UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
P.O. Box 21668
Juneau, Alaska 99802-1668

December 4, 2002

Mr. Dale Kanen
District Ranger
Tongass National Forest
Craig Ranger District
P.O. Box 500
Craig, Alaska 99921

ATTN: Mr. Chad Van Ormer

RE: Baker Island Trail Environmental Assessment (EA)
Scoping Comments

Dear Mr. Kanen:

Thank you for the opportunity to provide scoping comments for the referenced project. The Tongass National Forest, Craig Ranger District (Forest Service), is proposing to construct a trail from south Port San Antonio to Little Veta Bay on Baker Island. The project would include construction of a recreation cabin and placement of a dock for public use in south Port San Antonio. We have reviewed the scoping information packet and offer the following comments.

We were provided with photographs of south Port San Antonio by Alaska Department of Fish and Game personnel (Mr. Mark Minillo) that show an extensive eelgrass bed (*Zostera marina*) in the area proposed for the public dock. Eelgrass is considered a special aquatic site under the Clean Water Act 404 (b)(1) guidelines. According to these guidelines, special aquatic sites are "generally recognized as significantly influencing or positively contributing to the overall health or vitality of the entire ecosystem or region." Eelgrass provides nesting, spawning, nursery, cover and forage habitats for numerous species of fish and invertebrates, contributes to primary and secondary productivity of marine food chains, and protects shorelines from erosion and wave action (Fonseca et al., 1998).

In Alaska, eelgrass provides Essential Fish Habitat (EFH), as defined by the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA), for a number of commercially important species, including rockfish, Pacific cod and salmon (Murphy et al., 2000; Byerly, pers. comm., 2000). A pink salmon spawning stream, cataloged by the Alaska Department of Fish and Game (USGS Quad Craig, C-5, #104-30-10550), is located at the head of south Port San Antonio, in the area of the proposed dock. Adult and juvenile pink salmon will therefore be present in the eelgrass bed when spawning and outmigrating in the summer/fall and spring, respectively. Several other valuable Alaskan species may be present in this eelgrass bed, including Dungeness crab and herring, which use eelgrass for spawning, sheltering, feeding and rearing of young (Phillips, 1984; Stevens and Armstrong,1984).

Construction of the proposed dock would introduce both direct and indirect adverse impacts within the eelgrass bed in south Port San Antonio. Direct displacement of eelgrass habitat would result from placement of piles. Indirect impacts would include shading from the dock structure, sedimentation from boat prop wash, and introduction of hydrocarbons from boat engines. Hydrocarbons have shown to be extremely toxic to early life history stages of salmon and herring (Marty et al., 1997; Carls et al., 1997).

The EA should include a map showing the extent of the eelgrass bed in south Port San Antonio and the exact location of the proposed dock. Alternatives to placing the dock in the eelgrass bed to completely avoid impacts should be considered and analyzed. Alternative designs of the dock and its placement within the eelgrass bed should also be considered and analyzed to minimize adverse impacts. We have enclosed several documents that address placement of docks in eelgrass beds to minimize impacts. During informal discussions with scientists from the Battelle Marine Science Laboratory, we were informed that models are available to customize dock designs to minimize light impacts. We encourage the Forest Service to investigate these options. Finally, if a dock is placed in the eelgrass bed, a monitoring program should be used to assess long-term impacts of the dock, with corrective action, if necessary.

To meet EFH requirements of the MSFCMA, the EA should include an EFH Assessment. EFH is present in south Port San Antonio for all five species of Pacific salmon and the following species of groundfish: flathead sole, rock sole, sablefish, and walleye pollock. The EFH Assessment should be labeled as a section of the EA and include : 1) a description of the action; 2) an analysis of the potential adverse effects of the action on EFH and the managed species; 3) the Forest Services' conclusions regarding the effects of the action on EFH and 4) proposed mitigation, if applicable.

Within 30 days of receiving the EFH Assessment, NMFS will develop EFH conservation recommendations for the project which if implemented will reduce adverse effects on EFH from the project. Upon receipt of the EFH Conservation Recommendations, the MSFCMA requires the Forest Service to respond to NMFS within 30 days informing us of the agency's decision to implement these recommendations.

Sincerely,

Donald J. Berg

For James W. Balsiger
Administrator, Alaska Region

cc: Mark Minnillo, ADF&G, Klawock
Mark Jen, EPA, Anchorage
ADEC, AADGC, ADNR, USFWS, Juneau
Jon Kurland, NMFS

Enclosures:

"The Effects of Boat Docks on Eelgrass Beds in Coastal Waters of Massachusetts" by D.M. Burdick and F.T. Short.

"Evaluation of Mehods to Increase Light Under Large Overwater Structures: Improving Salmon Habitat Functions" by S. Sargeant, Battelle, with attached reference list.

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EVALUATION OF METHODS TO INCREASE LIGHT UNDER LARGE OVERWATER STRUCTURES : IMPROVING SALMON HABITAT FUNCTIONS

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OVERVIEW

Potential adverse impacts to juvenile salmon populations in the Pacific Northwest include shading from overwater structures. Shading may result in a variety of ecological consequences including:


Juvenile chum salmon

- loss of submerged aquatic vegetation (e.g., *Zostera marina*)
- alteration of habitat used by juvenile salmon
- potential loss of salmon prey resources, and
- potential interruption of fish migratory patterns (Penttila and Doty, 1990; Simenstad et al. 1999)


Harpacticoid copepod, part of the juvenile salmon food web

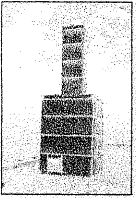
Light influences the rate of photosynthesis, plant distribution, and survival of eelgrass and algae that support prey resource composition and production. Any structure that interferes with the availability of light is likely to decrease the production of critical plant material essential to the juvenile salmonid food web.

Although researchers assume a direct correlation between juvenile salmon behavior (i.e., resting, movement, feeding) and light intensity, many data gaps exist. For example, juvenile salmon in Puget Sound have been observed to alter their behavior upon encountering docks (Simenstad et al. 1999), but light intensities that cause the altered behavior are unquantified. Potential adverse effects include migration delay and increased predation.

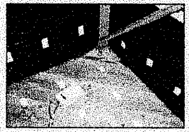

Construction at a Washington ferry terminal

Proposed mitigations for construction or alteration of large overwater structures have included incorporating means for light penetration through the structure to sustain eelgrass, promote fish passage, and minimize predation. The amount of light (hours and intensity) reaching the water and substrate below varies tremendously based on the dock height, width, orientation, and water clarity, as well as transmission of light through or from lighting technologies.

PROJECT OBJECTIVES and METHODS


Light-proof structure with solar tube installed

Controlled experiments were conducted inside a light-proof structure to evaluate the effectiveness of off-the-shelf technologies to emit or propagate light. The frame was constructed of fiberglass rigid plastic (FRP), two-by-fours, and plywood, then wrapped in two layers of black Visqueen (polyethylene) to block all light.

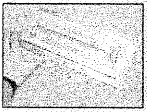

Inside the lightproof structure

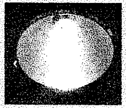
Products tested in the controlled environment included a solar tube, deck prisms, and a metal halide greenhouse light. The deck prisms and solar tube were field-tested at a dock in Port Townsend, Washington. Field measurements of light intensity were also recorded at the Clinton ferry terminal on Whidbey Island, Washington under glass blocks and metal grating. Light measurements were recorded using LI-COR LI-193SA spherical quantum sensors and a LI-COR LI-1400 Datalogger programmed to record photosynthetically active radiation (PAR), defined as the wavelengths between 400 and 700 nm associated with plant photosynthesis.

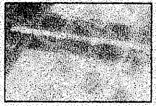
Using a site-specific attenuation coefficient and light level at the water surface, the amount of light reaching a particular depth in the water column was calculated using an equation from Kirk (1994).

$$\ln E_d(z) - \ln E_d(0) = -K_d z$$

where E_d = downward irradiance in μmol/m²/s , z = depth in meters, 0 = depth at the water surface, and K_d = the light attenuation coefficient


Deck prism


Metal halide greenhouse light



Glass blocks (above) installed as part of a pedestrian walkway at Clinton ferry terminal (right)



Temporary metal grating as seen from above (top) and from below (right). Note the sun/shade pattern on the water.

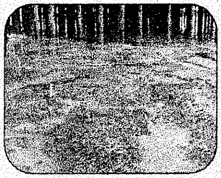
RESULTS & DISCUSSION

Light levels measured from these technologies were compared to known light requirements for eelgrass and to light levels associated with certain juvenile salmon behaviors. Utilizing eelgrass light requirements obtained from the literature, it was possible to estimate the number of light products needed to cover a particular area based on dock height and water quality at a particular site. In general, the products predicted to provide the most to the least light at substrate depth were grating → solar tube → glass blocks → metal halide greenhouse light → and prisms, although the order of effectiveness changed somewhat depending on site-specific conditions. A review of the literature indicated that strategically placed reflective material (e.g., reflective paint or Mylar) can also increase light underneath overwater structures. There are costs and benefits associated with each product tested, so all factors should be weighed before installation.

Costs & Benefits Associated with Light Products

Light Product	Costs	Benefits
Deck Prism	Less efficient at passing light	Inexpensive; may be able to be placed in deck surface aesthetically pleasing
Glass Blocks	Potential safety and strength issues	Pass a good amount of light; aesthetically pleasing
Grating	Expensive; potential safety and strength issues	Passes lots of light; little maintenance required
Greenhouse Light	Maintenance cost of electricity (unless solar powered); electrical safety	Constant, bright light source, even when dark outside
Reflective Material	Temporary (Mylar lasts 2-5 yrs; paint probably longer)	Provides a small amount of supplemental lighting
Solar Tube	Condensation/fixation may be problematic	Tubes extend easily through dock thickness; relatively bright light can be directed at an angle

Light requirements to sustain eelgrass growth are relatively high. *Z. marina* requires a minimum of 10 to 20 percent of ambient light levels (Duarte 1991, Dennison *et al.* 1993) or daytime light levels above 300 μmol/m²/s (Thom and Shreffler 1996) to saturate photosynthesis. Approximately 3.0 mol/m²/d are required in spring-summer for the plants to flourish through the winter (Thom, 1994 unpublished data). To optimize eelgrass success, products that transmit the greatest amount of light under the site-specific conditions should be concentrated in areas where the underlying substrate is suitable for eelgrass growth. Even then, it may be difficult to transmit enough light to support eelgrass growth under a large structure.


Low tide; Zostera marina (eelgrass) monitoring plot at Clinton ferry terminal

Kelp and macroalgae provide habitat for other fish and invertebrate species and require less light than eelgrass. The upper and mid-sublittoral macroalgae species generally require only 150-250 μmol/m²/s for saturation, and kelp species require even less (Lüning 1981).

Light levels required for juvenile salmon feeding are lower yet, around 1-2 μmol/m²/s (Ali1959). Thus, providing even a small amount of light in a regular pattern under a dock may encourage fish to swim underneath.

Placing light products to stimulate growth of eelgrass, macroalgae, and kelp and to promote the movement of small salmon would likely result in a nearshore lighting corridor, parallel to shore. The effective width of the corridor would be inversely related to the steepness of the slope offshore.

SUMMARY RECOMMENDATIONS

- Place light technologies where suitable eelgrass substrate exists and along the intertidal/subtidal contours where plants have the greatest chance for survival.
- Consider reflective material as a supplement to any other lighting product.
- Orient grating (if it is not square) so that the long axis runs north-to-south. Thin grating with wide spaces allows the most light to reach the water surface.
- Limit layering of light products (i.e., glass ceiling over glass block walkway) as it decreases effectiveness.
- Dissipate dark shadows and reduce the light-dark contrast along structure edges to promote juvenile salmon movement under overwater structures.
- Install light-enhancing products to increase light levels during relatively low light periods (i.e., early morning, late evening).
- Remember that fewer products are necessary to enhance growth/survival of kelp and macroalgae or to promote juvenile salmon movement under overwater structures for feeding or migration than to support eelgrass survival.

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More results can be found in the report:

Blanton, S., R. Thom, A. Borde, H. Diefenderfer, and J. Southard. 2002. Evaluation of Methods to Increase Light Under Ferry Terminals. Prepared for the Washington State Department of Transportation, Olympia, Washington, WA-RD 525.1, by Battelle, Pacific Northwest Division of Battelle Memorial Institute.

SPECIAL THANKS goes to the Washington State Department of Transportation and to the Northwest Maritime Center, Port Townsend, Washington for support of this research.

The Effects of Boat Docks on Eelgrass Beds in Coastal Waters of Massachusetts

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ABSTRACT / The effects of docks on eelgrass beds were measured using plant population characteristics (shoot density, canopy height, and growth rates), light levels, and an assessment of eelgrass bed quality in Massachusetts estuaries. Eelgrass populations were impacted under and directly adjacent to docks, as shown by depressed shoot density and canopy structure. Severe impacts can cause fragmentation of eelgrass beds, thus contributing to large-scale declines in estuaries such as Waquoit Bay. Impacts were fewer under docks supported by piers than under floating docks, and taller piers resulted in fewer impacts. Based on this investigation, we conclude that docks should be greater than 3 m in height above the bottom in areas with tidal ranges less than 1 m to allow enough light to sustain eelgrass beds under the docks. In addition to dock height, orientation and width were also found to be important factors affecting eelgrass. Narrow docks with a north–south orientation can best ensure the long-term survival of eelgrass under and near the dock.

Eelgrass is a submerged flowering plant that forms extensive underwater beds, providing a marine habitat of great ecological and economic value (Thayer and others 1984, Short and others 1993). Currently, the health of eelgrass habitats along the entire coastal United States is in decline. In larger estuaries, alarming reductions in the distribution of eelgrass have been studied intensively (Orth and Moore 1982, Short and others 1986, 1993, Dennison and others 1993) and have been primarily attributed to excess nutrient pollution (eutrophication) or wasting disease. However, there have been few investigations of the overall impact of commercial and recreational boating activities on eelgrass. This impact includes the effects of docks, moorings, and boating itself. Although they occur at smaller scales than disease or pollution effects, marine boating activities may have significant impacts and should be assessed (Thayer and others 1975) so that these effects may be minimized through management and education. Walker and others (1989) reported losses of seagrasses from boat moorings in Cockburn Sound, Australia. They found that although the direct damage to seagrass beds was small relative to the entire area of the beds (1.6% of the seagrass bed area was damaged), the physical integrity of the remaining habitat was compromised, leaving it more susceptible to other types of damage.

KEY WORDS. Docks, Shade, Eelgrass beds; *Zostera marina*; Seagrass

We investigated the direct impacts of docks on eelgrass, focusing on two Massachusetts estuaries: Waquoit Bay, Falmouth, and Nantucket Harbor, Nantucket (Figure 1). The goals of the study were twofold. The first was to measure the direct physical effects of docks and piers on individual beds, including direct displacement of eelgrass and reduction of available light. We examined dimensions and structural characteristics of docks running through or adjacent to eelgrass beds, physical characteristics of the sites (water depth and light penetration), and eelgrass population characteristics (shoot density, canopy height, and growth rate) to interpret the shading effects of docks. Using the field data, we modeled eelgrass bed quality and light availability to establish a scientific basis for minimizing impacts to seagrasses through improved dock design.

The second goal of the project was to assess the overall area of beds that have been lost on a bay-wide scale through displacement and shading by docks in Waquoit Bay. Waquoit Bay is an intensively studied estuary, being both a National Estuarine Research Reserve and a National Science Foundation Land Margin Ecosystem Research site, surrounded by residential development on the south shore of Cape Cod. Using an eelgrass distribution map of Waquoit Bay based on 1987 aerial photography (Short and others 1993), an estimate of the estuary-wide impact of docks on the distribution and area of eelgrass habitats was produced.

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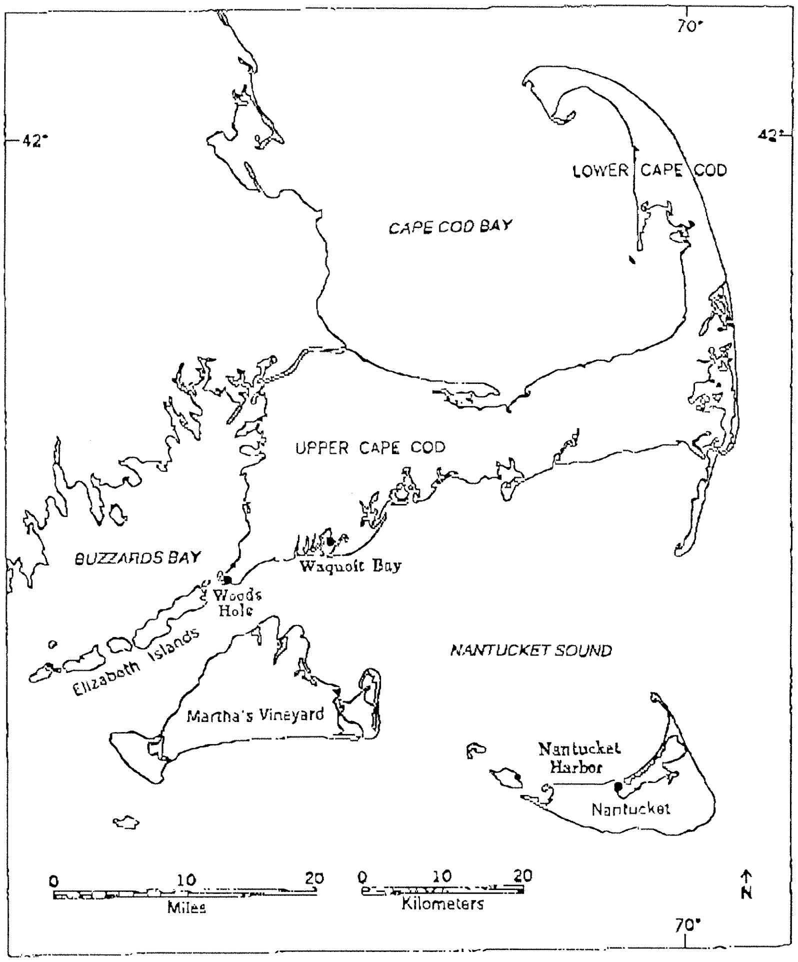

Figure 1. Map of southeastern Massachusetts, showing the two main study areas: Waquoit Bay and Nantucket Harbor, as well as Woods Hole. Ninigret Pond in Rhode Island is not shown. (Map modified from US Department of the Interior/Geological Survey 1976.)

Materials and Methods

Study Sites

The sampling design included investigation of several types of docks and tides that ranged from 0.3 to 0.9 m (mean tidal range). We included both seasonal and permanent docks, and docks with structural extremes (wide and narrow decks various heights above the water, floating and fixed on piers). Our study, limited to estuaries where substantial eelgrass beds currently coexist with docks, was conducted primarily in Nantucket Harbor and Waquoit Bay, Massachusetts (Figure 1). In addition, one dock was examined in Woods Hole Harbor, Massachusetts, and one was examined in Ninigret Pond, Rhode Island.

Dock Descriptions and Measurements

In the estuaries studied, boat docks are used as permanent walkways from shorelines to relatively deep water where boats are kept. Docks are usually wooden, with their walkways supported by piers: whole or milled posts driven into the marine sediments. Vessels are often tied onto floating portions of docks that rise and fall with the tides. Dock orientation is usually shore normal, with the long axis perpendicular to the shoreline. Most of the docks we examined were privately owned and maintained for seasonal recreational use.

Using rulers and tape measures, dock length, width, and thickness (from the top of the walkway deck to the base of the beams that connect the horizontal deck with the vertical piers), dock height above water, height above marine bottom, and dock length along eelgrass beds were measured. Dock orientation was taken with a compass while standing on the dock, facing seaward parallel to the long axis of the dock. Whether the dock was permanent or seasonal, and whether it was elevated on fixed piers or floating were noted. Age of the structure was estimated or obtained through local inquiries.

Collection of Biological and Light Data

Sampling was performed in August, at the time of maximum eelgrass standing stock, or biomass (Short

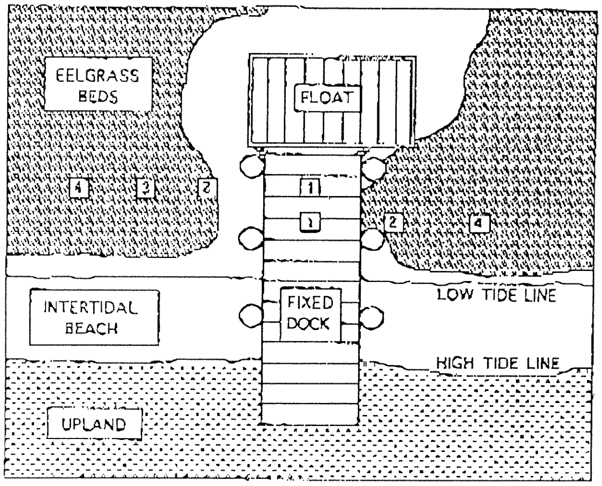

Figure 2. Typical dock showing fixed and floating portions in relation to associated eelgrass beds and stations along two transects from the fixed dock. Stations are coded: 1 = UNDER, 2 = ADJACENT, 3 = MID, 4 = FAR.

and others 1993), but before insolation was significantly reduced. Transects were established at each dock (Figure 2); each transect included one station under the dock (UNDER = 1) and extended perpendicular to the long axis of the dock to a station away from possible dock impacts (FAR = 4). For each transect, up to two other stations were sampled: if there was no eelgrass under the dock, a station was sampled in the first eelgrass bed encountered (ADJACENT = 2), or if there was eelgrass under the dock, the ADJACENT station was located within 2 m of the dock. Sometimes another station (MID = 3) was located between the ADJACENT station and the FAR station of the transect. Eelgrass beds were characterized by shoot density, canopy height (height of 80% of the blades from the bottom), and growth using methods developed in previous studies (Short 1987, Fonseca 1990), as well as by canopy structure, the product of canopy height and shoot density. The portions of the eelgrass beds found directly under the docks were rated to characterize eelgrass bed quality. Eelgrass beds under docks were assigned a number (0–9) representing bed quality when compared to nearby eelgrass beds removed from dock effects. The ratings were: 0 for no eelgrass under the dock, 5 if eelgrass under the dock was half of that found in surrounding beds, 9 if not visibly different from the surrounding beds, interpolating to the nearest whole number for intermediate conditions.

Light was measured with a spherical quantum sensor (Li-Cor 4π; Li-Cor, Inc. Lincoln, Nebraska 68504, USA) that was held 24 cm from the bottom at all transect stations, namely UNDER, ADJACENT, MID, and FAR. Light data was recorded on a Li-Cor LI-1000 data logger and is presented as a percentage of surface light using a comparison to simultaneous surface light measurements from a flat quantum sensor held above the water. Light values used for analyses are means of triplicate measurements.

Relative light levels under docks (measured between 10:00 and 16:00 h) declined from 10:30 h to 12:00 h, when the shadow fell most directly under the dock, increased until 15:00 h, and declined after 15:00 h due to low sun angle. To explain the variation in synoptic light levels under docks, the time of measurement was scaled to the nearest half hour, with 14:30 to 15:00 h the maxima (0) and 11:30 to 12:00 h the minima (−3), producing a variable with an approximately linear response to light. A third-order polynomial curve fit to the percentage of light under docks supported the scaling procedure ($P < 0.0001$).

At four docks in Waquoit Bay, eelgrass was marked with a pinhole just above the meristem to measure growth (Short 1987) using three to six stations per dock site (up to ten shoots at each station, as available). The stations were ADJACENT to docks, beyond the shade effects of the docks (FAR), and in between (MID). Plants were harvested seven days after marking; all surviving plants were collected (two to nine plants per station).

Statistical Analyses

In general, an alpha level of 0.05 was chosen for main and interactive effects in the models, for post hoc tests used to compare means (Fischer's protected *F* test), and for correlations. Residual plots using fitted Y values were examined for regression and ANOVA analyses to ensure assumptions of normality and variance homogeneity were met and to inspect the data for outliers. Descriptive equations for eelgrass bed quality and available light under docks were developed from multiple regressions using dock characteristics and time of sampling with StatView (Abacus Concepts 1992). To build and interpret the regression models, Pearson correlation coefficients were calculated for dock characteristics, eelgrass beds quality, and the average percentage of light under the docks.

Eelgrass population characteristics (shoot density, canopy height, and canopy structure) and growth were analyzed separately by station (UNDER, ADJACENT, MID, and FAR) using ANOVA (Super ANOVA, Abacus Concepts 1989). Data from nine sampling stations that were classified as ADJACENT or MID stations were omitted because the eelgrass appeared to be eliminated by stress not directly caused by docks (e.g., boat propellers). Shoot density was transformed with the natural

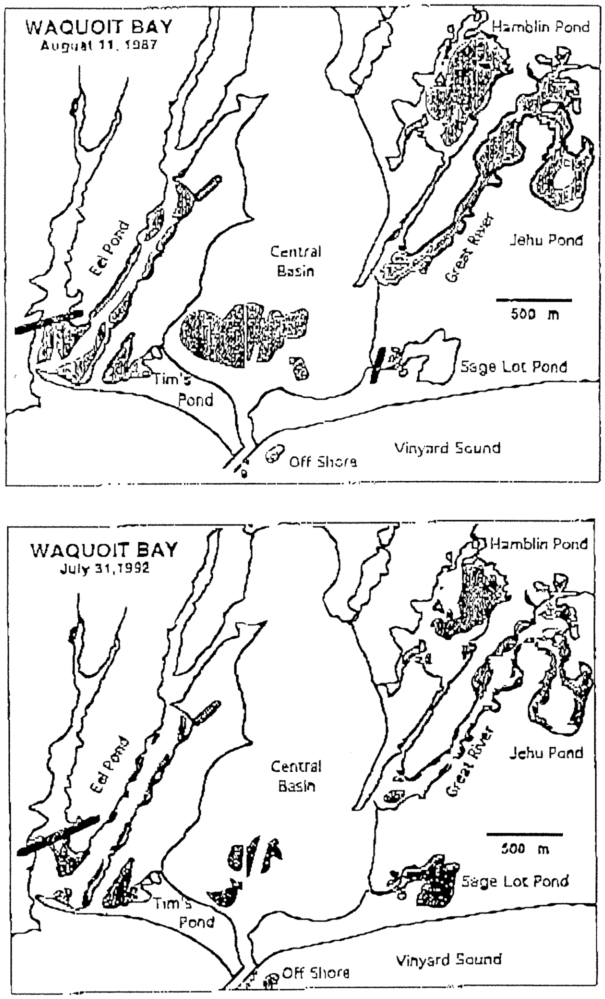

Figure 3. Waquoit Bay eelgrass distribution for 1987 and 1992, from Short and Burdick (1996).

logarithm to improve homogeneity of error variance and was analyzed using water depth as a covariate (ANCOVA). Similarly, canopy structure (transformed to its square root) was regressed on available light and stations were compared using ANCOVA.

Mapping and Methods for Estuary-Wide Assessment

Cumulative dock impacts in Waquoit Bay were assessed using eelgrass distribution maps that were developed from aerial photography of Waquoit Bay taken in 1987 and 1992 (Figure 3) (Short and Burdick 1996). Maps were coupled with extensive ground truthing of beds, especially around docks, in the summer of 1993. The maximum area of eelgrass beds that could be lost because the beds were directly under fixed and floating docks and boats tied to the docks was quantified. For the estuary-wide assessment, we were not able to distinguish the impacts of boat shading on eelgrass from impacts due to shading and direct displacement by docks. Thus, these effects are taken together in our assessment of estuary-wide dock impacts. The area of eelgrass impacted by docks was measured in four subbasins of the Waquoit Bay Estuary: Jehu Pond, Great River, Hamblins Pond, and Eel Pond (Figure 3).

Results

Dock Characteristics

Approximately 20 dock structures that were associated with eelgrass beds were examined (Table 1). Orientations of the docks included all quarters of the compass, with half having a northern aspect and half having a southern aspect. Nine were in an estuary with a mean tidal range of 0.92 m, and the remainder were in estuaries with smaller ranges (0.30 to 0.55 m). Most docks had a floating portion to which boats were tied. Four floating docks and one boat were examined for shading impacts, but the majority of sampling sites were fixed docks. Although most of the docks were 1–2 m wide, deck width varied considerably (0.7–6.9 m), as did the length (3.5–100 m), height above the marine bottom (0.77–3.40 m), and estimated dock age (2–20+ years).

Shading Impacts Under Docks

Bed quality. Although two thirds of the docks that were surrounded by eelgrass had no eelgrass directly under them (14 of 21), several docks had patches of eelgrass under them, and three were located over fairly well-developed eelgrass beds. A number for bed quality of the eelgrass under all docks was assigned (see Materials and Methods). Physical characteristics of the docks were compared to the bed quality using correlations (Table 2) and multiple regression (Table 5 below). When compared with fixed docks, floating docks were found to have severe impacts to eelgrass, and three of the four floats examined quantitatively had no rooted eelgrass under them (Table 1). For fixed docks, the regression model showed that the most important variables determining bed quality were height of the dock above the marine bottom, dock orientation, and width ($F = 12.1$, $P < 0.0006$, $R^2 = 0.75$, $N = 16$). Of these, height of the dock above the bottom was most important ($P < 0.0002$), with greater dock height positively related to bed quality (Table 5 below). Dock height was positively correlated with tidal range ($r = +0.63$; Table 2). Therefore, the effect of dock

Table 1. Characteristics of docks sampled in Nantucket Harbor, Waquoit Bay, and Woods Hole Harbor, Massachusetts, and Ninigret Pond, Rhode Island

			Dock								Deck height above bottom	Dock length along bed	
Estuary	Site	Tidal range (cm)	Width (m)	Length (m)	Thickness (cm)	Age (y)	Aspect of shore	Dock orientation (degrees)	Permanent/ seasonal (P/S)	Floating/ fixed (F/X)	(cm)	(m)	Bed quality (0–9)
Nantucket Hrbr	1	92	6.9	58	28	20	south	20	P	X	286	29	1
Nantucket Hrbr	2	92	1.35	21	34	16	south	0	P	X	221	8.7	7
Nantucket Hrbr	3	92	1.25	18.5	32	5	south	60	P	X	184	10	0
Nantucket Hrbr	4	92	1.8	18.5	35	5	south	60	P	X	128	8	0
Nantucket Hrbr	5	92	2.42	100	30	3	north	90	P	X	340	70	3
Nantucket Hrbr	6	92	4.8	3.6	71	3	north	90	S	F	157	3.6	1
Nantucket Hrbr	7	92	2.0	91.5	30	2	north	60	P	X	324	49	5
Nantucket Hrbr	8	92	1.8	93.3	35	20	north	60	P	X	288	70	9
Nantucket Hrbr	9	92	1.52	30	23	20	north	20	P	X	244	12	9
Ninigret Pond	10	30	0.76	5.0	50	5	north	30	S	F	119	37	0
Waquoit Bay	11	55	1.8	16.2	22	15	north	80	P	X	222	12	0
Waquoit Bay	12	55	1.45	13.6	33	5	north	85	P	X	218	3.6	0
Waquoit Bay	13	55	2.5	5.0	100	10	north	85	S	F	77	4	0
Waquoit Bay	14	55	0.73	7.9	16	8	north	70	P	X	134	4	0
Waquoit Bay	15	55	1.87	9.4	27	5	south	40	P	X	109	5.6	0
Waquoit Bay	16	55	3.5	4.8	50	5	south	40	S	F	82	4.8	0
Waquoit Bay	17	55	1.21	18.7	27	3	south	85	P	X	149	4.8	0
Waquoit Bay	18	55	1.22	10.6	23	18	south	40	P	X	128	6	0
Waquoit Bay	19	55	1.02	3.5	16	18	south	40	S	X	161	3.5	0
Waquoit Bay	20	55	1.83	3.7	34	18	south	40	S	F	142	1.8	2
Wood's Hole Hrbr	21	55	1.24	41.9	60	10	south	40	P	X	179	35	5
Minimum		30	0.7	3.5	16	2		0			77	1.8	0
Maximum		92	6.9	100	100	20		90			340	70	9

Table 2. Correlation matrix of dock characteristics

Variable	Tidal range	Width	Depth	Age	Aspect	Axis	Fixed/ floating	Deck base above bottom
A. Correlation of dock characteristics with eelgrass bed quality ($N = 21$)[a]								
Width	0.39							
Depth	−0.12	0.26						
Age	0.10	0.07	−0.26					
Aspect	0.02	0.05	−0.20	0.16				
Axis	−0.00	−0.01	0.24	−0.54	−0.49			
Fixed/Floating	−0.38	0.25	0.69	−0.17	−0.14	0.07		
Deck base height above bottom	0.63	0.20	−0.37	0.17	−0.34	−0.02	−0.52	
Bed quality	0.51	−0.09	−0.07	0.41	−0.22	−0.37	−0.26	0.59
B. Correlation of dock characteristics with percentage of available light under docks ($N = 17$)[b]								
Width	0.44							
Depth	−0.01	0.35						
Age	0.22	−0.03	−0.30					
Axis	−0.31	−0.03	0.33	−0.57				
Fixed/Floating	−0.12	0.42	0.70	−0.21		0.24		
Deck base height above bottom	0.73	0.13	−0.36	0.28		−0.19	−0.54	
% Light	0.48	−0.30	−0.28	0.43		−0.22	−0.56	0.55

[a] Correlations greater than 0.43 or less than −0.43 are significant at $\alpha = 0.05$ and are underlined.

[b] Correlations greater than 0.48 or less than −0.48 are significant at $\alpha = 0.05$ and are underlined.

height subsumes any potentially important effects of tidal range, and we found tidal range to be significantly correlated with bed quality ($r = +0.51$), all within the relatively small tidal ranges of the systems we examined.

Docks running east–west supported less eelgrass than those running north–south ($P < 0.0015$). Because the Sun's path is east to west, east–west-oriented docks shade any eelgrass directly under them all day, resulting in poorer bed quality than under north–south docks, which shade eelgrass for only part of the day (Table 5 below). Similarly, wider docks resulted in poorer bed quality ($P < 0.0053$). Dock height, width, and orientation were not correlated (Table 2), suggesting all these factors are important to eelgrass bed quality and survival.

Light. Light is considered the primary factor limiting eelgrass survival and distribution (Dennison and others 1993). Light and bed quality under the docks were positively correlated ($r = 0.59$, $P < 0.05$). Like bed quality, light levels under the docks were primarily controlled by dock height ($P < 0.0117$) as indicated by regression analysis ($F = 7.57$, $P < 0.0035$, $R^2 = 0.636$, $N = 17$). The higher the dock over the bottom, the more diffuse the shadow, resulting in greater light under the dock. As was true for eelgrass bed quality, variables strongly correlated with dock height (i.e., tidal range, dock type) may have important effects on the relative amount of light under docks (Table 2), but these effects were hidden by the effect of dock height. In addition to dock height, other important factors affecting light measurements under docks were dock width ($P < 0.0360$), and time of day ($P < 0.0198$). As dock width increased, less light could reach eelgrass growing under the dock.

Thus, both light and eelgrass bed quality under the docks were primarily dependent upon dock height. After the effects of dock height were accounted for, light levels were dependent upon dock width and time of day, whereas eelgrass bed quality, which reflects light levels reaching the canopy over weeks to months, was influenced by dock orientation and width.

Additional Dock Impacts

Both eelgrass shoot density and canopy height were affected by docks, but exhibited different patterns of response along the sampling transects. Shoot density was very low under docks (in most cases eelgrass was absent), and increased with distance from the dock (Figure 4A). Eelgrass canopy height was lowest adjacent to docks and increased away from docks. However, in the few instances where eelgrass was found under docks, canopy height was similar to beds unaffected by docks (Figure 4B).

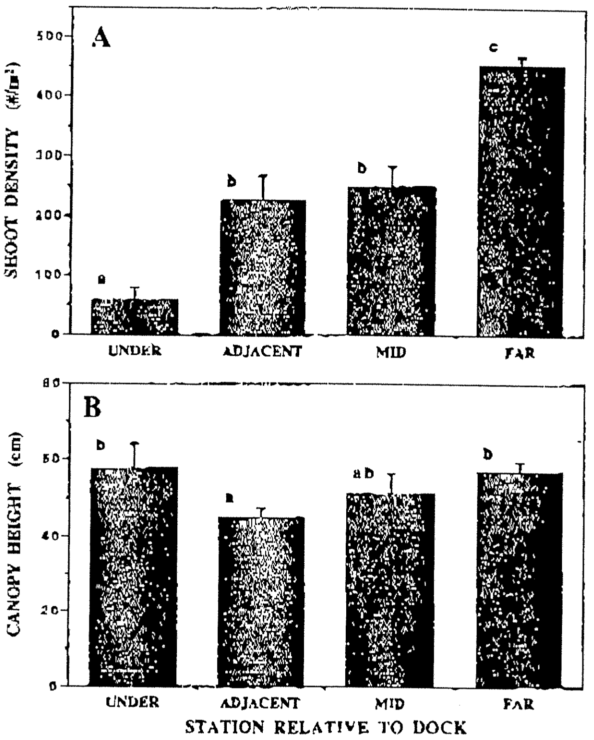

Figure 4. Eelgrass population characteristics of shoot density and canopy height in relation to distance from docks. Bars represent mean values ±SE of 13 to 47 replicates at 21 sites. Bars with the same letters are not significantly different using Fischer's protected F test for post hoc comparisons. (A) Shoot density; (B) canopy height.

Shoot density and canopy height may be combined into one variable (canopy structure) to describe the structure of the three-dimensional habitat created by eelgrass beds. The most important variable affecting canopy structure was relative light level, which results from a combination of dock variables such as height and width (Figure 5A). After variation due to light was accounted for, sampling station was the most important variable explaining differences in canopy structure. The effects of both light and station on canopy structure were highly significant ($P < 0.0001$), and resulted in a model with $R^2 = 0.572$. Station comparisons indicated the canopy structure was severely impacted in beds under and adjacent to docks (Figure 5B). The model of canopy structure as well as the short stature of eelgrass adjacent to docks (Figure 4B) suggests that not only shading under docks, but shading and/or disturbance from boat activities impacts eelgrass beds near docks. The strongest impact that we observed adjacent to docks was disturbance to the bottom sediments from prop dredging by boat propellers. Boat propellers can generate great turbulence that erodes the bottom

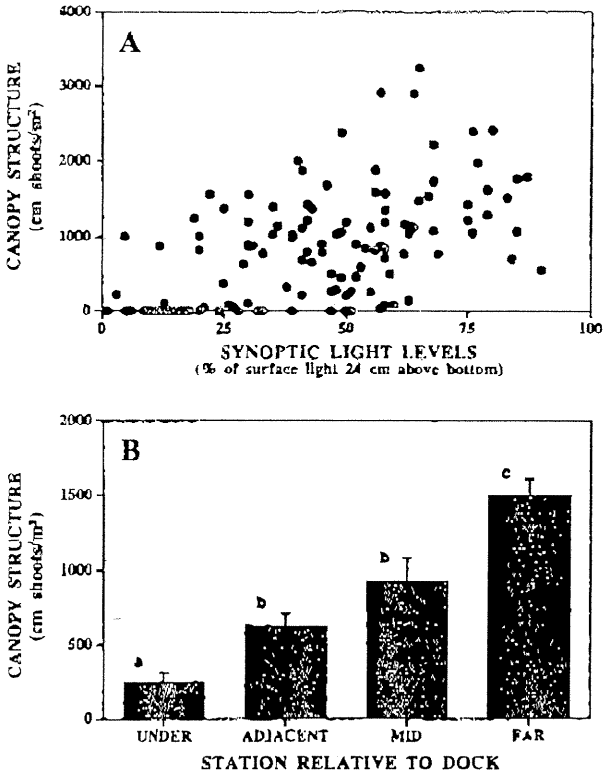

Figure 5. Eelgrass canopy structure as a function of light levels and distance from docks ($F = 35.7$; $P < 0.0001$; $R^2 = 0.52$. (A) Synoptic light levels and canopy structure; **(B)** canopy structure of eelgrass beds shown by station. Bars are the means ± SE of 13 to 47 replicates at 21 sites. Bars labeled with the same letters are not significantly different according to Fischer's protected *F* test.

sediments, including rooted eelgrass, when operated in the shallow water often found around docks.

In contrast to the strong patterns of eelgrass population characteristics in relation to docks, the data on leaf growth (growth per shoot, growth per square meter based on density measurements, and specific growth) showed no differences with respect to distance from the dock (Table 3). Growth measurements were performed in Waquoit Bay and included no stations directly under docks.

Estuary-Wide Impacts of Docks in Waquoit Bay

Using a map of eelgrass distribution for 1987, eelgrass beds were found close enough to the shoreline to be directly impacted by docks in three ponds (Jehu, Hamblins, and Eel) and in Great River (Figure 3). All docks in these four subbasins of Waquoit Bay were measured using vertical aerial photography obtained in 1992. A scaling coefficient to calculate dock area from the photography was developed from dock measurements in the field and on the photographs. The areas of the docks that would cover eelgrass beds based on the distribution of eelgrass in 1987 were summed (Table 4). Only about 360 m² of eelgrass beds were covered by docks out of a total coverage of 584,000 m² of eelgrass beds in these subbasins. In relative terms, docks covered less than 1% of the bed area in 1987. However, most of the docks were associated with boat scars that showed damage to eelgrass beds from boats approaching and leaving the docks.

Table 3. Growth of eelgrass by station on a per shoot basis, specific or relative growth, and growth on an areal basis[a]

Station	*N*	Shoot growth (cm/shoot/ day)	Relative growth (cm/cm/day)	Areal growth (g/m²/day)
UNDER	0	—	—	—
ADJACENT	7	2.95 ± 0.39	0.0199 ± 0.0014	1.98 ± 0.70
MID	3	2.64 ± 0.10	0.0198 ± 0.0022	1.33 ± 0.62
FAR	7	2.56 ± 0.19	0.0175 ± 0.0009	2.07 ± 0.60

[a] Values are means ± standard errors of *N* replicate groups of two to nine shoots per group at four sites (89 shoots total). No significant station effects were found.

Table 4. Direct dock impacts to eelgrass beds in Waquoit Bay, Massachusetts[a]

Subbasin	Eelgrass area (m²)	Dock area (m²)	Percentage of bed shaded
Jehu Pond	119,000	91	0.079
Great River	146,000	165	0.113
Hamblins Pond	174,000	11	0.006
Eel Pond	145,000	92	0.063
Total	581,000	362	0.062

[a] Area of eelgrass beds, area of docks that overlaps with eelgrass distribution, and percentage of bed area covered by docks in the Waquoit Bay Estuary. Eelgrass distribution is based on the 1987 map (Figure 3) and docks were measured from 1992 aerial photography.

Discussion

Impacts from Individual Docks

The height of the dock over the marine bottom was clearly the most important variable for predicting the relative light reaching the eelgrass and for predicting eelgrass bed quality under the docks. With increased dock height, the intensity of shading from a dock diminishes because sunlight has a greater distance to diffuse and refract around the dock surface before it reaches the eelgrass canopy. Similarly, light levels are greater under the centers of narrow docks than wide docks. The effect of dock orientation on eelgrass bed

Table 5. Dock heights needed to support eelgrass based on bed quality[a]

Eelgrass bed quality	Compass bearing of the dock long axis				
	0 (N)	30	60	90 (E)	120
9 (equal)	2.7	3.3	3.9	4.5	3.9
7	2.2	2.8	3.4	4.0	3.4
5 (1/2)	1.7	2.3	2.9	3.5	2.9
3	1.2	1.8	2.4	3.0	2.4
0 (none)	0.5	1.1	1.7	2.2	1.7

[a] Dock heights that are needed to support eelgrass as predicted by the model: eelgrass bed quality = 1.0 + 4.0 (dock height) − 0.081 (compass bearing) − 1.4 (dock width). Dock height and width are in meters; compass bearing is in degrees. Estimates are for a typical dock fixed on pilings that is 2 m wide. Underlined values are estimates within the range of observed data, others are extrapolations.

Table 6. Dock heights needed to support eelgrass based on available light[a]

Light under dock	Dock width (m)			
	0.75	1.0	1.5	3.0
50%	4.8	4.9	5.1	5.7
30%	2.9	3.0	3.2	3.8
20%	1.9	2.0	2.2	2.8
10%	0.9	1.0	1.2	1.8

[a] Dock heights and widths needed for eelgrass as predicted by the model: % light = 24.7 + 10.27 (dock height) − 6.97 (hour from 15:00) − 4.14 (dock width). Dock height is reported in meters from base of deck to the marine bottom. Available light is the percentage of surface light that reaches 24 cm above the bottom under docks at noon. Height estimates are for a typical dock fixed on pilings. Underlined values are estimates within the range of observed data; others are extrapolations. Light levels under 20% are not likely to support eelgrass; 30% light supported 50% of normal eelgrass production during summer in eelgrass mesocosms (Short and others 1995).

quality can also be explained in terms of light. If the dock is oriented north–south, its shadow falls directly under the dock for a few hours around solar noon; with an east-west orientation, the shadow falls under the dock the entire day. Thus, docks with a north–south orientation admit more light and can better support eelgrass.

The descriptive equations for eelgrass bed quality developed from the field data suggest that a typical fixed dock running north–south will support half the eelgrass of surrounding beds if it is 1.7 m above the bottom (Table 5). Our model indicates the same dock running east–west would have to be 1.8 m taller (Table 5). Since we sampled no docks greater than 3.4 m in height, estimates of impacts at greater heights are based on modeling alone and are speculative.

In order to connect these field results with previous investigations of the light effects on eelgrass within mesocosms (meso-scale model ecosystems) (Short and others 1995), descriptive equations developed from mesocosm data were used to predict the light levels needed to support eelgrass under docks of different heights and widths, regardless of orientation. For 20% of ambient light levels to reach the canopy under a 1-m-wide dock at noon, the dock must be 2.0 m above the bottom (Table 6). Several studies have suggested that the minimum light requirement to sustain eelgrass is in the range of 10%–20% surface light (Kenworthy and Haunert 1991, Dennison and others 1993, Short and others 1993). In our previous mesocosm studies, we found that any reduction of light impacted production, and in mesocosms with 10% of available light, no net growth was found over one growing season (Short and others 1993). A predictive equation for production in the mesocosms was developed: Production (g/m^2/day) $= -2.85 + 3.18 * \log(\%\ \text{light})$ with $r^2 = 0.856$. Using this equation, half of the eelgrass production relative to full light would be obtained at 30% light. Applying 30% light as a desirable minimum light level for support of eelgrass under docks, our model for light (Table 6) predicts a 1-m-wide dock must be 3.0 m above the bottom to achieve 50% production.

Mesocosm studies with eelgrass have also found important effects of eutrophication on plant production and success. The introduction of excess nutrients into mesocosms stimulated various forms and species of algae that outcompeted eelgrass for light and space, and thus severely reduced production and standing crop (Short and others 1993, 1995). Unfortunately, much of the Waquoit Bay Estuary is impacted by eutrophication (Valiela and others 1992); this problem is increasing, and it contributes to eelgrass loss (Short and Burdick 1996). The effects of docks on eelgrass beds are exacerbated by the reduced water clarity accompanying eutrophication. In addition, eelgrass beds in Waquoit Bay have some wasting disease, but the low level of disease activity here suggests wasting disease is not a primary agent reducing eelgrass distribution (Short and others 1993).

The results from eelgrass growth measurements, which showed no significant differences with respect to distance from the dock, are difficult to interpret. Eelgrass plants are composed of one or more shoots that propagate vegetatively by adding shoots as the rhizome grows. Plants growing adjacent to docks possibly curtail new shoot production rather than reduce the growth of any one shoot, with the result that growth of individual shoots is relatively stable across the station transects. This idea is supported by the changing relationship between canopy height and shoot density. Normally, eelgrass canopy height is negatively related to shoot density ($r = -0.52$, $N = 36$ for Waquoit Bay; data from Short and others 1993), but was positive for stations under and adjacent to docks ($P < 0.0001$). Further work should quantify shoot production and include measurements under docks to obtain a better picture of shading effects on growth.

Large-Scale Impacts

Docks and related structures (floats, ramps, and boats tied to docks) covered only 360 m^2, or 0.06%, of the eelgrass beds in subbasins of Waquoit Bay based on 1987 eelgrass distributions. The area of eelgrass impacted by these structures is potentially much greater than the areas directly under the docks because shading effects were important adjacent to docks and because beds associated with docks have been damaged by boats, as indicated by prop dredging effects and boat scars. Between 1987 and 1992, severe reductions in eelgrass bed area have occurred in Waquoit Bay (Figure 3), but these declines in eelgrass do not appear to be primarily caused by dock and boating activity. More likely, the declines are primarily caused by the effects of eutrophication, as described above. However, the effects of docks and boating activities do have a major role in the documented fragmentation of eelgrass beds in Waquoit Bay (Costa and others 1992, Short and Burdick 1996), and fragmentation may destabilize these valuable habitats.

A study of boat moorings in Western Australia showed that mooring chains and boats have severely impacted 1.6% of the seagrass area within the study sites (Walker and others 1989). As we found for Waquoit Bay, the impacted area was relatively small compared to the size of the seagrass beds, but Walker and others (1989) suggest these impacts might make the entire habitat more susceptible to damage from other stresses, such as storms. In Waquoit Bay, stresses to eelgrass habitats from eutrophication, disease, docks, and boating activities are leading to the large scale declines in eelgrass distribution recently observed (Costa and others 1992, Short and Burdick 1996).

Dock Design Considerations

Our descriptive models (Tables 5 and 6) indicate dock height above the marine bottom is the primary factor controlling light levels and eelgrass bed quality under docks. Dock orientation is more important to eelgrass than dock width. Poor orientation (east–west) can double the dock height required to support eelgrass, from 1.7 to 3.5 m (Table 5), whereas increasing the dock width from 1 to 2 m only increases the needed height by an estimated 0.4 m (Table 6). The independence of dock height, width, and orientation within our survey (i.e., they were not correlated, Table 2) strengthens our conclusions that all three factors must be considered in future research and in recommendations regarding dock design. Our overall recommendation is for fixed docks <2 m wide and oriented within 10° of north–south with the base of the dock decking at least 2.7 m above the marine bottom. If the orientation is beyond the 10° limit, then dock height needs to be 0.2 m greater for every additional 10° increment. Docks wider than 2 m need to add 0.4 m to their height for every meter increment in width.

The majority of docks we sampled had a floating portion to which boats were tied. Floating docks have severe impacts to eelgrass, and usually eliminate all shoots growing under them. Thus, floating portions should only be placed in water depths beyond the lower depth limit for eelgrass in a particular system. This arrangement also tends to reduce or eliminate boat damage to beds adjacent to the dock. If it is not practicable to extend the dock to a deep channel, a dingy kept at the dock could be used to access larger boats moored in a nonvegetated area. Additionally, we recommend docks be shared or jointly occupied. Consideration of seasonal docks that have removable decking on fixed pilings is suggested, since eelgrass beds with reduced productivity during a few summer months may recover substantially when the decking is absent.

Conclusions

Docks and their associated floats and boats placed over eelgrass beds can cause severe localized impacts to eelgrass. Impacts occur through shading from docks as well as boats, and prop dredging by boat motors, leading to the elimination of eelgrass under and around many docks. Impacts under floating docks generally result in complete eelgrass loss. Less severe impacts from shading were found for tall docks, especially those with long axis orientations running north–south. Shading and physical damage to eelgrass associated with docks are widespread in Waquoit Bay, and although small relative to the total area of the bay's eelgrass beds, these impacts may be an important stress that contributed to the rapid eelgrass declines.

This is the first study to examine the effects of docks on eelgrass and suggest designs based on models of dock impacts to eelgrass beds. We found that narrow docks greater than 3 m over the marine bottom and oriented north–south had the least amount of impact to eelgrass beds. The best dock design is a high dock with north–south orientation that extends to the edge of a navigable channel. Here a boat or a float may be kept with minimal damage to eelgrass if the channel is normally too deep to support eelgrass. The models of dock impacts to eelgrass reported here should be tested at more sites and in estuaries with greater tidal ranges, since covariation between dock height and tidal range occurred in the data set. Our work focused on the impacts of docks on eelgrass; in considering dock regulations, other issues include boat effects on eelgrass and impacts of docks on other marine habitats and resources, as well as aesthetic considerations (e.g., scenic vistas). To reduce fragmentation and stress to eelgrass beds in estuaries like Waquoit Bay, dock regulations that minimize impacts to eelgrass beds must be adopted and enforced.

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