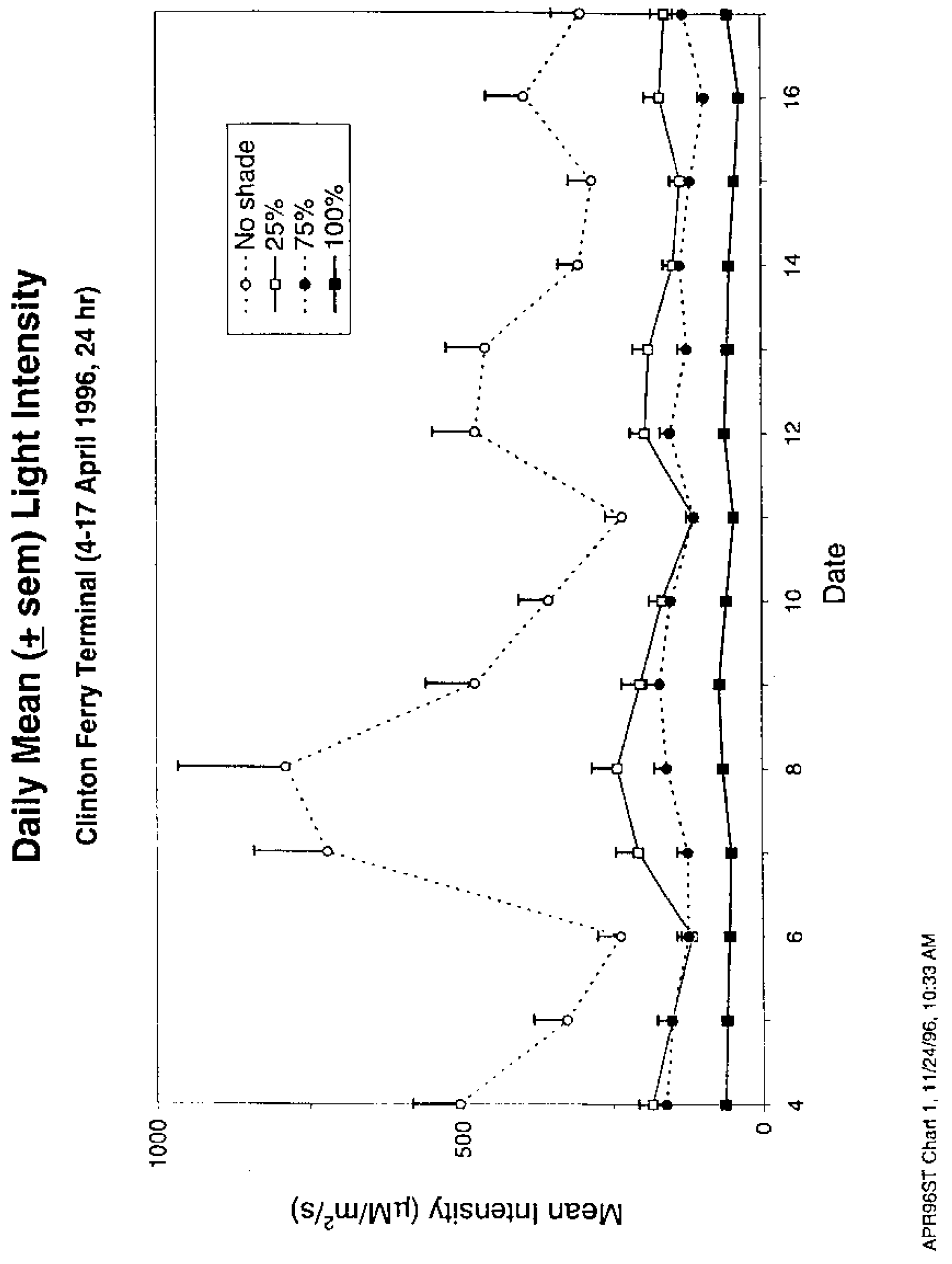


Figure 31. Daily mean (with standard error) light intensity at the Clinton Ferry Terminal, April 1996.

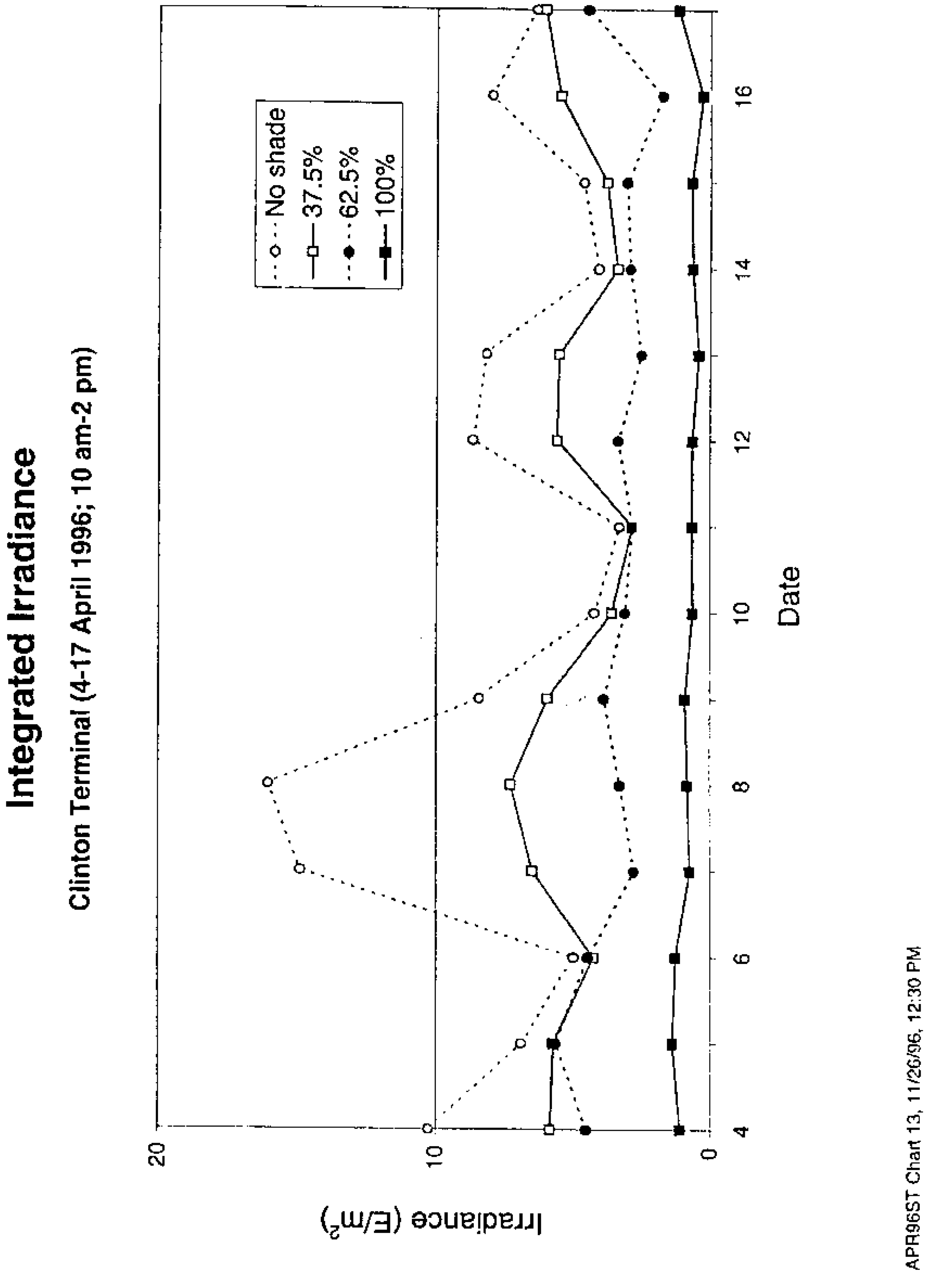


Figure 32A. Integrated irradiance for the period from 10:00 to 14:00 hr.

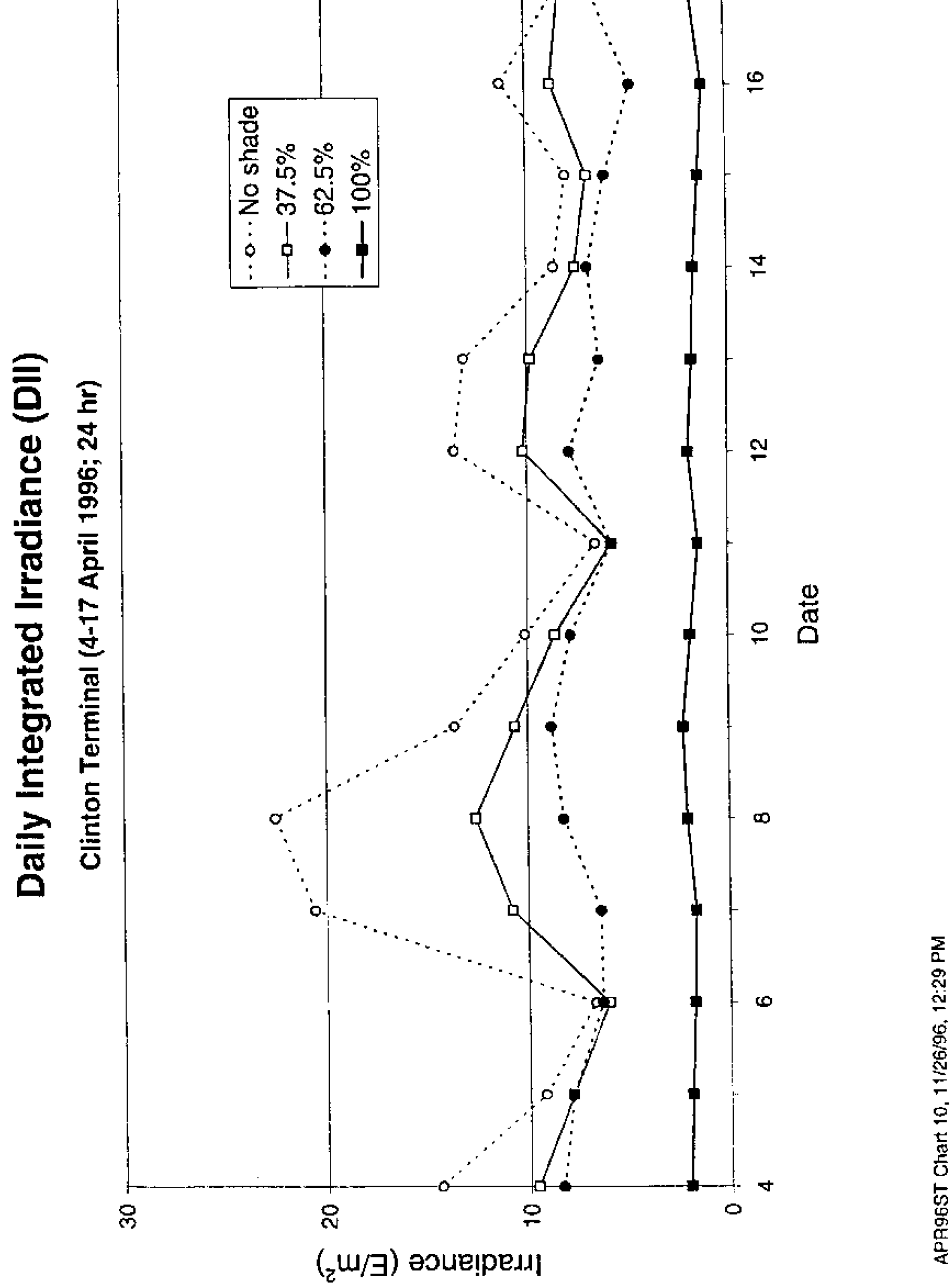


Figure 32B. Integrated irradiance over a 24-hr diel period.

predicted, light levels grew proportionately greater across the shade gradient from 100 percent shade to 0 percent shade per day. Total daily (24 hr) integrated irradiance (DII, Figure 32B ) relates *in situ* light levels to the light requirements of eelgrass. Assuming that eelgrass requires a minimum DII of 3 to 5 M $m^{-2}d^{-1}$ for plant growth (Thom 1996), there appeared to be enough light for eelgrass to survive during this test period at all but the 100 percent shaded station.

*Daily Hours of Saturating Irradiance ($H_{sat}$)*

Photosynthesis requires light levels high enough to support leaf respiration. As light levels increase, photosynthetic production also increases. However, at light levels above a certain point (saturating irradiance, or $I_{sat}$), the plant can no longer increase production. Because DII over-estimates the amount of light available for photosynthesis (Zimmerman *et al.* 1994), the number of hours that irradiance exceeds saturating irradiance ($H_{sat}$) is also used to measure light availability . We did not have data on the seasonal photosynthetic performance of eelgrass plants at the study site, so we chose to consider two possible values for $I_{sat}$ for hypothetically winter- and summer-adapted plants (100 μM $m^{-2}d^{-1}$ and 500 μM $m^{-2}d^{-1}$, respectively).[6]

For hypothetically winter-adapted plants (Fig. 33A), it appeared that there is enough light to sustain eelgrass productivity in the three locations receiving the most light, while at the most shaded station there is insufficient light for plant survival. For hypothetically summer-adapted eelgrass plants (Fig. 33B), it is likely that there is not enough light to support growth and reproduction any of the stations.

## DISCUSSION

### Eelgrass Habitat Light Environment and Effects of Ferry Terminal Structure and Disturbance

*Irradiance and Eelgrass Growth*

On the basis of the data in the previous section and the existing literature on eelgrass light requirements (see previous section ), we found that integrated daily PAR must be above 3 M $m^{-2}d^{-1}$, especially during spring to fall, to assure adequate light for the growth and survival of eelgrass in Puget Sound. In a modeling study, Zimmerman *et al.* (1994) illustrated that daily production declined dramatically at daily integrated PAR below about 4 M $m^{-2}d^{-1}$. In our study, eelgrass occurred down to a maximum depth of about -5 m MLLW, with the lower depth limit varying somewhat among the terminals. Phillips (1984) noted that eelgrass generally does not occur deeper than about -6.6 m MLLW in Puget Sound. Although we do not have long-term PAR data from each terminal, we suggest that irradiance probably explains some of the inter-terminal differences in eelgrass distribution. In our diel monitoring of PAR, we did find that below about -5.5 m MLLW

---

[6] Thom (1996) found that *in situ* photosynthesis (measured seasonally in ambient seawater at ambient temperatures and irradiances) appears to saturate at 400 μM/$m^2$/s, a value bracketed by our analysis.

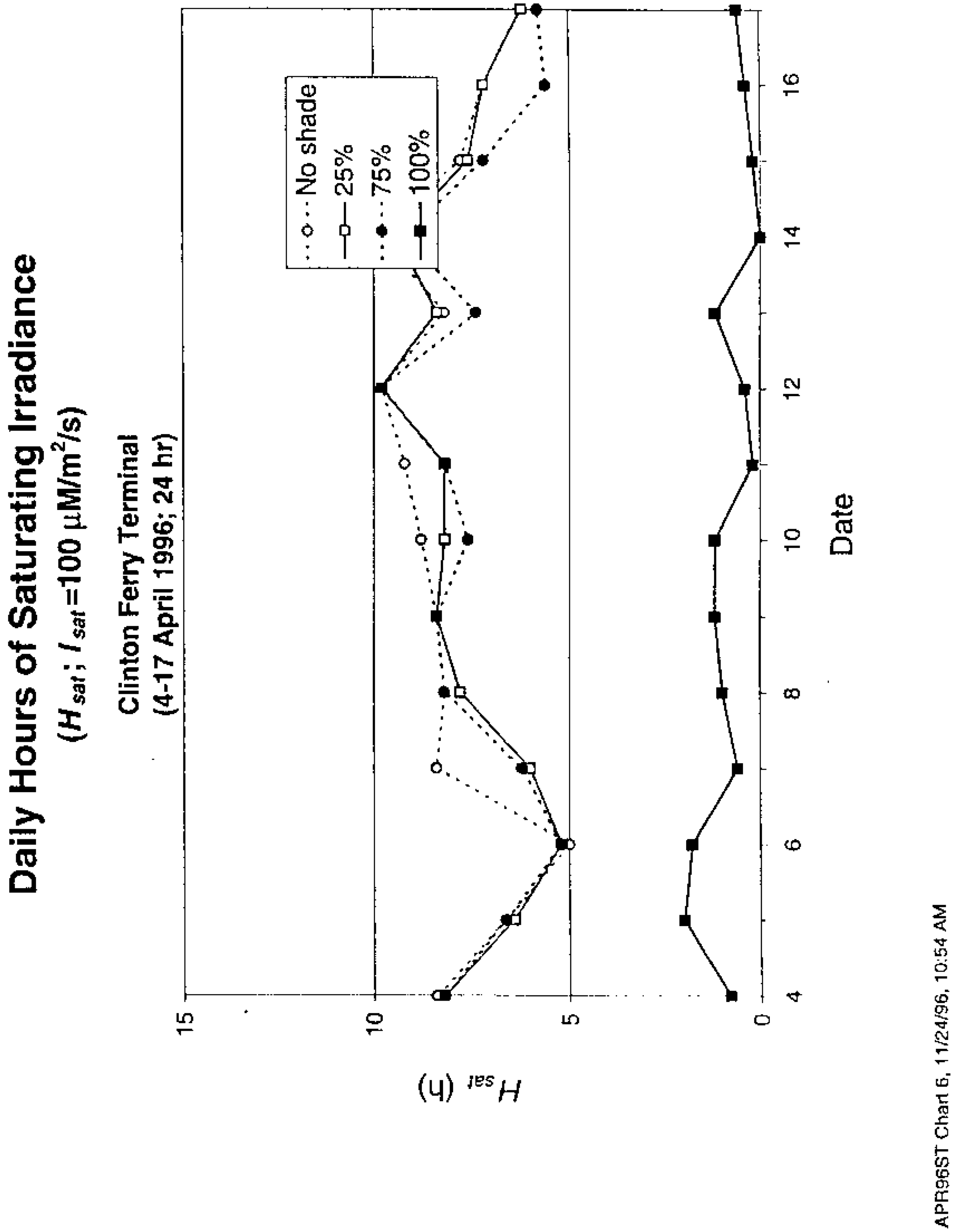


Figure 33A. Daily hours of saturating irradiance ($H_{sat}$) for hypothetically winter-adapted ($I_{sat}$ = 100 µM m$^{-2}$d$^{-1}$) plants.

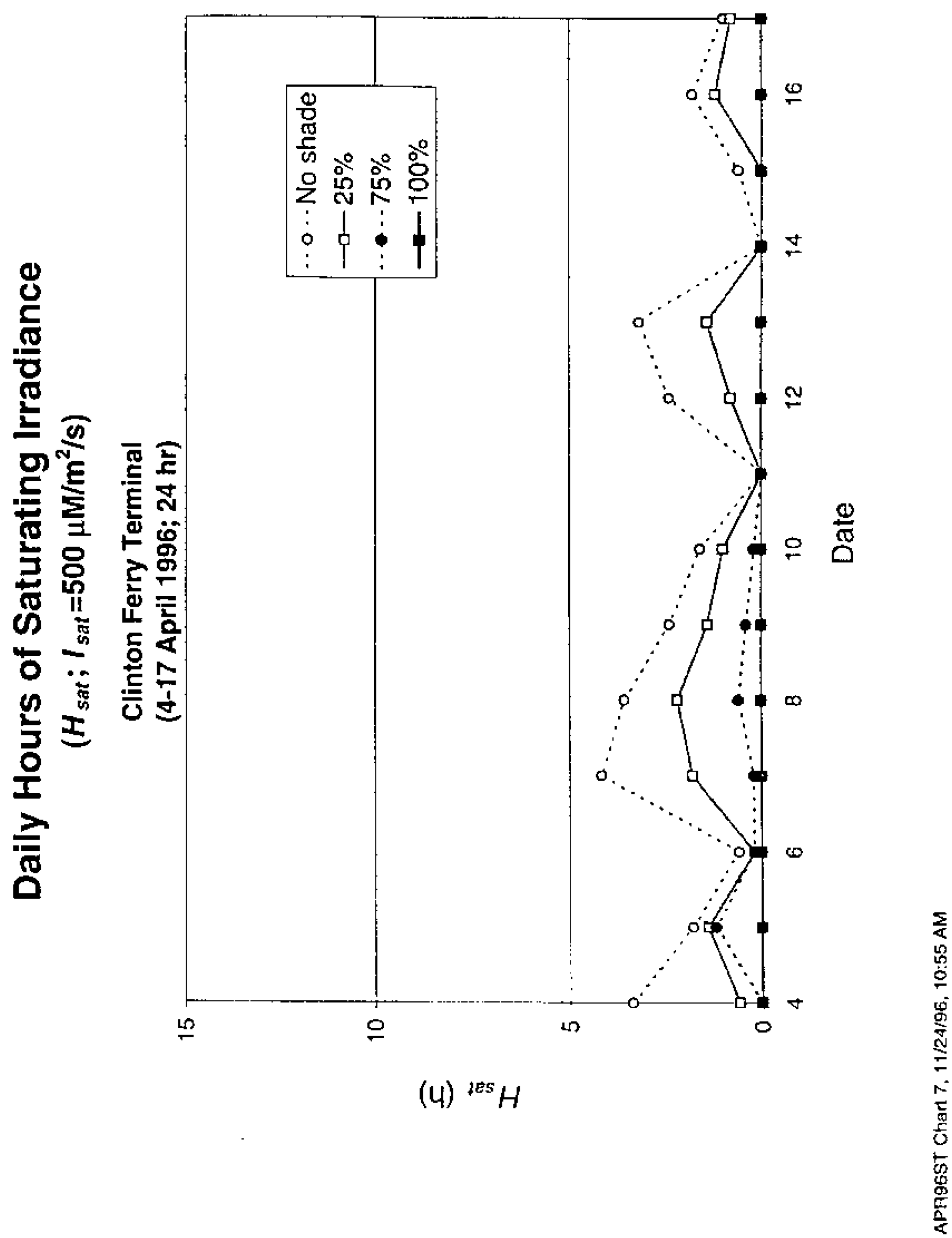


Figure 33B. Daily hours of saturating irradiance ($H_{sat}$) for hypothetically summer-adapted ($I_{sat}$ = 500 µM $m^{-2}d^{-1}$) plants.

instantaneous irradiance values were much less than those found at shallower depths. Values of PAR below -5.5m were primarily below about 150 μM $m^{-2}d^{-1}$. These values were for summer conditions when ambient light is near maximum for the year. Our short-term experiments on NPP versus instantaneous PAR indicated that light limitation occurs below about 300 μM $m^{-2}d^{-1}$. This indicates that there may be a general threshold in eelgrass distribution at about the 4 to 6 m depth range that is due to light limitation in Puget Sound.

The effect of depth on eelgrass distribution is complex and may depend not only on daily PAR, but also on the season. Plants attempting to colonize the deepest edge of the meadow may be highly affected by light conditions in summer. If they cannot build up adequate reserves in summer, survival in winter may be impossible. During years when summer light is great, plants may extend to greater depths and vice versa.

*Ferry Plume Impacts on Light*

At present, we believe that frequently reduced irradiance associated with the plume has caused a reduction in the seaward extent of the eelgrass habitat near the Clinton terminal, and perhaps the at Edmonds and Port Townsend terminals. Observations made by us at the terminals, and examination of aerial photographs of several other terminals, indicated that propeller wash is likely a significant factor affecting eelgrass distribution near the terminals. The net effects of the propeller wash are to scour and redistribute sediments and associated biota and to lower irradiance. Redistribution of sediments is evident as a characteristically disturbed "ring" adjacent to the slip channel. This ring is barren of eelgrass. The periodic reduction of irradiance reaching the bottom may have effects on the growth rate and survival of eelgrass. As pointed out by Zimmerman *et al.* (1994), frequent incidents of light reduction during a diel or longer period can have significant impacts on eelgrass survival. In general, eelgrass exists as deep as light requirements and suitable substrata will allow. At the outer (deepest) edge of the habitat, eelgrass growth is probably at a threshold and is highly dependent on some critical level of light reaching the plants. In areas where light is reduced, such as in the propeller wash plume, eelgrass photosynthesis may be inhibited enough to reduce growth below this critical threshold for survival.

Onuf (1994) documented declines in seagrasses in deep parts of Laguna Madre, Texas, caused by sediment-derived turbidity associated with dredging of the navigation channel. In addition, high rates of sediment input to estuaries can result in both significant shading and burial of seagrasses (Talbot *et al.* 1990). Although suspended sediments were noted by us, massive quantities of bubbles also were generated by the propellers, which totally obscured vision of the bottom from the surface. The bubble plume, which expanded to cover a wide area in the wash zone, persisted for several minutes after arrivals and departures. Bubbles would tend to persist longer in the water column than did sediment particles. We believe that bubbles are at least as important in reducing irradiance on the bottom as are suspended sediments.

**Shading Model**

On the basis of the *in situ* light measurements, we found that the computer shading model was able to predict the light environment at the Clinton Ferry Terminal with some accuracy. However, using the predictions of the computer model to assess actual impacts of shade on eelgrass survival and persistence is difficult because of the lack of scientific information on Pacific Northwest eelgrass populations. In fact, when the literature review portion of the WSDOT study was undertaken, no published studies of the light requirements of eelgrass in the Pacific Northwest were found (Appendix A).

*Strengths and limitations of the model*

We require a better understanding of the use and applicability of the model to make connections between eelgrass health and shading. In order make these links, it is important to be explicit about the strengths and limitations of the model, as well as the potential for its improvement. We identified four primary limitations in the CAD model: data availability, hardware and software limitations, labor limitations, and model error.

Data availability. We relied on public agencies and subcontractors to supply digitized information for construction of the models. Frequently, these data were in formats incompatible with FormZ© and MapII©, and file conversion was not possible. In other cases, the data were unavailable. For example, for the Clinton model, superstructures on the dock were not included in the model because the data were not available in digital form. Superstructures include guardrails and other equipment storage and personnel buildings located on the dock. Without this information, areas that are covered by shade cast from the structure could not be identified by the computer. Additionally, at the Clinton dock, a public pier was built over the center of the eelgrass bed and, because of its location and orientation, this pier may have a significant impact on the eelgrass beneath it.

Modeling Requirements. Hardware and software problems also consumed a large percentage of our time. One major obstacle was the conversion between the PC-based software FormZ© and the Macintosh-based GIS software Map II©. We chose FormZ© for the PC over FormZ© for the Macintosh because the digitized information given to us from agencies was in a PC format, usually AutoCAD©. Files had to be channeled through a graphics program such as Adobe Photoshop© or Canvas© to save them in a format usable by MapII©.

We also experienced a lack of both memory and hard drive space in generating maps. To generate a three-dimensional wire frame of the bathymetry of the study area, our computer required at least 24 MB of random access memory (RAM). In addition, each map generated in MapII©, a temporary file, was at least 600 kilobytes (KB), and some exceeded 4 to 5 MB. We quickly used up over 500 megabytes (MB) of hard drive space on one computer.

Labor limitations. In order for our model to be useful for assessing impacts and aiding in the design of more environmentally sensitive docks, it must be available to designers in a useable format. Currently, the process of transferring data from dock construction plans to GIS map is extremely labor intensive and complicated. In addition, the recoding process, in which 300 to 500 numbers must be manually sorted and recoded, makes it unrealistic for use in a dock design process without improvements in the automation technology.

Model Error. Despite their simplistic nature, our models were able to predict shadows cast by overwater structures with some accuracy. Simulations were restricted to realistic conditions. For example, when rendering shadows, FormZ© assumes a point source of light and simulates a shadow based on a perfectly clear day. This does not take into account scatter diffraction in clouds or air. In addition, our model does not incorporate effects of tides, water, or water clarity. Shadows are cast across a dry bathymetry, so the effect of water column depth on light penetration is not taken into account.

*Strengths and limitations of the light sensors*

We chose to use HOBO™ light sensors for a number of reasons, including price, size and ease of use. HOBO™ sensors are reasonably priced at about $150 each (as opposed to sensors that take measurements in PAR, which can cost thousands of dollars). In addition, HOBO™s are small, weigh only a few ounces, and are easily moveable. These sensors are also relatively accurate, and data can be easily downloaded into spreadsheet software for analysis. Finally, the HOBO™ sensors can be deployed from the surface (we used an inflatable boat) rather than being deployed by divers, making the process safer, faster, and less expensive.

HOBO™ light sensors were chosen on the basis of the aforementioned strengths, but they are not without deficiencies. For example, the sensors measure light intensity in Langleys per unit area, rather than photosynthetically active photon flux density ($\mu M\ m^{-2}\ s^{-1}$), which is the desired measurement for analyzing eelgrass light requirements. HOBO™ readings must be converted to PAR-based on lab calibrations, providing the possibility for measurement error.

The HOBO™ sensors are also hyper-sensitive to infrared. Because they were deployed underwater, the readings may not accurately reflect PAR because of selective attenuation of red wavelengths in the water. As the tides fluctuate, the amount of water above the sensors, and subsequently the amount of light diffusion, can also alter the readings. We recorded some readings above 2000 to 3000 $\mu M\ m^{-2}s^{-1}$ (full sunlight), likely because of an extreme low tide exposed the meters to infrared light, producing artifically high readings.

Another weakness of our deployment of the sensors was the difficulty in placing them in precise locations on the benthos, and after they have been retrieved for data analysis, it is almost impossible to replace them in their original location. In addition, the HOBO™s are enclosed in clear plastic casings, which will under long deployments accumulate algae and other fouling organisms during some seasons if not regularly cleaned. This can result in an under-estimation of light intensities. Finally, field measurements were replicated because we could deploy only one sensor for each predicted shade level, and thus we could not undertake spatially statistical comparisons.

Despite these caveats, this research represents a necessary step in the process of developing scientifically based standards for assessing and mitigating the shading impacts of overwater structures on eelgrass. An immediate benefit is the production of a tool for evaluating the relative degree of shading produced by alternative design options.

# ACTIVE AND PASSIVE MITIGATION STRATEGIES FOR IMPACTS TO EELGRASS FROM FERRY TERMINAL CONSTRUCTION

by

Ronald M. Thom
Marine Science Laboratories
Battelle Pacific Northwest Laboratories
1529 West Sequim Bay Road
Sequim, Washington 98382

and

Sandy Wyllie-Escheverria
School for Marine Affairs
Box 355685
University of Washington
Seattle, Washington 98195-5685

## INTRODUCTION

Mitigation for eelgrass impacts from ferry terminal construction and operations was approached from alternative measures of avoidance, minimization, rectification, reduction, and compensation for loss of eelgrass habitats. We investigated both strategies to alter ferry terminal design to reduce or eliminate predicted impact, and strategies to restore eelgrass habitat that would be initially or unavoidably lost. Because the major ongoing impacts from the terminals and boats are reduced light and physical disturbances from propeller wash, we conducted experiments to evaluate how to address these impacts.

In addition, we conducted studies to evaluate eelgrass growth in a variety of sediment types commonly encountered near ferry terminals in order to determine the relative ability of the substrata type to support transplanted eelgrass. Phillips (1983) and others have noted that eelgrass occurs in a variety of substrata types but is found most frequently in mixed sand and silt. Since substrata often vary substantially at potential transplant sites, we evaluated the growth of eelgrass that was planted in substrata types commonly found near ferry terminals in Puget Sound.

Finally, we evaluated the use of seeds for propagating transplant material. The recognition that eelgrass seed had potential for eelgrass transplants was first noted by Addy in 1947. His results indicated that seeds germinate and seedlings develop before the onset of winter. Subsequent studies (e.g. Phillips 1972; Churchill *et al.* 1978), however, cautioned the use of seeding on two counts: annual fluctuations in the production of flowering stalks and low rates of seedling germination. In addition, recent studies indicate that although the "broadcast" method of seeding may not be efficient, the use of "pelletized" seed may aid the potential of seed burial, which may limit seed predation and increase germination rates (Orth *et al.* 1994; Granger *et al.* 1996).

In the Puget Sound, eelgrass seed dispersal begins in mid-August and continues to October, and germination, although occurring all year, is most common from April to July (Phillips 1972; 1984). In addition, planting relative to restoration or mitigation plans is recommended in the months of April through June (Fonseca *et al.* in prep). Therefore, seeds should be collected in the Fall, stored overwinter, and planted in the Spring or early summer.

Although earlier work documents the viability of Puget Sound eelgrass seed (Phillips 1972), no studies have examined the viability of seed stored overwinter in this region. If eelgrass mitigation and restoration plans are to conform to the current guideline of Spring and summer planting, experiments that describe the most effective and efficient method of seed collection and storage are necessary. Our study was designed to 1) determine whether eelgrass meadows at Clinton or an alternative site could provide viable seed, 2) establish that captured seed could be stored overwinter, and 3) ascertain the most efficient method of transfering seed to mitigation and restoration projects. Herein we discuss both collection and storage of seeds as well as seed germination and viability.

## METHODS

### Glass-Centered Concrete Blocks

We measured PAR during daylight hours under concrete blocks that contained a center section (ca. 10 cm on a side) of thick, clear plastic. The blocks are used for walkways or walls. These blocks were being considered for incorporation into terminal passenger walkways. The sensor was placed under the block at a point immediately below the plastic center. Ambient light was monitored also.

### Reflective Material

To increase albedo under docks, we placed a rectangular piece of plywood affixed with aluminum foil under the dock at PNL/MSL. We measured PAR directly under the foil, under the adjacent dock area, and ambient incoming PAR, as well as PAR reflected off the surface of the water under the dock. This experiment evaluated whether highly reflective material may be useful in increasing reflected light under terminals.

### Quartz Halogen Lamps

We measured photosynthesis of 10-cm sections of eelgrass under quartz halogen lamps and ambient light. Photosynthesis was measured as oxygen flux in 2-hr incubations under each treatment (Thom 1990). Ten replicate jars were used for each treatment. The oxygen flux was normalized to dry weight tissue biomass used in the incubations.

### Evaluation of Substrata Requirements for Eelgrass

The assay of sediment type was carried out by planting three shoots (with roots and rhizome segments) into 10-cm diameter x 30-cm long Plexiglass tubes containing various substrata types. The tubes were capped at one end and filled with six substrata types: (a) natural substrata, which consisted of medium sand/silt from the middle of the eelgrass meadow at PNL/MSL; (b) *Ulva* mud, which consisted of a silt and sand substrata from a organically enriched intertidal area; (c) an organically enriched mud/fine sand mixture from a channel in a salt marsh at PNL/MSL; (d) medium to course beach sand collected from the upper intertidal zone; (e) a medium to course sand plus gravel mixture from the high intertidal zone; and (f) gravel/small cobble mixture from the high intertidal zone. With the exception of treatments "e" and "f," this range of substrata types is often considered for transplanting of eelgrass. Five replicate tubes were established for each substrata type.

The tubes were placed at random positions within a flowing seawater tank (3.1 m long x 1.2 m wide x 0.6 m deep) on 29 August 1995. Growth was measured at 7 to 9 day intervals, except for a 21-day interval in October, between 29 August and 20 November 1995. Growth was assessed using the leaf trim method as described previously.

**Evaluation of Transplantation Using Seeds**

*Seed Collection*

On 9 August 1995, we sampled intertidal plants at Clinton Ferry Dock, Whidbey Island. Our intent was to gather generative (flowering) shoots in the fifth stage of flowering (DeCock 1980), transport these shoots to the laboratory, and allow the seeds to disperse in culture (e.g., Churchill 1992). Using the ferry dock as a bench mark, we sampled a distance of approximately 200 m both north and south within the tidal elevation bounded by 0 and -5 m MLLW. No flowering plants were present either attached to the bottom or in the beach wrack. Therefore, during August, we sought other collection sites and were able to obtain generative shoots (n=14) from a concurrent eelgrass restoration site on Shaw Island in northern Puget Sound (Wyllie-Echeverria and Turner 1996). On 30 August, divers collected the shoots, kept them cool, and mailed them (Express mail in Styrofoam cooler with blue ice) to the laboratory. They were immediately placed in covered containers filled with approximately 1.3 l of sand filtered sea water (salinity 27°/oo; temperature 18° C) on 1 September (Churchill 1992). Seawater containers were kept dark and cool (room temperatures not exceeding 20° C). After 10 days bottom water and flower material was sieved for seeds which were blotted dry and surfaced sterilized for 20 minutes in a 20 percent Clorox-sterile seawater solution (Churchill 1992). Captured seeds were partitioned into 8 scintillation vials in four different temperature and salinity treatments.

Four vials were filled with 10 ml. of 35°/oo salinity seawater and approximately 40 seeds and placed in temperatures of 5° C and room temperature (approx. 15° C). Four additional vials were filled with 10 ml. of 27°/oo salinity seawater and approximately 30 seeds and placed in temperatures of 5° C and room temperature (approx. 15° C). All vials were in storage treatments by 13 September.

*Viability Tests*

Five seeds were extracted on 21 November 1995 from the vials stored at 5° C. The seed coats were split and immersed in a 5 percent solution of distilled water and tetrazolium chloride and placed in the dark (Phillips 1972). Seeds were examined hourly for 3 hours and 24 hours after the stain treatment. The experiment was terminated on 22 November.

On 25 June 1996, we extracted 86 seeds from the vials stored at both room temperature and 5° C. The seed coats were split and immersed in a 5 percent solution of distilled water and tetrazolium chloride and placed in the dark (Phillips 1972). Seeds were examined at 4 hours, 24 hours, and on 19 July. The experiment was terminated on 19 July.

*Germination Experiments*

On 13 September 1995, 58 seeds were separated into two salinity treatments (27 ‰ and 35 ‰) at room temperature (did not exceed 20° C), kept dark and aerated until 3 November. Seeds were then placed in two different sediment treatments (sand and silt/sand) in aquariums filled with 27 ‰ sand filtered sea water and kept in the dark until 16 November. On 16 November the aquariums were placed in natural light. During the two-week period between 17 December and 1 January, artificial light (ABCO Plant Light™) was added to compensate for decreased light availability. The experiment was terminated on 2 February 1996.

On 15 May 1996, two vials from each temperature storage treatment (5° C and room temperature) were removed and checked to see whether seeds had germinated during storage. Seeds that had germinated (emergence of the cotyledon) and those that were dark blue (color associated with viable seeds) were removed from each vial (n=33). In cases where no germinated or dark blue seeds were present, seeds that were dark green in color were chosen. The seed coats of the non-germinated seeds were split. All seeds were placed in petri dishes in 12 ‰ salinity that had been saturated with air (Churchill 1992), placed in the dark, and checked daily for eight days. When the cotyledon had elongated to 4 cm or longer or foliage leaves were present, seeds were transferred to a grow-out treatment.

## RESULTS

### Mitigation Measures at the Clinton Terminal resulting from the Research Findings

The terminal expansion will have short-term direct effects and longer-term impacts on eelgrass. Initial construction activities are predicted to have limited effect on eelgrass, although they will largely be conducted away from existing beds. The new terminal deck will cover 320 m$^2$ of eelgrass presented located on the south side of the terminal. The proposed mitigation measures are directed at eliminating any longer-term effects.

With potential impacts to eelgrass identified through a series of meetings with State and Federal Resource Agencies, the Washington State Department of Transportation undertook a program to identify necessary actions to avoid, minimize and compensate for these imapcts. Impacts expected under the original design plan for the terminal have been either avoided or minimized. For example, ferry propeller wash impacts have been avoided by moving the slips further offshore. Light impacts have been minimized through incorporation of light transmitting structures (cement blocks with clear plastic centers) in the walkway of the terminal, and lengthening the terminal. Lengthening the terminal reduced the width of the terminal at the point where it crosses the eelgrass meadow. In addition, the underside of the terminal will be painted with a bright white paint to increase the reflected light under the terminal. Maintenance activities have been reduced dramatically through the use of concrete piles and decking as opposed to timber (as was proposed in the original plan). Construction using concrete will result in placement of 1/3 fewer pilings than presently exist. This will reduce the amount of space for piling communities to develop and hence support fewer seastars and Dungeness crab. Fewer seastars and crab should result in less bioturbation of eelgrass.

*Avoidance*

Avoidance of impacts to eelgrass will be accomplished through decreasing the dock width by extending the dock further offshore, and relocating a public fishing pier and float away from eelgrass. These actions not only decrease the area of eelgrass impacted by direct shading but also remove propeller wash disturbances, thus allowing eelgrass to be restored in disturbed areas. Actions under alternative F result in a total area where impact is avoided of 391 $m^3$.

*Minimization*

Shading impact will be minimized by placement of concrete block containing glass centers in the walkway that spans the width of the eelgrass meadow on the south side of the terminal The walkway will be 12 feet in width and will cover a total area of 218 $m^2$. Measurements made under this type of block indicate that at least 60 percent of incident ambient photosynthetically active radiation (PAR) reaches the are beneath the blocks. Observations at Port Townsend, a relatively new concrete terminal, show that eelgrass does occur very near the dock and even a short distance under it. Light will tend to penetrate further under this terminal than under timber pile terminals because of reduced pile density in the concrete structure and, to a much lesser degree, the lighter color of the piles. As a passive method to increase light penetration and albedo under the Clinton terminal, the underside of the terminal will be coated with a white paint containing reflective particles. This will result in a slight increase in reflected light and generally increase the brightness under the dock.

Finally, construction activities will be conducted in a way to minimize bottom disturbance by construction vessels, pile driving and associated activity. The perimeter of eelgrass patches next to the terminal will be identified and the impacts will be minimized. This will be a condition of the construction contract, and compliance will be monitored by WSDOT.

*Habitat Compensation*

Habitat compensation will be accomplished through <u>transplantation of eelgrass</u> into areas that probably formerly contained eelgrass. This action will be preceded by removal of potential sources of disturbance to the transplant plots. In addition, loss of large brown algae, will be compensated through placement of <u>collars around selected pilings and rubble rock mounds</u> at depths beyond the outer edge of the eelgrass meadow. These latter structures will also enhance rockfish habitat in the vicinity of the terminals.

A total of 13 areas or subareas have been identified for transplanting of eelgrass (Figure 34). These areas constitute a total of 3,077 $m^2$ (Table 3A). Our observations and studies indicate that eelgrass in these areas has been damaged by initial dock construction, maintenance operations, propeller wash (A, F, E), small boat damage (G), or sunken debris

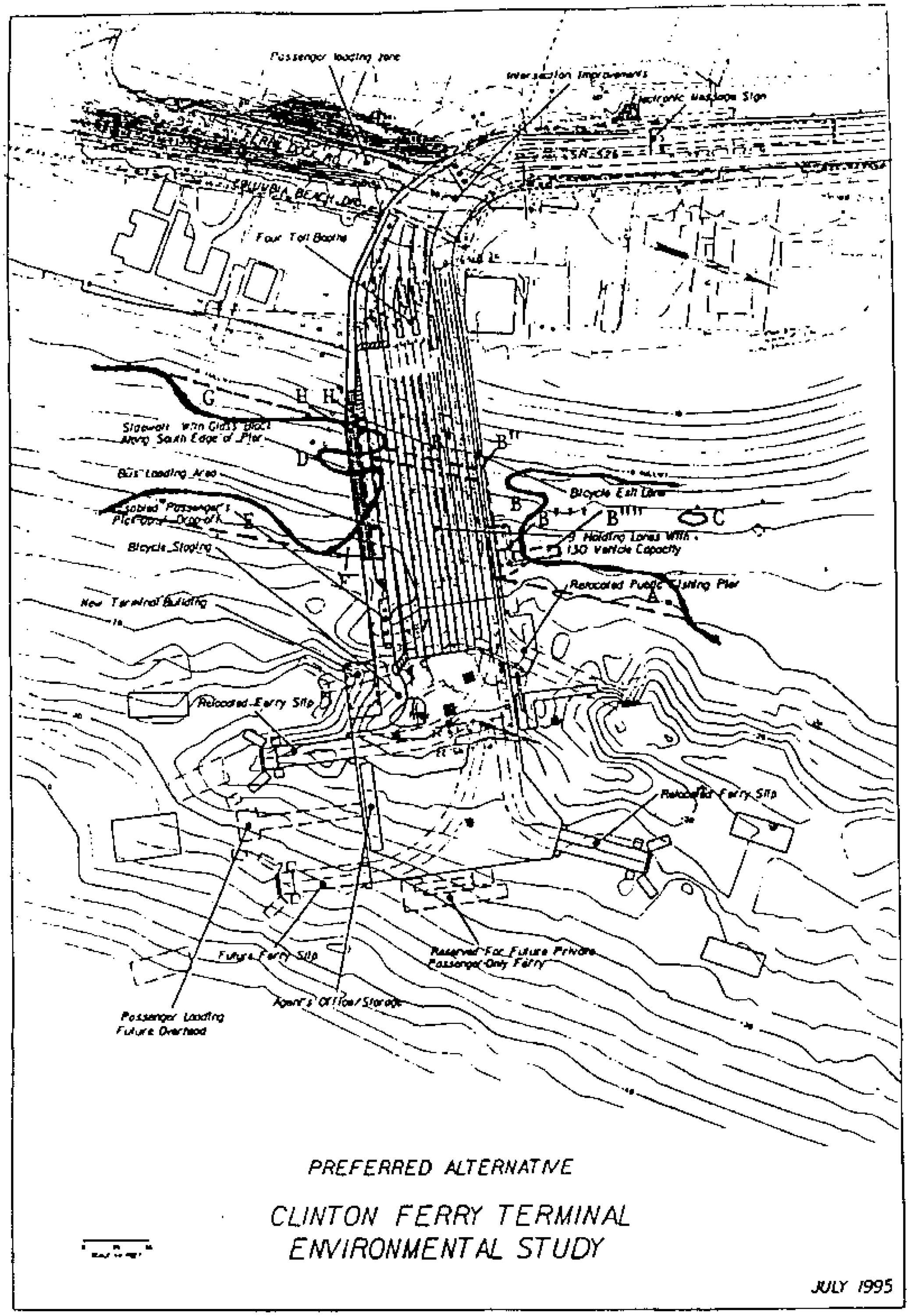


Figure 34. The design of the Clinton Ferry terminal expansion; potential eelgrass transplant areas are designated by letters.

Table 3. Eelgrass impact area and transplanting areas.

A. Total area of existing eelgrass within project boundaries as shown in Figure 1

| | |
|---|---|
| North Side | 2,269 $m^2$ |
| South Side | 3,274 |
| Total | 5,543 |

*Total area of eelgrass directly covered by project:* 320

B. Eelgrass transplant/rehabilitation by phases

| Phase | Subarea | Area ($m^2$) | Potential Success | Replacement Ratio |
|---|---|---|---|---|
| I | A | 1,044 | Low-Mod. | 3.3 |
| | C | 47 | High | 0.1 |
| | D | 19 | High | 0.1 |
| | E | 233 | Mod. | 0.7 |
| | F | 65 | Mod. | 0.2 |
| | G | 233 | Mod. | 0.7 |
| | H | 201 | Low-Mod. | 0.6 |
| | H' | 167 | Low | 0.5 |
| II | B | 251 | Mod. | 0.8 |
| | B' | 430 | Low | 1.3 |
| | B" | 195 | Low | 0.6 |
| | B"' | 83 | High | 0.3 |
| III | B"" | 110 | High | 0.3 |

*Total eelgrass transplant/rehabilitation areas*

| Phase | Area ($m^2$) | Percent of Total | Replacement Ratio |
|---|---|---|---|
| I | 2,008 | 65 | 6.3 |
| II | 959 | 31 | 3.0 |
| III | 110 | 4 | 0.3 |
| Total | 3,077 | 100 | 9.6 |

C. Total Area of Potential Success

| | |
|---|---|
| High | 258 $m^2$ |
| Moderate | 781 |
| Low-Moderate | 2,037 |

*Net change in total eelgrass area within project boundaries as shown in Figure 1*

| | |
|---|---|
| Total area after project + Transplant area | 5,223 + 3,077 $m^2$ |
| Total area before project | 5,543 |
| Net Change | +2,757 (+50 percent) |

(D, C). Table 3B shows the general strategy for dealing with each of the potential impacts. In areas where construction will damage beds (D, B, H), these areas will be replanted. Moving the slips offshore will open areas A, F, and E to transplantation.

We have identified the potential for success expected with transplanting at each area (Table 3C). These predictions are based upon information gained from a review of past transplanting projects in the Pacific Northwest as well as nationwide (Thom 1990; Fonseca, *personal communication*). In general, small bare areas which are surrounded by eelgrass, and where disturbances (e.g., sunken debris) can be removed, represent areas of high probability for successful establishment of eelgrass. Areas of located on the fringe of the bed (A, F, E) represent areas of moderate probability of success. Several areas are considered experimental; for example, areas B', B"and H are located under the northern edge of the dock and glass blocks. It is uncertain how well transplants will do under these conditions. Hence, the potential success in these areas is categorized a low-to-moderate. Finally, we will overplant under the dock (e.g., H') to evaluate whether at least some eelgrass can be maintained in these conditions. Expected success is very limited in these areas.

The sediment grain size was evaluated in transplant areas A, E and G, and was compared to grain size in the middle of the existing eelgrass meadow. Areas E and G contained sediments that were very similar to those in the existing eelgrass meadow. The percentage of sand ranged from 80-92 percent in areas E and G as compared to 83-91 percent in the eelgrass meadow. The percentage of silt was also very similar among the areas, ranging from 5 to 12 percent. Sediments in area A were comprised of more gravel (34-50 percent), less sand (28-57 percent) and about the same amount of silt (5-17 percent) as the eelgrass meadow sediments. Eelgrass occurs naturally in sediments over the range of sediment sizes measured at the three transplant areas. Greater gravel content in area A may indicate higher erosion rates, which could impair somewhat eelgrass transplant survival.

If all of the transplanted areas were successful, a replacement ratio for the 320 $m^2$ of eelgrass covered would be 9.6 to 1.0. This would result in a net increase in total present eelgrass area within the bounds of the study area (see Figure 2) of 50 percent. When the areas are grouped according to probability of success, the ratios are as follows:

| | Area ($m^2$) | Ratio |
|---|---|---|
| Highly Likely to Succeed | 258 | 0.8 |
| Good Probability with Disturbance Removed | 977 | 3.1 |
| Experimental | 1,675 | 5.2 |
| Overplant, Limited Survival Expected | 167 | 0.5 |

Areas with either a high or moderate probability of success account for a total replacement ratio of approximately 3.9 to 1.0.

Eelgrass transplanting will coincide with the three project phases (Table 3B). Transplanting will be done in all areas that will not be directly disturbed by the construction process. This includes area A which will be under the influence of propeller wash until phase III. It is anticipated that some plantings will survive in area A, which can then be supplemented during phase III. A limited transplanting effort (approximately 10 percent of the area) in spring 1996 is planned prior to the initiation of construction in 1997. This limited effort will be used both to implement compensatory mitigation up-front, and to refine methods for transplanting. Most of the effort will be concentrated in areas (i.e., C, D, G) where little or no disturbance is expected during construction. Most of the remaining transplanting will be conducted in Phase I (55 percent), with less in Phases II (31 percent) and III (4 percent).

### Glass-Centered Concrete Blocks

The experiment indicated that the glass-centered blocks let through substantial quantities of light. PAR measured under the glass block was about 60 percent of that in ambient light (Figure 35). The amount varied with time of day (i.e., sun angle), with greatest values under the block occurring near and within four hours after noon.

### Reflective Material

The results showed that the foil could reflect substantially more light than the wooden underside of the dock. We measured PAR values under reflective foil placed under the dock at PNL/MSL that were approximately 60 percent greater than values measured under the wooden dock without foil (Figure 36).

### Quartz Halogen Lamps

Eelgrass photosynthesis was approximately five time greater under quartz halogen lamps than under ambient light, indicating that the lamps could support eelgrass growth (Table 4).

Table 4. Net productivity of eelgrass leaf sections under quartz halogen lamps (mean PAR = 358 $\mu M\ m^{-2}\ s^{-1}$). NPP in mg $O_2\ g^{-1}\ hr^{-1}$

| | AMBIENT | LAMPS |
|---|---|---|
| Mean | 0.74 | 4.42 |
| SD | 0.64 | 1.02 |
| N | 10 | 10 |

### Evaluation of Substrata Requirements for Eelgrass

Transplanted eelgrass grew in all substrata types including gravel/rock, but showed greatest growth in finer material (Figure 37). Surprisingly, the substrata where the eelgrass was growing naturally had an intermediate cumulative growth rate. There was indication that substrata containing greater potential organic matter (i.e., *Ulva* mud, marsh channel, and natural eelgrass sediment) supported the greatest growth. The growth rate in all treatments tapered off after about 60 days as the experiment entered a period of lower PAR (November). The ratio of total cumulative growth for each treatment indicated that *Ulva* mud and marsh channel sediments supported 33 and 26 percent higher growth, respectively, than growth in natural eelgrass substrata.

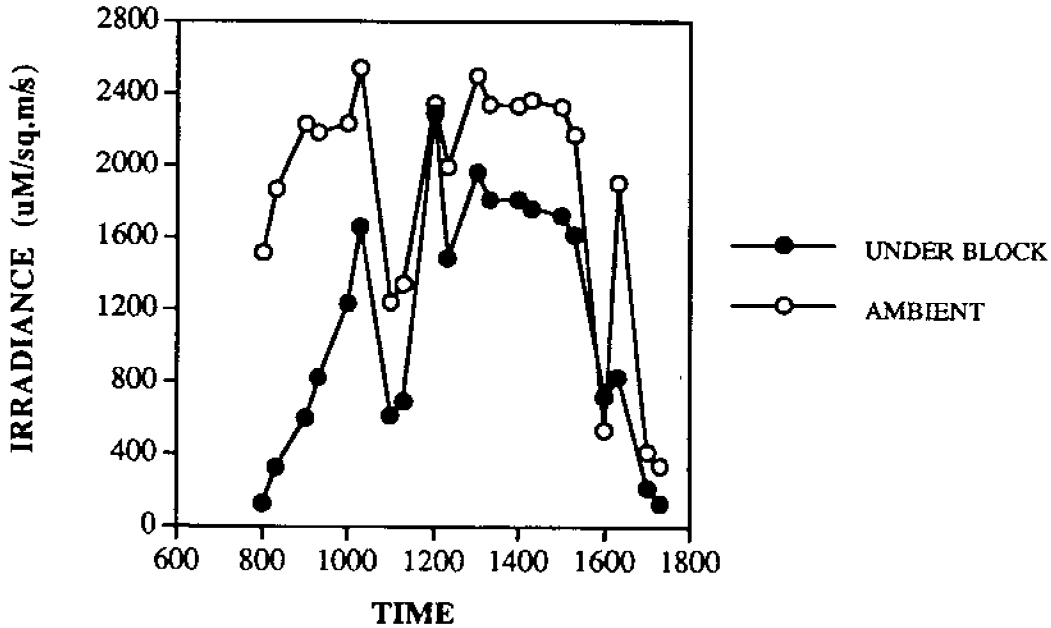


Figure 35. Irradiance passing through transparent blocks.

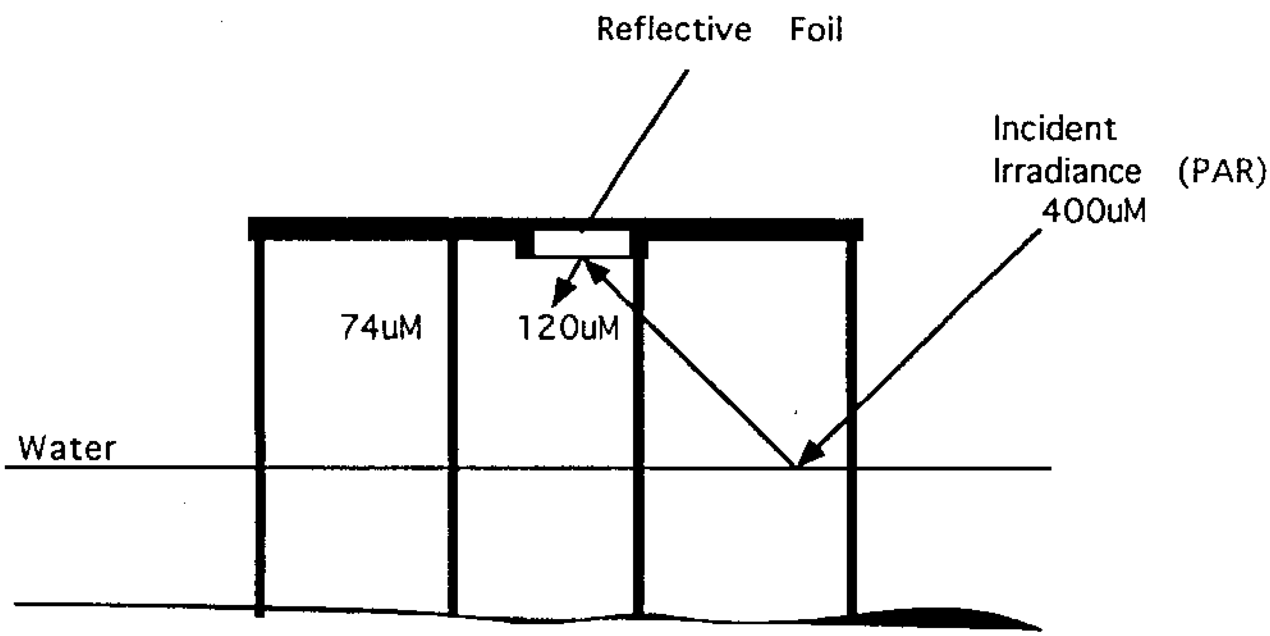


Figure 36. Examples of irradiance measured under dock at PNL/MSL in areas under aluminum foil and wood.

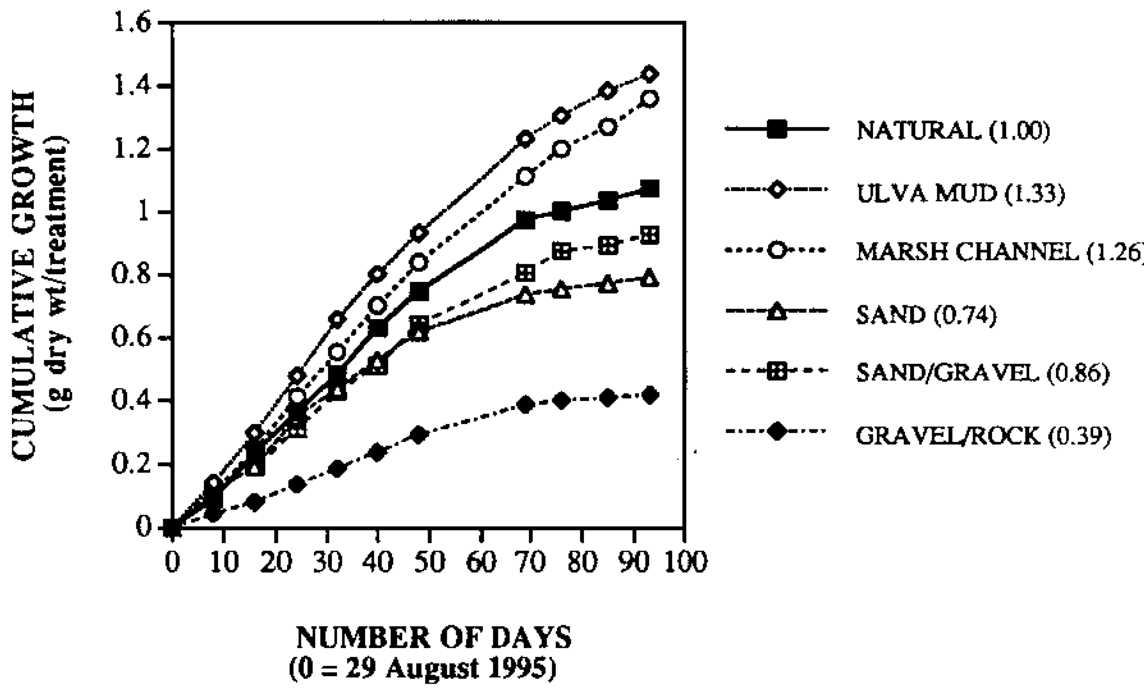


Figure 37. Growth of eelgrass in various substrata types; numbers in parentheses indicate ratio of treatment to growth in natural eelgrass substrata.

**Evaluation of Transplantation Using Seeds**

*Viability Test*

Approximately 338 seeds were extracted from the 14 generative shoots. Viability is detected because either the hypocotyl is stained red or the radicle stained either red or brown (Taylor 1955; Conacher *et al.* 1994). Seeds that were viable were usually dark blue in color before staining was visible. Seventeen of the 20 seeds tested on 17 November 1995 were viable (Table 5). Although the number of viable seeds varied with treatment, this difference was not significant (at alpha = 0.05).

On 25 June 1996, nine months after being placed in storage, eight seeds of the 86 were stained red, indicating that they were potentially viable. All eight viable seeds had been stored 5 ° C in the dark but in different salinity treatments.

*Germination Test*

Nine of the 58 seeds planted in the sediment treatments sprouted (Table 6). Sprouting was first observed on 16 December 1995 with emergence of the cotyledon (Churchill 1992), and sprouts continued to emerge until the termination of the experiment (2 February 1996), when some had two foliage leaves. Five seeds sprouted in the sand/silt sediments, while four sprouted in sand environments, and this rate of germination for the different environments was not significantly different (alpha = 0.05). However, more seeds pre-treated in 27 ‰ salinity sprouted (n=6) than those pre-treated in 35 ‰ salinity (n=3), and this difference was significant (at alpha = 0.05).

On 15 May, eight months after storage began, nine of the seeds in the 27 ‰ salinity vial stored at 5° C had sprouted. None of the other seeds in any other treatment had sprouted (Table 7). After the seeds were immersed in 12‰ salinity aerated sea water in the dark, five more seeds from the 27 ‰, 5° C treatment and two seeds from the 35 ‰, RT germinated.

## DISCUSSION

Glass-centered blocks and reflective aluminum foil potentially could improve light conditions significantly under terminal decks. The blocks would increase light enough to significantly enhance photosynthesis under terminals if the blocks cover a substantial portion of the deck surface. Our tests indicated that a single block, of which about 50 percent of the surface is glass, lets through about 60 percent of ambient light throughout the day. Increasing light under terminals by 60 percent would greatly improve light conditions and predictably support eelgrass growth, especially during periods that may be critical to the survival of the plant (i.e., summer to autumn). It is unclear whether reflective material would increase albedo enough to significantly affect photosynthesis under the terminal. However, increased albedo may be important in improving conditions for fish passage, which is believed to be inhibited by overwater structures. This point needs to be investigated.

Eelgrass grew in a wide variety of sediment types, from fine sands and mud through cobble. Nutrient availability is often cited as a major factor affecting eelgrass growth (e.g., Dennison *et al.* 1987, Short 1983, 1987, Williams and Ruckleshaus 1993). The fact that eelgrass can assimilate inorganic nutrients through roots and leaves (Short and McRoy

Table 5. Seed Viability Tests. (RT=Room temperature).

| Date | Treatment | Total seeds tested | Total # seeds viable | percent viable |
|---|---|---|---|---|
| 17 Nov 95 | 35 °/oo; 5 ° | 5 | 3 | 60 |
| | 27 °/oo; 5 ° | 5 | 5 | 100 |
| | 35 °/oo; 5 ° | 5 | 5 | 100 |
| | 27 °/oo; 5 ° | 5 | 4 | 80 |
| 25 June 96 | 27 °/oo; 5 ° | 22 | 2 | .9 |
| | 35 °/oo; 5 ° | 23 | 6 | 26 |
| | 27 °/oo; RT | 22 | 0 | 0 |
| | 35 °/oo; RT | 19 | 0 | 0 |

Table 6. Results of salinity pre-treatment and subsequent planting in two different sediment environments (1a/2a = 27 ‰ salinity pre-treatment; 1b/2b = 35 ‰ salinity pre-treatment).

| Treatment | Sediment | # Sprouted |
|---|---|---|
| 1a (n=15) | sand | 1 |
| 2a (n=14) | sand/silt | 5 |
| 1b (n=14) | sand | 3 |
| 2b (n=15) | sand/silt | 0 |

Table 7. Number of seeds germinating from treatments after storage for seven months.

| Treatment | Total # of seeds in vial | # sprouts on 15 May | # seeds extracted from vial | # germinated seeds after 8 days |
|---|---|---|---|---|
| 35 °/oo; 5 ° | 36 | 0 | 3 | 0 |
| 27 °/oo; 5 ° | 23 | 9 | 14 | 13 |
| 35 °/oo; RT | 36 | 0 | 2 | 2 |
| 27 °/oo; RT | 28 | 0 | 5 | 0 |

1984) may explain why the plants were able to grow for at least three months even in substrata with essentially no nutrients. It appeared that the plants grew best in organically enriched fine sediments like those from which the plants were collected. Surprisingly, cumulative growth was somewhat less in eelgrass meadow sediments than in unvegetated sediments from an intertidal mudflat and marsh channel. We cannot be sure, but nutrients may have been reduced in the eelgrass meadow sediments simply because ambient nutrients are depleted by the growing eelgrass. The data suggest that eelgrass can be planted in a wide range of sediment types as long as sufficient nutrients are available and physical disturbances such as waves and currents (or propeller wash) does not dislodge the plants.

Our results on the use of seeds for transplanting suggest that, although seeds may be potential contributors to eelgrass restoration and mitigation planning, further research is needed before a protocol can be recommended. First, an appropriate collection time should be established. From 14 generative shoots, we captured approximately 338 seeds or 24 seeds per shoot. An individual generative shoot has the potential to produce 200 seeds (Churchill *et al.* 1978); therefore, the 14 shoots harvested could have potentially yielded 2800 seeds. However, seeds can be released at different times during the flowing cycle. In the Puget Sound, seeds are released from mid-August to October (Phillips 1972; 1984) and, it is quite possible that seeds were released prior to our harvest in September.

Young and Young (1986) argued that continued observations over time are necessary to accurately predict the appropriate time to collect seeds from wild plants. This may be especially true with eelgrass in the Puget Sound. Recent studies have suggested that low numbers of generative shoots or variability in their production may be common. In one study, investigators noted low numbers for two years at two sites in relatively close proximity (Wyllie-Echeverria *et al.* 1995), while at another location observations documented year to year changes in flowering frequency (Roni and Weitkamp 1996). In addition we found no generative shoots at the Clinton site, which suggests that seeds may not be present at particular restoration sites. Flowering frequency observations, coupled with repeated harvesting at several sites, are necessary before the appropriate collection times or locations can be postulated.

Second, our results confirm earlier work by Phillips (1972) that documented the viability of Puget Sound eelgrass seed. In the earlier test (17 November 1995), although the number of seeds (n= 20) was small, 85 percent of these were viable. In the later test in June of 1996, the number of viable seeds was not high (Table 4), but viable seeds were present. Because there is a strong correlation between seeds that test positive in viability studies in the Genus *Zostera* (Conacher *et al.*, 1994), we suggest that viable seeds from this later batch could have grown into seedlings.

On balance, seeds stored at 5 °C exhibited higher rates of viability over time than those stored at room temperature (Table 4). The June 1996 test showed that although the number of viable seeds was small for seeds stored at 5° C, it was significantly greater than those stored at room temperature. These results are in keeping with Conacher *et al.* 1994. Results from this study demonstrated that seeds of *Zostera capricorni* stored at colder temperatures were more viable over time. Our preliminary results indicate that it may be possible to keep Puget Sound eelgrass seed over one winter in cold storage. Repeated tests are necessary, however, before appropriate storage temperatures can be determined.

Third, although seawater salinity does appear to affect germination, it did not appear to affect storage in this study. In the germination experiments, seeds that were pre-treated in lower salinity before planting had significantly higher rates of germination. In addition, and in keeping with earlier studies (Phillips 1972; Churchill 1992), seeds immersed in lower salinities, regardless of storage treatment, germinated. It is also curious to note that nine seeds sprouted in cold storage batch kept in the lower salinity treatment, and this did not occur in other treatments. Because eelgrass seed is known to sprout in storage (A.C. Churchill pers. com), this result is difficult to interpret. Conacher *et al.* 1994 did not factor salinity differences into their experimental design, and their storage experiments were concluded within 50 days. Churchill (1992) reported that seeds stored in salinities ranging from 25 to 30 ‰ (at 5° C) "retained a high viability" for 9 to 10 months. Neither of these experiments evaluated the effects of different salinity environments relative to viable storage procedures. Because lowered salinity has such a profound effect on germination, it would seem this information is necessary.

Finally, our results demonstrate that the use of eelgrass seed may have potential as a contributor in re-planting or restoration planning in the Puget Sound region. Viable seed is produced, and these seeds can grow into plants. Harper (1977) remarked that " a plant is the means by which a seed makes more seeds." In the case of Puget Sound eelgrass, this axiom appears to be true. If appropriate protocols can be developed for seed collection and storage, seeds can be folded into transplant and restoration designs or seedlings can be reared in culture systems. In fact, we are continuing our experiment by culturing seedlings sprouted from seeds collected; however, this work is still in progress.

If seeds can be used in transplant and restoration projects, the process may have direct relevance to both the science and economics of seagrass management in this region. Currently, restoration and transplant projects require whole plants harvested from "donor" sites. This practice is costly in terms of both plant collection and monitoring. This project, which resulted in the capture of at least 49 viable seeds (Tables 4-6), demonstrated the promise of seed collection. Because each viable seed can potentially become a plant, we can theorize that 49 plants could have potentially been contributed to the transplant effort. The cost of this portion of our seed transplant study was approximately $2000 or about $41 per plant. However, there is no requirement to monitor a donor site, which would reduce overall project costs. Additionally, the loss of eelgrass cover from a donor site, which may have an impact on habitat functions at this site, was prevented. Although it could be argued that resources for seed predators (e.g., Wigand and Churchill 1988) or generative shoot contribution to the detrital food chain (e.g., Harrison 1989) were extracted from the system, we submit that the impact is minimal.

Before mitigation or restoration projects can seriously evaluate "seeding" (either as seed or cultured seedlings) relative to other techniques (e.g. Whole Plant Bare Root Units or Whole Plant Rhizocore [Plug] Units), more research is required to articulate collection and storage protocols. For example, if a transplant or restoration effort was 1 hectare (2.47 acres) in size and plants were spaced on 1.0-m centers, 10,000 planting units (PU) would be needed (Fonseca *et al.* in prep). Given our results and if each planting unit was composed of one plant (3 to 5 plants are more common), approximately 115,000 seeds would need to be collected. Again, if the percentage of seeds to generative shoots was similar to our study, approximately 4800 generative shoots would be harvested, thrashed, and the seeds stored. Future studies may indicate that this level of effort may be economically efficient and scientifically sound.

# SUMMARY AND PERSPECTIVES ON FUTURE MITIGATION STRATEGIES AND RESEARCH

by

Ronald M. Thom
Marine Science Laboratories
Battelle Pacific Northwest Laboratories
1529 West Sequim Bay Road
Sequim, Washington 98382

Charles A. Simenstad
Wetland Ecosystem Team
School of Fisheries
Box 357980
University of Washington
Seattle, Washington 98195-7980

Annette M. Olson
School for Marine Affairs
Box 355685
University of Washington
Seattle, Washington 98195-5685

Sandy Wyllie-Escheverria
School for Marine Affairs
Box 355685
University of Washington
Seattle, Washington 98195-5685

Jeffery R. Cordell
Wetland Ecosystem Team
School of Fisheries
Box 357980
University of Washington
Seattle, Washington 98195-7980

and

James Norris
School of Fisheries
Box 357980
University of Washington
Seattle, Washington 98195-7980

## INTRODUCTION

The research has shown that ferry terminals and boat operations have impacts on eelgrass meadows ranging from immediate and long-term loss of eelgrass meadows to enhanced populations of an important fishery resource (i.e., Dungeness crab). Although light reduction from overwater structures is often cited as the most prevalent factor resulting in eelgrass losses, we found that disturbances from construction, maintenance operations, propeller wash, shading and bioturbation were probably active in either the elimination of eelgrass or the retardation of its recruitment into formerly disturbed areas. Our field measurements and experiments provided some intermediate indication of methods and actions that may mitigate these impacts. In addition, we developed valuable information that can help evaluate the impacts of future terminal development, including the following:

- a shade model for predicting the shadow cast by new terminal structures
- an estimate of the amount of PAR required to sustain eelgrass growth in Puget Sound
- evidence regarding the lower depth limits for eelgrass
- an understanding of the range of substrata types that may support eelgrass transplants
- data on passive methods for avoiding and minimizing impacts
- evaluation of the use of eelgrass seeds for establishing meadows.

The cumulative information from our study should help improve terminal design and ferry operations in order to truly minimize damage to eelgrass meadows and, ultimately reduce the cost of terminal expansion projects. We strongly feel that our findings may have wider application to other regions where seagrasses are affected by boat operations, as well as to other types of overwater structures.

In the next section we illustrate the application of some of the information developed during the study toward mitigating the effects of expansion of the Clinton Ferry Terminal, Whidbey Island, Washington. In the final section, we provide some recommendations for further research that may lead to improvements in ferry terminal design and boat operations to more fully avoid and minimize damage to eelgrass meadows and other marine resources in Puget Sound.

## MITIGATION STRATEGIES APPLIED TO THE CLINTON FERRY TERMINAL EXPANSION PROJECT

The Clinton terminal expansion project provides an example of impacts and potential mitigation measures. The Clinton project will involve replacement of the existing timber pile structure with a concrete pile structure, and expansion of the holding area to accommodate increased ferry traffic (Figure 38). The dock will be widened by approximately 19 m and lengthened by approximately 44 m. A new south slip, steel wing walls, floating dolphins, towers, and headframe will also be constructed.

Our studies and observations at all three terminals showed that eelgrass is impacted by both historical (not presently active) and current processes. The disturbance processes and appropriate mitigation alternatives are shown in the conceptual model presented in Figure 38. In the model, disturbance to the habitat is partitioned into two phases: (1) construction and (2) maintenance and operation.

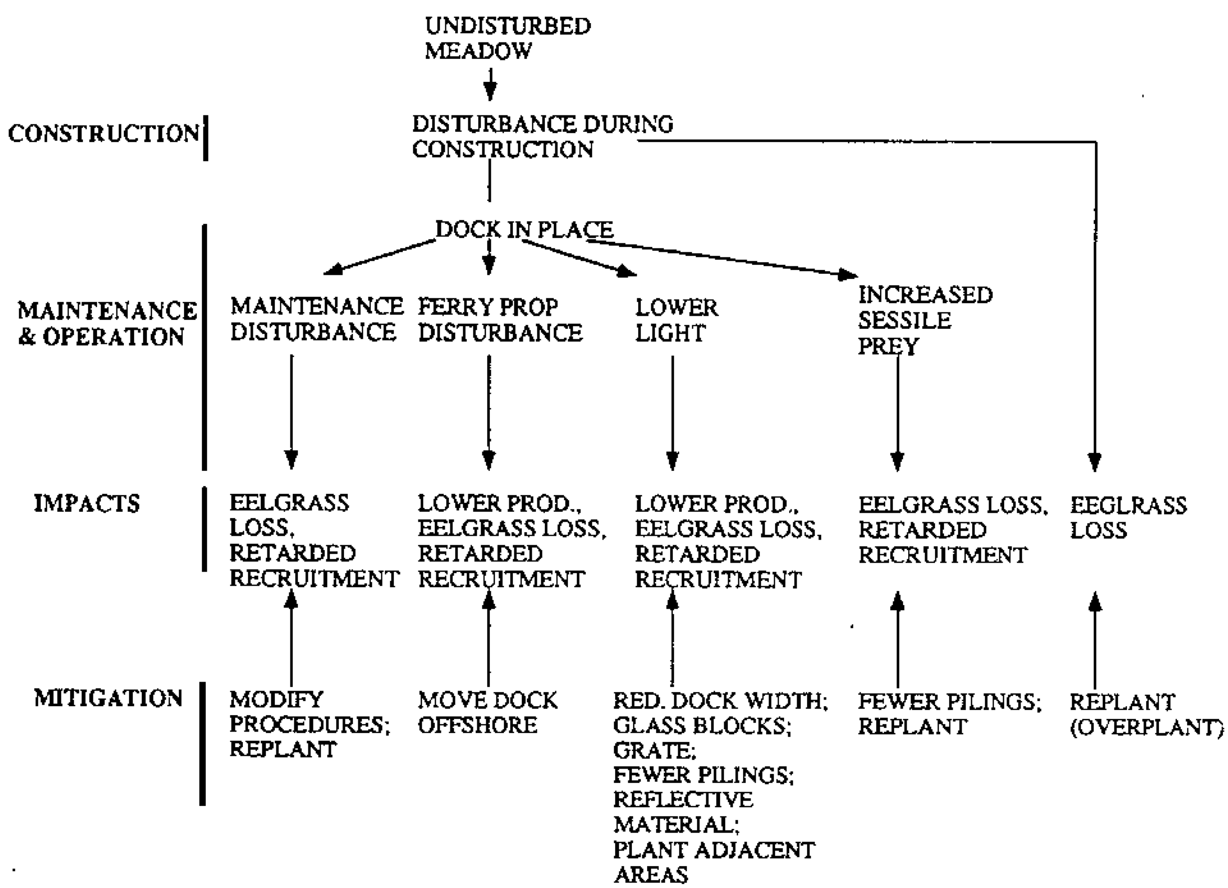


Figure 38. The conceptual model of dock effects and potential mitigation measures.

Terminal expansion will have short-term, direct effects and longer-term impacts on eelgrass. Initial construction activities are predicted to have some limited effect on eelgrass, although these activities will be largely conducted away from existing beds. The new terminal deck will cover $320m^2$ of eelgrass presently located on the south side of the terminal. The proposed mitigation measures are directed at eliminating any longer-term effects.

Impacts expected under the original design plan for the terminal can be either avoided or minimized (Figure 38). For example, ferry propeller wash impacts can be avoided by moving the slips further offshore. Light impacts can be minimized by incorporating light transmitting structures (concrete blocks with glass centers) in the terminal deck and by lengthening the terminal. Lengthening the terminal will reduce the width of the terminal where it crosses the eelgrass habitat. In addition, highly reflective paint (i.e., the type used for painting white lines on roads) can be used under the terminal to enhance the albedo. Use of quartz halogen lights (or some equivalent) would improve light conditions and support eelgrass growth under the terminals. However, energy and maintenance requirements would be great. More passive methods for increasing light, such as plastic material in decks and reflective material under the dock, are recommended.

Maintenance activities can be reduced dramatically through the use of concrete piles and decking as opposed to timber. Use of concrete pilings will result in the placement of 1/3 fewer pilings than presently exist. This will reduce the amount of space for piling communities to develop and may support fewer seastars and Dungeness crab. This may result in less bioturbation effects on eelgrass. Fewer pilings will predictably also allow more light to penetrate under the terminal.

We believe that, with appropriate modifications in the terminal expansion, eelgrass can be restored in many of the areas where eelgrass has been eliminated by past or ongoing disturbances. These areas are identified by letters A through H in Figure 25. The probability of success varies among the areas. For example, areas A, B, C, D, E, F and G are considered areas where disturbances can be essentially eliminated, and eelgrass transplants have a moderate to high probability of being successfully established. Other areas are less likely to succeed because of their experimental nature (e.g., area H under glass blocks). On the basis of the substrata assay experiments conducted, it appears that the substrata observed in these areas is suitable for the growth of transplanted eelgrass.

## RESEARCH RECOMMENDATIONS

A variety of topics surfaced during our study that either require more investigation to develop or may be fruitful in producing information of direct use to WSDOT. The research areas are provided below with some discussion of their benefits.

### Shade Model Development

The shade model was adapted from architectural applications and needs further development to make it more easy to apply to future projects.

### Eelgrass Habitat Quality for Fisheries Resources

This and current WDFW research suggests shading from sunlight is one mechanism of indirect degradation, but altered disturbance regimes from increased sediment resuspension, etc. may also be important. Although these alterations may reduce eelgrass habitat value for estuarine and marine fishes such as migrating juvenile salmon, the distrubtion and magnitude of any impacts, as well as the existence of mitigating conditions that would point to alternative design features to reduce or eliminate impacts, are still unknown. Quantitative assessment of resident prey (i.e., epibenthic and epiphytic invertebrates) presents one unambiguous measure of fish rearing potential that could be utilized to evaluate shoreline structure effects on eelgrass communities.

Studies should be conducted to define the responses of prey communities to both local and regional variations and to contrast different characteristics of over-water structures; differences should also be evaluated between native (*Zostera marina*) and exotic (*Z. japonica*) species of eelgrass. Specific ferry terminal and other dock sites should be systematically sampled for epibenthic/epiphytic invertebrates, with specific focus on known fish prey taxa, and the results should be compared to the results of comparable sampling in adjacent reference or "control" sites unaffected by shoreline structures.

The results of such studies and analyses would both expand upon past and existing WSDOT and WDFW research on the effects of shoreline structures on eelgrass communities by evaluating the consequences of indirect habitat degradation on fish use and survival. If found necessary at all, the resulting recommendations for the design and placement of shoreline structures to minimize or eliminate impacts to eelgrass communities and fish resources would likely result both in reduced fisheries resource losses and in considerable savings to WSDOT by facilitating environmental permit approval.

**Fish Passage Under Terminals**

In preliminary studies (not reported here), we found that juvenile coho salmon (*Oncorhynchus kisutch*) vastly preferred dark areas to light, suggesting that fish movement between darkened areas and lighter areas may be inhibited, which may result in increased predation pressure on small salmon. Further research is needed to investigate more species and more conditions, as well as whether this is an issue at ferry terminals, and if so, how to avoid the problem. This research should include experimental evaluation of the actual light level that stimulates the fish to move out of the dark, field studies on fish movement and behavior and experimental investigations on how to cost-effectively remove the barriers to movement.

**Improved Light Conditions Under Terminals**

Passive technologies exist for improving light conditions under terminals. For example, fiber optical cables and light tubes (i.e., tubes with mirrored interior walls) may potentially be incorporated into terminal decks to pass ambient light under the terminals. Experiments to demonstrate the feasibility of these and other methods are recommended.

**Use of Drift Wrack and Seeds as Donor Stock**

Very limited experiments indicated that seeds and drift wrack (i.e., floating mats of eelgrass) may be viable sources of transplant material. Further work is needed to fully evaluate these methods.

**Barriers to Propeller Wash**

We proposed extending the Clinton Terminal as a method of removing the impact of propeller wash on eelgrass. However, in many situations this may be cost-prohibitive or unfeasible for safety reasons. In these situations, floating or anchored structures that dissipate propeller wash energies may be recommended. However, these methods need to be investigated to avoid problems such as scouring or further concentrating current speeds around the sides and under the barriers.

## ACKNOWLEDGMENTS

We sincerely thank the Washington State Department of Transportation (WSDOT) for its support of this research; in particular, we gratefully acknowledge Jim Schafer, Art Lemke, Mark Nelson, Ted Bell, Mark Morin, and Stan Stumbo for their dedicated interest and commitment to these studies, and the terminal mangers for their help in the logistics of studies at the terminals. We are equally indepted to many individuals who assisted and contributed significantly to the success of our research. Lou Schwartz and Ian Fraser mastered and crewed the *Brendan II* while conducting the eelgrass videography surveys. Bruce Higgins and Liam Antrim, Battelle Marine Sciences Laboratory, provided their critical SCUBA diving skills in conducting eelgrass sampling and other near-dock environment measurements underwater. Amy Borde, Chris Alliman, and Kevin Jorgensen, also of the Battelle Marine Sciences Laboratory, and Eric Doyle, School of Marine Affairs-University of Washington, were exceedingly helpful during our field and laboratory studies. Tom Wilson, at the Washington State Department of Transportation, assisted us in obtaining what CAD information was available for the dock, shoreline, and other spatial features in the three study areas. The personnel at the Washington State Transportation Center provided considerable assistance in administering the grant, particularly Bev Green, Ron Porter, and Don Metcalf; and Amy O'Brien provided invaluable editing assistance in preparing our reports.

## REFERENCES

Addy, C.E. 1947. Germination of eelgrass seed. *J. Wildl. Manag.* **11**:279.

Baldwin, J.R. And J.R. Lovvorn. 1994. Expansion of seagrass habitat by the exotic *Zostera japonica*, and its use by dabbling ducks and brandt in Boundary Bay, British Columbia. *Mar. Ecol Prog. Ser.* **103**:119-127.

Batiuk, R.A., R.J. Orth, K.A. Moore, W.C. Dennison, J.C. Stevenson, L.W. Staver, V. Carter, N.B. Rybicki, R.E. Hickman, S. Kollar, S. Bieber, and P. Heasly. 1992. Chesapeake Bay submerged aquatic vegetation habitat requirements and restoration targets: a technical synthesis. Chesapeake Bay Program, Annapolis, Md. CBP/TRS 82/92.

Bulthuis, D.A. 1994. Light environments/implications for management. Pages 23-27 *in* S. Wyllie-Echeverria, A.M. Olson, and M.J. Hershman (eds.). Seagrass science and policy in the Pacific Northwest: proceedings of a seminar series. (SMA 94-1) EPA 910/R-94-004.

Burdick, D.M. And F.T. Short. 1995. The effects of boat docks on eelgrass beds in Massachusetts coastal waters. Report submitted to Waquoit Bay National Estuarine Research Reserve, Waquiot, Mass., and Massachusetts Coastal Zone Management, Boston, Mass. Department of Natural Resources and Jackson Estuarine Laboratory, Durham, N.H.

Camp, D.K., S.P. Cobb and J.F. Van Breedveld. 1973. Overgrazing of seagrasses by a regular urchin, *Lytechinus variegatus*. *Bioscience* **23**:37-38.

Churchill, A.C., A.E. Cok and M.I. Riner. 1978. Stabilization of subtidal sediments by the transplantation of the seagrass *Zostera marina* L. New York Sea Grant Series. NYSSGP-RS-78-15. 48pp.

Churchill, A.C. 1992. Growth characteristics of *Zostera marina* seedlings under anaerobic conditions. *Aquat. Bot.* **43**:379-392.

Conacher, I.R., Poiner, J. Butler, S. Pun, and D.J. Tree. 1994. Storage and viability testing of sees of *Zostera capricorni* Aschers. From a tropical bay in Australia. *Aquat. Bot.* **49**:47-58.

Courtemanch, D.L., S.P. Davies, and E.B. Laverty. 1989. Incorporation of biological information in water quality planning. *Environ. Mgmt.* **13**:35-41.

DeCock, A.W.A.M. 1980. Flowering, pollination and fruiting in *Zostera marina* L. *Aquat. Bot.* **9**:201-220.

Dennison, W.C. 1987. Effects of light on seagrass photosynthesis, growth and depth distribution. *Aquat. Bot.* **27**:15-26.

Dennsion, W.C., R.C. Aller and R.S. Alberte. 1987. Sediment ammonium availability and eelgrass (*Zostera marina*) growth. *Mar. Biol.* **94**:469-477.

Dennison, W.C., R.J. Orth, K.A. Moore, J.C. Stevenson, V. Carter, S. Kollar, P.W. Bergstrom, and R.A. Batiuk. 1993. Assessing water quality with submersed aquatic vegetation. *BioScience* **43**:86-94.

Dixon, L.K., and J.R. Leverone. 1995. Light requirements of *Thalassia testudinum* in Tampa Bay, Fla. Final report submitted to Surface Water Improvement and Management Program, Southwest Florida Water Management District. Mote Marine Laboratory Technical Report #425.

Dumbauld, B.R., D.A. Armstrong and T.L. McDonald. 1993. Use of oyster shell to enhance intertidal habitat and mitigate loss of Dungeness crab (*Cancer magister*) caused by dredging. *Can. J. Fish. Aquat. Sci.* **50**:381-390.

Ehringer, J.N. 1993. Results of analysis of prop scar damage at the Fort Desoto aquatic habitat management area 1992/1993. Unpublished report. Hillsborough Community College, Tampa, Fla.

Fonseca, M.S., J.S. Fisher, J.C. Zieman and G.W. Thayer. 1982. Influence of the seagrass, *Zostera marina* L., on current flow. *Est. Coastal Shelf Sci.* **15**:351-364.

Fonseca, M.S., J.C. Zieman, G.W. Thayer and J.S. Fisher. 1983. The role of current velocity in structuring eelgrass (*Zostera marina* L.) meadows. *Est. Coastal Shelf Sci.* **17**:367-380.

Fonseca, M.S., W.J. Kenworthy, and G.W. Thayer. (in prep). Guidelines for mitigation and restoration of seagrass in the United States and adjacent waters. Natl. Ocean. Atmospheric Admin., Natl. Mar. Fish. Serv.

Fonseca, M.S. and J.S. Fisher. 1986. A comparison of canopy friction and sediment movement between four species of seagrass with reference to their ecology and restoration. *Mar. Ecol. Prog. Ser.* **29**:15-22.

Fresh, K.L. 1994. Seagrass management in Washington State. Pages 38-41 *in* S. Wyllie-Echeverria, A.M. Olson, and M.J. Hershman (eds.). Seagrass science and policy in the Pacific Northwest: proceedings of a seminar series. Rep. EPA 910/R-94-004, US Environ. Prot. Agency, Region 10, Seattle, Wash.

Fresh, K.L., B. Williams, and D. Penttila. 1995. Overwater structures and impacts on eelgrass (*Zostera marina*) in Puget Sound, Wash. Puget Sound Research '95: Proceedings **2**:537-543.

Granger, S., S. Nixon, M. Traber, and R. Keyes. 1996. The application of horticulture techniques in the propagation of eelgrass (*Zostera marina* L.) from seed. Pg. 377 *in* Kuo, J., R.C. Phillips, D.I. Walker, and H. Kirkman (eds.), Seagrass Biology: Proc. Intl. Workshop. 385pp.

Harper, J.L. 1977. Population biology of plants. Academic Press. London. 892pp.

Heinsohn, G.E., J. Wake, H. Marsh and A.V. Spain. 1977. The Dugong (*Dugong dugong* (Müller)) in the seagrass system. *Aquaculture* **12**:235-248.

Loflin, R.K. 1993. The effects of docks on seagrass beds in the Charlotte Harbor estuary. Unpublished report. City of Sanibel, Sanibel, Fla.

Kentula, M.E. And C.D. McIntire. 1986. The autecology and production dynamics of eelgrass (*Zostera marina* L.) in Netarts Bay, Ore. *Estuaries* **9**:188-199.

Kraemer, G.P. And R.S. Alberte. 1993. Age-related patterns of metabolism and biomass in subterranean tissues of *Zostera marina* (eelgrass). *Mar. Ecol Prog. Ser.* **95**:193-203.

Morris, L.J., and D.A. Tomasko (eds.). 1993. Proceedings and conclusions of workshops on: submerged aquatic vegetation initiative and photosynthetically active radiation. St. Johns River Water Management District, Palatka, Fla. Special Publication SJ93-SP13.

Nomme, K.M., and P.G. Harrison. 1991a. A multivariate comparison of the seagrasses *Zostera marina* and *Zostera japonica* on the Pacific coast of Canada. *Can. J. Bot.* **69**:1984-1990.

Nomme, K.M., and P.G. Harrison. 1991b. Evidence for interaction between the seagrasses *Zostera marina* and *Zostera japonica* on the Pacific coast of Canada. *Can. J. Bot.* **69**:2004-2010.

Olesen, B. And K. Sand-Jensen. 1993. Seasonal acclimation of eelgrass *Zostera marina* to light. *Mar. Ecol. Prog. Ser.* **94**:91-99.

Olson, A.M. And E.G. Doyle. 1995. Light requirements of eelgrass, a literature survey. Draft Interim Report. School of Marine Affairs, University of Washington, Seattle, Wash.

Olson, A.M., S. Visconty, and C. Sweeney. 1996. A new approach to modeling the shade cast by overwater structures. (abstract) Pac. Est. Res. Soc., 19th Annual Meet., Wash. Dept. Ecol., Olympia, Wash.

Onuf, C.P. 1994. Seagrasses, dredging and light in Laguna Madre, Tex., U.S.A. *Est. Coastal Shelf Sci.* **39**:75-91.

Orth, R.J. 1975. Destruction of eelgrass, *Zostera marina*, by the cownose ray, *Rhinoptera bonasus*, in the Chesapeake Bay. *Chesapeake Sci.* **16**:205-208.

Orth, R.J., M. Luckenbach and K.A. Moore. 1994. Seed dispersal in a marine macrophyte: implications for colonization and restoration. *Ecology* **75**:1927-1939.

Pawlak, B.T. And A.M. Olson. 1995. Policies and management practices of Washington State agencies as they pertain to the seagrasses *Zostera marina* and *Zostera japonica*: an ecological analysis. Proc. Puget Sound Research '95 **2**:516-522.

Pentilla, D. And D. Doty. 1990. Results of 1989 eelgrass shading studies in Puget Sound. Unpublished draft report, Wash. Department of Fisheries, Olympia, Wash.

Phillips, R.C. 1972. Ecological life history of *Zostera marina* L. (eelgrass) in Puget Sound, Wash., Ph.D. dissertation. Univ. of Washington. 154pp.

Phillips, R.C. 19984. The ecology of eelgrass meadows in the Pacific Northwest: A community profile. U.S. Fish Wildl. Serv. FWS/OBS-84/24.

Roni, P. And L.A. Weitkamp. 1996. Environmental monitoring of the Manchester Naval Fuel Pier replacement, Puget Sound, Wash., 1991-1994. Coastal Zone and Estuarine Studies Division, NOAA, NMFS, Seattle, Wash. 40pp+append.

Short, F.T. 1983. The seagrass, *Zostera marina* L.: plant morphology and bed structure in relation to sediment ammonium in Izembek Lagoon, Alaska. *Aquat. Bot.* **16**:149-161.

Short, F.T. 1987. Effects of sediment nutrients on seagrasses: literature review and mesocosm experiment. *Aquat. Bot.* **27**:41-57.

Short, F.T. And C.P. McRoy. 1984. Nitrogen uptake by leaves and roots of the seagrass *Zostera marina* L. *Botanica Marina* **17**:547-555.

Shreffler, D.K. And J. Schafer. 1996. Mitigation plan for impacts to subtidal vegetation associated with reconstruction and expansion of the ferry terminal at Clinton, Whidbey Island, Wash. (PNL10844), Wash. Department of Transportation, Olympia, Wash.

Simenstad, C.A. 1994. Faunal associations and ecological interactions in seagrass communities of the Pacific Northwest coast. Pages 11-18 *in* S. Wyllie-Echeverria, A.M. Olson, and M.J. Hershman (eds.). Seagrass science and policy in the Pacific Northwest: proceedings of a seminar series. Rep. EPA 910/R-94-004, US Environ. Prot. Agency, Region 10, Seattle, Wash.

Talbot, M.M.B., W.T. Knoop and G.C. Bate. 1990. The dynamics of estuarine macrophytes in relation to flood/siltation cycles. *Botanica Marina* **33**:159-164.

Taylor, A.R.A. 1955. A developmental study of *Zostera marina* L. Ph.D. dissertation, University of Toronto. 200pp.

Thom, R.M. 1990. A review of eelgrass (*Zostera marina* L.) transplanting projects in the Pacific Northwest. *Northwest Environ. J.* **6**:121-137.

Walker, D.I., R.J. Lukatelich, G. Bastyan and A.J. McComb. 1989. Effect of boat moorings on seagrass beds near Pert, Western Australia. *Aquat. Bot.* **36**:69-77.

Williams, S.L. 1988. *Thalassia testudinum* productivity and grazing by green turtles in a highly disturbed seagrass bed. *Mar. Biol.* **98**:447-455.

Williams, S.L. And M.H. Ruckleshaus. 1993. Effects of nitrogen availability and herbivory on eelgrass (*Zostera marina*) and epiphytes. *Ecology* **74**:904-918.

Witherspoon, B. And R. Rawlings. 1994. Shoreline access design guidelines for Washington marine shoreline habitats. Wash. State Department of Natural Resources, Aquatic Research Division, Olympia, Wash.

Worcester, S.E. 1995. Effects of eelgrass beds on advection and turbulent mixing in low current and low shoot density environments. *Mar. Ecol. Prog. Ser.* **126**:223-232.

Wyllie-Echeverria, S., A.M. Olson, and M.J. Hershman (eds.). 1994. Seagrass science and policy in the Pacific Northwest: proceedings of a seminar series. Rep. EPA 910/R-94-004, US Environ. Prot. Agency, Region 10, Seattle, Wash.

Wyllie-Echeverria, S., J.R. Cordell, J. Haddad, L.M. Tear, and M.J. Hershman. 1995. Biological monitoring of vegetation characteristics and epibenthic organisms from transplanted and reference eelgrass patches at LaConner, Skagit County, Wash. Rep. 95-3, School Mar. Affairs, University of Washington, Seattle, Wash. 22pp+appendices.

Wyllie-Echeverria, S. And T. Turner. 1996. Eelgrass (*Zostera marina*) restoration plan for Picnic Cove, Shaw Island, Wash. Unpubl. Rep. Submitted to Wash. Department of Fish. Wildl., April 1996. 13pp.

Young, J.A. And C.G. Young. 1986. Collecting, processing and germinating seeds of wildland plants. Timber Press, Portland, Ore. 236pp.

Zimmerman, R.C., A. Cabello-Pasini and R.S. Alberte. 1994. Modeling daily production of aquatic macrophytes from irradiance measurements; a comparative analysis. *Mar. Ecol. Prog. Ser.* **114**:185-196.

Zimmerman, R. C., J. L. Reguzzoni, S. Wyllie-Echeverria, M. Josselyn, and R. S. Alberte. 1991. Assessment of environmental stability for growth in *Zostera marina* L. (eelgrass) in San Francisco Bay. *Aquat. Botany* **39**: 353-366.

Zimmerman, R.C., R. Smith, and R. Alberte. 1989. Thermal acclimation and whole-plant carbon balance in *Zostera marina* L. (eelgrass). *J. Exp. Mar. Biol. Ecol.* **130**:93-109.