Western Regional Aquaculture Center

Ecological Role and Potential Impacts of Molluscan Shellfish Culture in the Estuarine Environment of Humboldt Bay, CA

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I. Executive Summary

The potential ecological effects of commercial oyster mariculture activities on eelgrass beds (*Zostera marina*) and estuarine tideflat communities are the focus of regional concern for several natural resource agencies throughout Washington, Oregon, and northern California. In particular, empirical studies are currently underway at several locations throughout the Pacific Northwest to evaluate alternative shellfish farming practices and develop policies designed to minimize degradation to eelgrass beds and still allow for oyster cultivation on a commercial scale that is profitable to the mariculture industry. Pacific oysters (*Crassostrea gigas*) have been grown in the intertidal zone of Humboldt Bay, CA for over 60 years, and recent management steps have been taken to discontinue the practices of bottom-culture and harvesting with a mechanical dredge in an effort to reduce damage to eelgrass beds. To further understand the potential ecological effects of off-bottom (long-line) oyster culture on eelgrass communities, we worked in cooperation with the Humboldt Bay - Mariculture Monitoring Committee to establish a series of experimental oyster long-line plots and eelgrass reference areas (controls). The experimental design included evaluation of Best Management Practices (BMPs) for the spacing between off-bottom oyster long-lines. Experimental oyster plots (30 m X 30 m) were established at line spacing distances of 1.5 ft (narrow), 2.5 ft (standard), 5 ft (wide) and 10 ft (very wide). We sampled the study plots quarterly between 2001-03 for the presence of eelgrass, residual oysters, algae, shell rubble, and other cover types, and we collected benthic infauna cores, deployed baited fish traps and measured water quality, sedimentation, light intensity, and oyster growth. After a period of two years, eelgrass

spatial cover and shoot density were consistently high within the control (reference areas) and lowest within the 1.5 ft oyster line spacing plot. Eelgrass metrics generally scaled directly with oyster density, and the spatial cover and density of eelgrass plants within the 10 ft spacing plot were within the range of variability observed in the reference (control) study plots. Preliminary analysis of benthic infauna cores produced a species list of over 100 taxa, including several invertebrates that are known prey items for estuarine and anadromous fish. Comparisons of incident light levels inside and outside oyster cultivation areas suggest that factors other than light availability are probably responsible for the reduced abundance of eelgrass in closely-spaced off-bottom oyster culture sites. Results from this set of field experiments indicate that eelgrass beds and commercial oysters can coexist in Pacific Northwest estuaries, and that implementation of BMPS for reduced density of oysters may aid the recovery and restoration of eelgrass communities.

II. Introduction and Background

The Humboldt Bay - Harbor, Recreation, and Conservation District (HB-HRCD) has management responsibilities over commercial activities within all tidal and submerged lands of Humboldt Bay, CA. These responsibilities include land-use decisions that are guided by the Humboldt Bay Management Plan (1996-2006) which seeks *to "provide a comprehensive framework for balancing economic needs of the region while optimizing conservation and preservation of the natural resources of Humboldt Bay."* Long-term use of Humboldt Bay for the commercial cultivation of Pacific oysters (*Crassostrea gigas*) poses a management challenge for the HB-HRCD because oyster aquaculture activities are known to have measurable effects on a variety of natural resources within Pacific northwest estuaries (Waddell, 1964; Tiranni, 1995; Carlton *et al.*, 1991; Pregnall, 1993; Everett *et al.*, 1995; Simenstad and Fresh, 1995; Rumrill and Christy, 1996; Dumbauld, 1997; Griffin, 1997; Shreffler and Griffin, 1999). Technical information from these previous studies conducted inside and outside of Humboldt Bay must be coupled with results from further empirical investigations to fully understand the economic and environmental costs, benefits, and policy implications associated with sustained mariculture operations within the tideflats of Humboldt Bay. To this end, the HB-HRCD has convened the Humboldt Bay Mariculture Monitoring Committee (HB-MMC) in order to evaluate existing and new information regarding the environmental impacts of oyster aquaculture activities, and to develop recommendations for best management practices designed to minimize degradation of sensitive estuarine habitats and communities. Progressive mariculture management measures undertaken over the past several years within Humboldt Bay include: (1) conversion of oyster aquaculture activities from bottom to off-bottom culture; (2) elimination of shell deposition as a method to stabilize soft-sediment growing areas; (3) elimination of depredation activities designed to reduce losses of oysters to bat rays; and (4) the phase-out of dredging as a method to harvest oysters (Chew, 2001). These management measures, coupled with additional changes to ongoing oyster cultivation practices, address the California Environmental Quality Act (CEQA) finding of a Negative Mitigation Declaration for mariculture activities in Humboldt Bay.

Extensive areas of the estuarine intertidal zone are currently used for commercial cultivation of Pacific oysters in California, Oregon, and Washington. Oysters are cultured by a variety of techniques including: (1) placement of shells and cultch directly on the bottom, (2) elevation of oysters above the bottom on vertical stakes, (3) cultivation of oysters on long-lines suspended between stakes, and (4) suspension of oysters from floating or fixed racks. These mariculture practices result in a variety of different physical and ecological disturbances to intertidal and shallow subtidal estuarine habitats (Griffin, 1997; Dumbauld, 1997). In particular, several authors have documented significant reductions in the spatial cover and density of eelgrass plants in response to oyster cultivation directly on the bottom (Humboldt Bay, CA; Waddell, 1964; Tiranni, 1995; Coos Bay, OR; Rumrill and Christy, 1996; Tillamook Bay, OR; Shreffler and Griffin, 1999). Additional studies have also demonstrated reductions in eelgrass beds, alteration of benthic invertebrate communities, and disruption of sedimentary processes in response to cultivation of oysters off-bottom on stakes and racks (Coos Bay, OR; Carlton *et al.*, 1991; Pregnall, 1993; Everett *et al.*, 1995). New empirical studies are needed to investigate the ecological impacts of oyster cultivation on long-lines suspended between stakes (this study; see below). Moreover, the direct and indirect effects of large-scale oyster mariculture and harvest operations activities including cultch placement with respect to tidal hydrodynamics, manipulation of cultch densities, periodic trampling, redistribution of oysters by raking and harrowing, and the mowing and transplanting of eelgrass have not been fully investigated. It is clear, however, that intensive commercial cultivation of oysters typically results in chronic and variable levels of disturbance to eelgrass beds and their associated communities (Simenstad and Fresh, 1995; Griffin, 1997; Dumbauld, 1997), and that new best management practices are needed to minimize the adverse ecological consequences.

Native eelgrass (*Zostera marina* L.) is widely recognized to serve numerous important ecological functions in Pacific nortwest estuaries (Phillips, 1984; Simenstad, 1983). Meadows of *Z. marina* support diverse assemblages of infaunal and epifaunal invertebrates by several processes including: (1) the provision of physical structure both above and below ground in the shallow subtidal and intertidal flats, (2) by the localized modification of tidal water flow and sediment deposition, (3) by the enhancement of nutrient exchange between sediments and the water column, and (4) by creation of large quantities of organic matter that serve as living and detrital food sources for estuarine consumers (Simenstad *et al*., 1988; Pregnall, 1993; Orth and Heck, 1980; Heck and Thoman, 1984; Orth *et al*., 1984; Peterson *et al*., 1984; Edgar, 1990; Orth 1977; Harlin *et al*., 1982; Fonseca *et al*., 1983; Fonseca and Fisher, 1986; McRoy *et al*., 1972; Hemminga *et al*., 1991; McConnaughey and McRoy, 1979; Bach *et al*., 1986; Nienhuis and Groenendijk, 1986). In addition, beds of *Z. marina* can also serve as nurseries and refuge areas for resident and migratory juvenile fishes, waterfowl, and invertebrates (Phillips, 1984). Western black brant geese (*Branta bernicla nigricans*) have a winter diet that consists largely of eelgrass (Cottam *et al*., 1944; Cottam and Munro, 1954), and several other waterfowl including greater scaup (*Aythya marila*), wigeon (*Anas penelope*), and teal (*Anas crecca*) also utilize eelgrass in their diets (Cottam *et al*., 1944; Tubbs and Tubbs, 1983). Simenstad and Wissmar (1985) determined that eelgrass provides the fundamental basis of the food web for out-migrating juvenile chum salmon,

and eelgrass also supports communities of preferred invertebrate prey items for juvenile chinook salmon in Pacific northwest estuaries (Simenstad, *et al.*, 1982; Simenstad, 1983). In some estuaries, Pacific herring (*Clupea harengus*) spawn on eelgrass where the blades provide a substratum for development and aeration of the adherent egg massess (Levings, 1990). Eelgrass meadows also function as hunting grounds or refuges from predation for juvenile and adult stages of other ecologically, recreationally, and commercially important finfish and shellfish species (Summerson and Peterson, 1984; Leber, 1985; Fredette *et al*., 1990).

In addition to the detrimental effects of oysters on eelgrass beds, it is possible that oyster cultivation may also have beneficial impacts to estuarine habitats and their associated epibenthic communities. For example, the presence of oyster shells can modify tidal flow and enhance deposition of fine sediments, thereby contributing to decreased turbidity and enhanced water quality. Large expanses of living oysters and shell rubble have been shown to serve as important nursery and refuge habitat for juvenile fishes, shrimps, crabs, and other invertebrates (Ambrose and Anderson, 1990; Doty *et al.*, 1990; Breitburg, 1991; Dumbauld *et al.*, 1993; Eggleston and Armstrong, 1995; Simenstad and Fresh, 1995). Oyster shells typically have little, if any, adverse impact on the species diversity and density of estuarine communities, although they may result in localized shifts in species abundance and dominance. Densities of epibenthic invertebrates, including harpacticoid copepods, gammarid amphipods, and cumaceans, were elevated at some oyster cultivation sites where they can serve as prey items for outmigrating chinook and coho salmon (Simenstad *et al*., 1991; Brooks, 1995; Thompson, 1995). Finally, living oysters and other suspension-feeding bivalves may play an important beneficial role in turbid estuarine waters when they function as biofilters to reduce excessive particulate material from the water column and allow enhanced levels of light penetration (Officer *et al*., 1982; Gottleib and Schweighofer, 1996; Dame, 1996). Alternatively, it is also possible that dense reefs of non-indigenous oysters may deplete phytoplankton food sources and compete with native bivalves and other filter-feeders (Peterson and Black, 1987; Alpine and Cloern, 1992).

Cultivation of Pacific oysters in Humboldt Bay poses a difficult management problem because decisions must be made that take into consideration the magnitude, extent, and liklihood of adverse and potentially beneficial impacts of oysters in the tideflat environment. The purpose of the present study undertaken in 2001-03 is to assist the HB-MMC with their decision-making by provision of empirical datasets to describe the ecological impacts of Pacific long-line oyster culture on eelgrass beds, communities of infaunal and epibenthic invertebrates, and sedimentation in representative regions of the Humboldt Bay estuary.

III. Project Goal and Objectives

The primary goal of this ecological assessment project is to *identify and quantify the potential role and ecological impacts of commercial Pacific oyster (Crassostrea gigas) long-line mariculture on tideflat habitats, eelgrass beds (Zostera marina), and*

invertebrate communities in Humboldt Bay, CA. Quarterly field surveys have been conducted in experimental mariculture plots and representative control areas throughout the northern region of Humboldt Bay (Arcata Bay) to evaluate the capacity of oyster cultivation areas and eelgrass beds to serve as habitat for communities of infaunal and epibenthic invertebrates, young-of-the-year Dungeness crabs, juvenile salmonids, and other estuarine fish.

Field surveys and laboratory work was conducted between August 2001 and July 2004 to meet the following objectives:

> Objective 1. Conduct empirical field experiments to directly examine the ecological impacts of Coast Seafoods Co. oyster bottom culture and long-line operations on eelgrass beds and their associated infaunal and epifaunal communities;
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> Objective 2. Compare species diversity, density, and biomass of infaunal and epifaunal macro-invertebrates among commercial oyster cultivation plots in Humboldt Bay (bottom-culture and long-line culture) and representative control areas (adjacent tideflats, former oyster sites, and eelgrass beds); and
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> Objective 3. Assess the relative capacity of Coast Seafoods Co. commercial oyster cultivation areas and control areas to serve as habitat and forage areas for various fish and invertebrates such as juvenile salmon and Dungeness crabs.

IV. Project Overview

The overall project goal, sampling strategies, and methodology were presented, revised, and approved during several meetings held in Eureka, CA with members of the Humboldt Bay Mariculture Monitoring Committee (HB-MMC / 29 August 2001, 27 Sepember 2001, and 2 November 2001). The HB-MMC is convened by the Humboldt Bay Harbor, Recreation, and Conservation District, and includes participation by representatives from the HBHRCD, Coast Seafoods Co., Humboldt State University, the University of California-Agricultural Extension Service, California Sea Grant Program, California Department of Fish and Game, US Fish and Wildlife Service, US Army Corps of Engineers, NOAA - National Marine Fisheries Service, private environmental consultants, and public interest groups.

Experimental oyster long-line plots were established within the circular dredge area from a recently-harvested oyster bottom culture site to quantitatively measure continued habitat impacts and recovery during the transition of mariculture operations from bottom to off-bottom culture. In particular, four 30 X 30 m experimental oyster plots and an adjacent 30 X 30 m control site were established in September 2001 within Coast Seafoods Co. East Bay Management Area EB #2-3. The field experiment was designed to evaluate the ecological impacts of suspended Pacific oyster long-lines, and to develop a Best Management Practice (BMP) for the optimal spacing or density of suspended

oyster long-lines that will minimize detrimental impacts on eelgrass habitats and still allow for commercially viable mariculture of Pacific oysters. Eelgrass habitat and invertebrate communities in the experimental plots were compared to an adjacent control plot and with several representative sites located throughout northern Humboldt Bay, CA (Arcata Bay; see Figure 1). This research project is one of several ongoing studies required by an interim operations permit that address the California Environmental Quality Act (CEQA) finding of a Negative Mitigation Declaration for Coast Seafoods Co. oyster mariculture activities in Humboldt Bay.

Twelve study sites were established in Arcata Bay: (a) 4 experimental Pacific oyster long-line plots (with variable spacings of 1.5', 2.5', 5', and 10' between the suspended lines), (b) an adjacent long-line control plot (no oyster lines), (c) an oyster ground culture plot, and (d) six eelgrass study plots (no recent history of oyster mariculture) that are broadly representative of eelgrass beds throughout Arcata Bay (Figure 1). Sampling activities were conducted on a semi-quarterly basis over a period of two years (August 2001 to August 2003), and included archival photoquadrats, measurement of eelgrass spatial cover and shoot density, collection of infaunal cores, measurement of sediment accumulation, and monitoring of water quality characteristics. All field work and *in situ* observations of eelgrass communities were conducted in Arcata Bay by Dr. Steven Rumrill and Victoria Poulton (Oregon Department of State Lands; South Slough National Estuarine Research Reserve / NERR) during eight low-tide sampling occasions between August 2001 and August 2003 (see Table 1). Greg Dale (manager) and field operations staff at Coast Seafoods Co. (Pong Xayavong and Roberto Ruiz-Guerrero) provided on-site transportation as well as valuable logistic and technical assistance in the field. Ken Morefield (California Department of Fish and Game) worked with site selection criteria developed by the HB-MMC to identify candidate sites for the eelgrass control areas and to produce Geographic Information System (GIS) maps of the study plots. Tom Moore (California Department of Fish and Game) conducted site visits to the proposed study sites and worked with Coast Seafoods Co., South Slough NERR, and the HB-MMC to finalize selection of the study plots. Long-line cultures of Pacific oysters were established within the experimental plots in September 2001, and the oyster lines were harvested by Coast Seafoods Co. in June 2003 after a grow-out period of 22 months (Figure 2). We conducted post-harvest sampling in the study plots and adjacent control areas in July 2003 within two weeks of the removal and harvest of oysters. At the request of the California Coastal Commission (March 2003), we also conducted additional field sampling in August 2003 to compare eelgrass presence, size, and biomass in the experimental plots and larger-scale commercial long-line plots (see Table 2 for site descriptions).

V. Field Sampling

Initial field surveys and sampling activities were conducted during August 2001 (Table 1) prior to installation of the oyster long-lines. Results from this initial survey and subsequent quarterly surveys conducted in December 2001, May 2002, and August 2002 are reported in our August 2002 Annual Report. Field surveys continued in December

2002, May 2003, July 2003, and August 2003, and results specific to these sampling dates are presented in the 2003 Annual Report. This Final Report for 2004 summarizes results from the field surveys and laboratory work conducted over the entire project period from August 2001 to July 2004.

During a typical sampling period spanning about 5 days of an extreme minus tide series (lower than -0.7 ft. MLLW) the following tasks were completed: (a) collection of archival photographic images of bottom habitat conditions within randomly-placed 0.25 m^2 photoquadrats; (b) estimates of spatial cover for several classes of bottom type including eelgrass, macroalgae, oysters, shell rubble, and unvegetated mud; (c) counts of the number of oyster shells and eelgrass plants within all photoquadrats, (d) collection of infaunal invertebrate cores, (e) deployment and recovery of baited minnow traps, (f) measurement of sedimentation in the experimental oyster long-line plots, (g) measurement of oyster shell size and width in the experimental long-line plots, (h) recovery and deployment of six continuous Onset TidBit temperature recorders, (i) deployment and recovery of aYellow Springs Instruments / YSI-6000 automated multi-parameter datalogger, and (j) measurements of surface water temperature, salinity, Secchi depth, and light attenuation (with a LI-COR spherical quantum meter) in the primary tidal channels. Detailed descriptions of field activities for each sampling date are provided in Table 1.

The four experimental oyster long-line plots (OLN-1.5 ft, OLN-2.5 ft, OLN-5 ft, OLN-10 ft) were harvested by Coast Seafoods Co. at the end of June 2003. Harvesting was conducted by hand and all long-line ropes and attached oyster clusters were removed, but the PVC support posts were purposely left in the tideflat sediments (Figure 2). The living oysters were cleaned and packed at the Coast Seafoods Co. (Eureka, CA) facility, and trucked to the Coast Seafoods Co. (South Bend, WA) facility for further processing. We conducted a post-harvest survey of the experimental plots during 11-15 July 2003. Acting on the request put forward by the California Coastal Commission, we also conducted supplemental sampling during 10-13 August 2003 to compare eelgrass metrics (percent cover, shoot density, size, and biomass of *Zostera marina*) in the experimental long-line plots (now harvested of oysters) with eelgrass communities that exist in other Coast Seafoods Co. commercial oyster long-line beds. During the August 2003 low-tide series we re-sampled the experimental oyster long-line plots (OLN-1.5 ft, OLN-2.5 ft, OLN-5 ft, OLN-10 ft, OLN-CON), and two commercial long-line beds (EB 6-2 and EB1-1) that had been established at least 18 months earlier with a range of line spacings between 2 and 10 ft. (see Table 2). In addition, we also measured light intensity within the eelgrass canopy along a transect that ran beneath commercial oyster long-lines (2.5 ft spacing in plot EB #6-2) and along a transect within an adjacent eelgrass bed.

VI. Laboratory Analyses and Statistics

Infaunal core samples were washed through a 0.5-mm mesh within a few hours after collection. Samples were fixed and preserved in 70% isopropyl alcohol and stained with rose bengal before sorting. All samples of infaunal and epibenthic invertebrates were

transported to the South Slough NERR / Estuarine and Coastal Science Laboratory (University of Oregon – Institute of Marine Biology, Charleston, OR) for identification to the lowest possible taxon and enumeration under a dissecting microscope. Total biomass (blotted wet weight) was measured for each sample. Taxonomic voucher specimens were sent to outside consultants (Marine Taxonomic Services, Corvallis, OR; Dr. John Chapman, Oregon State University, Corvallis, OR; Dr. Jeff Cordell, University of Washington, Seattle, WA) for independent confirmation and correction of problematic specimen identifications.

Individual eelgrass plants were collected in August 2003 to compare plant sizes and biomass among the experimental oyster long-line study plots, representative commercial oyster cultivation areas, and a control plot. Twelve plants were collected at each of 16 study sites (4 experimental oyster long-line plots, 1 control site, and 11 commercial long-line beds; see Table 2 for site descriptions). Immediately upon returning from the field, plant length was measured for the longest intact blade, and blade width was measured at half the length of the longest blade. Large epiphytes, epizootic invertebrates, and clumps of detritus were removed, plants were blotted dry, and each plant was measured for wet weight. The *Zostera marina* plants were then frozen until they could be dried to constant weight at 40°C and measured for dry weight.

All numerical data were examined to determine skweness, normal distribution, and homoscedasticity prior to conducting parametric statistical analyses. In cases where mathematical transformations were not effective to meet the requirements for parametric tests, we used rank transformations of the data. Eelgrass metrics were compared among the different sampling periods and among the various study plots using two-way repeated measures ANOVA and Bonferroni pairwise comparisons (Minitab, Inc. statistical sub-routines). Eelgrass blades collected during the August 2003 sampling period were tested for differences in size (length and width) and mass (wet and dry weight, square-root-transformed) among the oyster long-line spacing plots using one-way ANOVA and Tukey's pairwise comparisons (Minitab, Inc.). Measurements of oyster shell width and length were compared among the experimental oyster long-line plots using nested ANOVA (oyster sizes nested in clusters, clusters nested in study plots; Minitab, Inc.). Results from the statistical comparisons were considered as significant if $a < 0.05$, unless otherwise stated.

The structure and composition of infaunal and epibenthic invertebrate communities was investigated by non-parametric multivariate methods with PRIMER (Plymouth Routines In Multivariate Ecological Research) statistical software. The PRIMER sub-routines were applied after rare taxa (<10 observations for all sample periods) were removed from the dataset. Differences among sampling sites and seasons were identified and tested with non-denominational multi-dimensional scaling (MDS), and analysis of similarity (ANOSIM) was performed using Bray-Curtis similarity measures on root-root-transformed data on invertebrate abundances. Influential invertebrate taxa were identified using the BVSTEP procedure of PRIMER.

Several different indices of invertebrate community diversity (no. individuals, no. species, Margalef's species richness, Pielou's species evenness, and Shannon-Wiener diversity) were compared among the quarterly sample dates and among the various study sites with two-way ANOVA tests (Minitab, Inc.). Site differences were further examined using one-way ANOVA and Tukey's pairwise comparisons. Diversity indices were also used in a principal components analysis (PCA, PRIMER) to look for patterns by sample date and site. Relationships between invertebrate diversity indices and environmental parameters (eelgrass cover, eelgrass density, algae cover) were examined using multiple linear regression.

VII. Results and Discussion

A. Tideflat Temperatures and Estuarine Water Parameters

Time-series measurements of tideflat temperatures were recorded on an hourly interval with Onset TidbiT dataloggers deployed about 2 cm below the surface of the mud at six of the study plots in Arcata Bay. Tideflat temperatures exhibited a distinctly seasonal cycle and ranged from warm values of 15-20 ^{o}C in spring and summer months to low values below 7-8°C in late fall and winter (Figure 3). The semi-diurnal tidal cycle was also apparent in the temperature time-series data; the warmest temperatures occur during summer days at low tides when the tideflats are drained and warmed by the sun. Conversely, tideflat temperatures were seasonally cooler in the winter, and the coldest temperatures sometimes occurred at low tide in the winter when the sensors are briefly exposed to cold air. Differences in the time-series measurements of tideflat temperatures were negligible among the various study sites, and provide evidence that tideflat temperature conditions are generally similar throughout the different regions of Arcata Bay. Consequently, any effects of local temperature differences on growth of eelgrass, macroalgae, and oysters are expected to be slight.

Time-series measurements of several estuarine water parameters (recorded by a YSI-6000 multi-parameter datalogger deployed in the East Bay Slough drainage inlet) provide records of short-term variability and seasonal changes in tidal waters that inundate and drain the experimental oyster long-line plots (Figure 4). Tidal amplitude within the inlet was generally about 3 m during each of the quarterly sampling periods, and salinity values fluctuated between 23-34.5 practical salinity units (psu). The semi-diurnal tidal signal was also evident in pH values which ranged between 7.7 and 8.3. Water temperatures in the East Bay Slough mirrored temperatures in the tideflat sediments (Figure 3) and exhibited seasonal warming with coolest temperatures in the winter, intermediate temperatures in the spring, and highest temperatures in summer. Low temperatures within the tidal inlet were usually coincident with high tides and ranged between 10-12 ^{o}C in the winter (i.e. 2-6 December 2002), between 11-17 ^{o}C in the spring (15-19 May 2003), and between 14-22 ^{o}C in the summer (11-15 July 2003). The tidal waters of East Bay Slough (that inundate the adjacent tideflats and experimental oyster long-line plots) were well oxygenated with typical dissolved oxygen (DO) values between 8 and 11 mg/L in the cold winter and spring months, and in the range of 7-9

mg/L in the warmer summer months. These measurements of estuarine water parameters in the East Bay Slough are similar to surface and sub-surface water temperature, salinity, and pH values measured in the primary tidal channels at various locations throughout Arcata Bay. These measurements of estuarine water parameters are also well within the range of values that allow for growth and persistence of *Zostera marina* beds in Pacific northwest estuaries.

B. Eelgrass Spatial Cover and Density

B1. Initial Eelgrass Conditions (August 2001): Spatial cover and density of *Zostera marina* were variable in the experimental oyster long-line plots in August 2001 prior to establishment of Pacific oyster long-lines. Spatial cover of eelgrass initially ranged from 14% to 51%, and plant densities ranged from 15 plants m^{-2} to 46 plants m^{-2} (Figure 5). By comparison, initial spatial cover and density of *Z. marina* were highest within the eelgrass bed control plot (91% cover and 76 plants m^{-2}) and comparable to the oyster ground culture plot (45% cover and 38 plants m^{-2}). These values provide a starting point from which to gauge the temporal dynamics of eelgrass habitat in undisturbed sites as well as the recovery of eelgrass beds under conditions of variable oyster long-line spacing.

A one-way ANOVA conducted on rank-transformed spatial cover data (% cover of *Zostera marina*) detected no significant differences in the initial starting conditions of eelgrass beds among the experimental oyster long-line study plots ($F_{4, 45}$=2.5, p=0.06). Rank-transformed eelgrass density data, however, differed significantly among the experimental oyster plots in August 2001 (one-way ANOVA, $F_{4, 45}$=2.7, p=0.04). This result was driven entirely by the high density of *Z. marina* plants in the control plot in comparison with lower plant densities in the OLN-5 ft. spacing plot. Eelgrass metrics in the oyster ground-culture site were not significantly different from eelgrass metrics in the experimental oyster long-line plots (two-group t-test; *Z. marina* % cover: t_{12}=1.36, p=0.20; *Z. marina* density: t_{11}=0.97, p=0.35). Eelgrass presence in the eelgrass reference site (91% cover, 76 plants m^{-2}) was significantly higher than at the experimental oyster long-line spacing plots (% cover: t_{56}=12.0, p<0.001; plant density: t_{51}=10.0, p<0.001).

B2. Temporal Changes in Eelgrass Beds during Oyster Grow-Out (August 2001-03): Metrics of *Zostera marina* spatial cover and density differed significantly between quarterly sampling dates over the period of August 2001-03 (ranked data; % cover: $F_{7,919}$=9.6, p<0.001, plant density: $F_{7,919}$=5.9, p<0.001; Figures 5 and 6). Lower eelgrass % cover and density values were generally observed in the study plots in the winter (November 2001 and December 2002) and higher eelgrass metrics were observed in the spring and summer sample periods (Figure 5). In addition, eelgrass metrics also differed significantly among the various study sites (% cover: $F_{7,919}$=9.6, p<0.001, plant density: $F_{7,919}$=49.4, p<0.001; see Figure 5). Eelgrass beds also exhibited substantial variation in comparisons among the five reference sites added in May 2002. Eelgrass spatial cover and plant density were generally highest within the eelgrass bed control site and the Bird Island and Sand Island reference sites where they ranged from 45-80% cover and 40-65 plants m^{-2} in December 2002 to 70-80% cover and 45-62 plants m^{-2} in May and July

2003. Eelgrass beds followed a similar seasonal pattern at the reference sites located at Mad River, East bay, and Arcata Channel (see Figures 1 and 6). These seasonal changes and site-specific differences are indicative of inherent variability among eelgrass beds located in different regions of Arcata Bay, and the datasets from the reference sites were subsequently lumped to reduce the number of pairwise statistical comparisons with the experimental oyster long-line plots.

Spatial cover and density of eelgrass plants exhibited a seasonal pattern and response that was directly related to the density of oysters in the experimental long-line study plots (Figure 5). The eelgrass control site (EB-CON) consistently exhibited the greatest spatial cover and density of *Zostera marina* plants during the period from August 2001 to July 2003 (Figures 5-7). In contrast, the very narrow oyster long-line spacing plot (OLN-1.5 ft) consistently exhibited the lowest spatial cover and density of eelgrass plants during August 2001 to July 2003 following installation of experimental oyster long-lines in September 2001 (Figures 5-7). During 2003 we observed a strong trend toward decreased spatial cover and density of *Z. marina* with decreased distance between suspended oyster long-lines. Low eelgrass metrics were consistently observed within the narrow line spacing / high-density oyster plots (OLN-1.5 ft and OLN-2.5 ft), where eelgrass cover was generally less than 15% and densities were typically less than 10 plants m^{-2} after a period of 20 months. Eelgrass beds in the wide oyster long-line spacing plots (OLN-5 ft) were intermediate (35-45% cover, 20-37 plants m^{-2}), and high spatial cover (55-65% cover) and density values (33-48 plants m^{-2}) were observed in the very wide oyster long-line plot (OLN-10 ft; Figures 5-7). These eelgrass metrics in the wider oyster long-line plots tended to have slightly lower spatial cover values than the reference plots, but were within the range of variation exhibited by undisturbed eelgrass beds located in other regions of Arcata Bay. Eelgrass metrics within the oyster ground culture plot were intermediate and similar to the wide oyster long-line spacing plot (OLN-5 ft).

Comparisons of eelgrass metrics in the experimental oyster long-line plots and Arcata bay reference sites are shown in greater detail in Figure 7 at the end of the field experiment and immediately following removal of the oyster long-lines. At the end of the 22 month oyster grow-out period (September 2001 to June 2003), spatial cover and density of *Zostera marina* were low in the narrowest oyster long-line plots (OLN-1.5, OLN-2.5). Spatial cover values for these narrow oyster line spacing plots averaged 5.2 % cover (OLN-1.5) and 4.5 % cover (OLN-2.5), and density values averaged 2.7 plants m^{-2} and 10.3 plants m^{-2}, respectively. In contrast, eelgrass % cover and density values were intermediate at the end of the experiment in the wide oyster long-line plot (OLN-5) where they averaged 39.2 % cover and 21.3 plants m^{-2}. Eelgrass spatial cover and density values were even higher within the very wide oyster long-line plot (OLN-10) where they averaged 67.5 % cover and 48.7 plants m^{-2}. Eelgrass metrics within the OLN-10 plot were nearly identical to those within the adjacent control plot (no oyster line; OLN-CON), and very similar to the spatial cover values measured within the five eelgrass reference sites located throughout Arcata Bay (Mad River Slough, Mad River, Sand Island, East Bay, Arcata Channel; see Figures 1 and 7). Eelgrass % cover values were substantially higher only at the Bird Island reference site. Eelgrass density values within the very wide oyster long-line plot (OLN-10) were also comparable to the *Z. marina*

density values measured within the adjacent control plot (OLN-CON) and within the range of plant density values observed for the eelgrass reference sites located throughout Arcata Bay (Figure 7).

We observed a consistent pattern in the spatial cover, density, and sizes of *Zostera marina* plants that grew in the experimental oyster long-line plots and several larger-scale commercial oyster long-line plots (Figures 8 and 14; Table 2). Eelgrass metrics in the experimental oyster long-line plots were compared with metrics in two large commercial long-line cultivation areas managed by Coast Seafoods Co. (Figure 8). During August 2003 (about 8 weeks after the harvest of oysters from the experimental plots), the spatial cover and density of *Z. marina* remained low in the experimental plots OLN-1.5 and OLN-2.5. Spatial cover values for these narrow oyster long-line plots averaged less than 10%, and density values averaged less than 2.5 plants 0.25 m^{-2}. Similarly, eelgrass cover and density values were also low (<10 % cover and < 2.5 plants 0.25 m-2) along three transect lines placed in commercial 2.5 ft oyster line grow-out areas in Coast Seafoods Co. management areas EB #1-1 and EB #6-2a,b (Figure 8). Eelgrass spatial cover values were also low along transect lines in management areas EB #6-2/5-2.5 where oysters were grown on pairs of suspended long-lines placed 2.5 ft apart separated from adjacent pairs by a distance of 5 ft (see Table 2). In contrast, eelgrass spatial cover values were generally higher in the wider commercial oyster line plots (EB #1-1/5, EB #1-1/5-2.5, EB #6-2/5) where oysters are grown at distances of 2.5 and 5 ft apart (Table 2). Eelgrass spatial cover values were consistently greatest (60-80 % cover) in undisturbed control areas (EB #1-1/CON, EB #6-2/CON), and they were high (35-60 % cover) in the widest experimental (OLN-10) and commercial oyster long-line plots (EB #1-1/10, EB #6-2/10, EB # 6-2/10-2). The recovering eelgrass bed located adjacent to the experimental oyster long-line plots (OLN-CON) exhibited lower spatial cover values (ca. 35 % cover) in comparison to the undisturbed eelgrass beds adjacent to the commercial oyster mariculture areas (Figure 8). Eelgrass density values followed a similar pattern and were generally lower in the high-density commercial oyster mariculture areas (EB #1-1/2.5, EB #1-1/5, EB #1-1/5-2.5, EB #6-2/2.5a,b, EB #6-2/5, EB #6-2/5-2.5) where oysters are grown at distances of 2.5 and 5 ft apart (see Table 2). These results indicate that the patterns of eelgrass spatial cover and density observed within the experimental oyster long-line plots (OLN-1.5, OLN-2.5, OLN-5, OLN-10) are comparable and directly applicable to commercial oyster mariculture areas in other regions of Arcata Bay.

Eelgrass plant lengths and widths varied substantially among the study plots and commercial cultivation sites (Figure 14), and plants collected from experimental and commercial oyster long-line plots (August 2003) tended to be smaller (length and width) and weigh less (wet and dry weight) in locations where oyster cultivation was dense (i.e 1.5 and 2.5 ft spacing). Significant differences were evident for all four eelgrass metrics among the various oyster long-line spacing plots (one-way ANOVA; blade length: $F_{6,184}$=9.3, p<0.001; blade width: $F_{6,184}$=6.3, p<0.001; wet weight: $F_{6,184}$=9.1, p<0.001; dry weight: $F_{6,184}$=9.3, p<0.001). Eelgrass metrics within the experimental oyster long-line plots (OLN-1.5, OLN-2.5, OLN-5, OLN-10) were also directly comparable to those measured in several larger-scale Coast Seafoods Co. commercial oyster mariculture areas that were established with similar spacings of oyster long-lines (e.g. Figure 14; August

2003; EB1-1/various spacings, EB 6-2/various spacings; 2-group *t*-tests; % cover: t_{128}=0.6, p=0.54, plant density: t_{109}=-0.9, p=0.36).

C. Infaunal Invertebrate Communities

We identified a total of 129 taxa of infaunal invertebrates from the series of 840 benthic cores collected from the experimental oyster long-line plots and eelgrass reference sites. Rare taxa ($\leq$ 10 observations for all sample dates) were excluded from the dataset, leaving 70 taxa of invertebrates for statistical analyses. Rare taxa were retained within the dataset, however, when calculating diversity indices. Five diversity indices were calculated for each sample using the entire 129-taxa dataset. The indices of taxonomic diversity were: number of species (s), number of individuals (n), Margalef's species richness (d), Pielou's evenness (J'), and Shannon-Wiener diversity (H'). Principal components analysis (PCA, PRIMER) indicated consistent patterns in the infaunal invertebrate communities among the study sites in Arcata Bay. The first two principal components explained at least 86.3% of the variation among study sites. PC1 was characterized by decreasing s, d, and H' for most sample dates, while PC2 was characterized by decreasing n and increasing J' for most sample dates. For some sampling dates, the oyster ground culture plot and the eelgrass bed sites were distinguished along PC1, indicating that those sites had slightly lower species numbers, richness, and diversity. However, the distinction between these and other sites was not strong; there was much overlap with the experimental oyster long-line sites and sometimes with the eelgrass reference sites.

We used multiple linear regression to examine the effects of *Zostera marina* % cover, macrobenthic algae % cover, and *Z. marina* density on invertebrate species diversity indices and biomass. The number of invertebrate species, species richness, and biomass were not related to eelgrass or algae presence (p>0.05). While the other diversity indices had statistically significant relationships with eelgrass and algae, the relationships were very weak: for species evenness R^2(adj.)=2.2%, p<0.001, diversity R^2(adj.)=0.9%, p=0.02, and number of individuals R^2(adj.)=4.7%, p<0.001). Total invertebrate biomass (wet weight) varied significantly within the study plots over time (ANOVA; $F_{6,800}$=13.0, p<0.001), and the highest biomass values occurred in August and November 2001. Invertebrate biomass also varied among the study sites (ANOVA; $F_{11,795}$=3.4, p<0.001) where highest biomass was found in the experimental oyster long-line sites and lowest biomass occurred in some of the eelgrass reference sites and in the oyster ground culture site.

Infaunal invertebrate communities differed significantly over the sample dates and among the various study sites (two-way ANOSIM; Global R=0.41, p<0.001). Date-by-date multi-dimensional scaling (MDS) analyses of site differences revealed patterns that were consistent through time. The horizontal MDS analysis distinguished three loosely coherent groups of infaunal invertebrates: (a) the eelgrass reference sites, (b) the experimental oyster long-line sites, and (c) the ground culture plot and adjacent eelgrass bed. For some dates, the vertical axis further separates the ground culture and eelgrass bed sites. Stress levels of the two-dimensional MDS plots were moderately high (0.21 –

0.25), meaning that they are not a precise representation of spatial relationships reflecting similarity amongst the sites. Consistency of the pattern along with significant results from the analysis of similarity (ANOSIM) indicates that the group differences are real. However, insignificant ANOSIM results occurred for some dates when the experimental oyster long-line plots were held separate for the analysis, and insignificant comparisons among the long-line plots affected the global R-value.

Out of the 70 species of infaunal invertebrates in our analyses, only about 20 species were largely responsible for the structures of the MDS plots and for the differences in the ANOSIMs. These influential species of invertebrates were generally the most abundant in the tideflat sediments. The most influential species common to all sample periods were polychaetes (spionidae: *Polydora pygidialis*, *Streblospio benedicti*; syllidae: *Sphaerosyllis californiensis*), cumaceans (leuconidae: *Eudorella pacifica*), tanaids (leptocheliidae: *Leptochelia savignyi*), gammarid amphipods (corophiidae: *Paracorophium* sp.), copepods, oligochaetes, and nematodes. Composition of the invertebrate communities did not differ substantially among the study sites; the differences we observed were largely the result of varying numbers of individuals within similar community assemblages. While several common species of polychaetes could be considered as biotic indicators of disturbed, nutrient-enriched, or contaminated soft sediment habitats (ie. spionidae: *S. benedicti*, capitellidae: *Capitella* sp.), other polychaetes that were common in our samples are generally considered to prefer clean, undisturbed habitats (ie. orbiniidae: *Leitoscoloplos armiger*; terebellidae: *Polycirrus* sp.). Overall similarity of the invertebrate communities among the oyster long-line and eelgrass reference sites provides evidence that oyster long-line culture activities are not particularly stressful to the benthic infaunal communities of Arcata Bay.

D. Motile Invertebrates and Fish

We deployed baited minnow traps in the experimental oyster long-line plots to assess the potential of the commercial mariculture areas to serve as habitat and forage sits for macrobenthic invertebrates and resident estuarine fish (Table 4). Baited minnow traps were deployed over periods of 24 hrs in the experimental oyster long-line plots (OLN-1.5 ft and OLN-5 ft) in May 2002 – July 2003. In December 2002 traps were deployed in plot OLN-2.5 ft instead of plot OLN-5 ft. Motile invertebrates and fish captured by the minnow traps included several Dungeness crabs (*Cancer magister*), red rock crabs (*Cancer productus*), staghorn sculpins (*Leptocottus armatus*) and caridean shrimps (*Crangon franciscorum*; see Table 4). Low numbers of these species recovered from the minnow traps did not allow for statistical comparisons, but two trends were evident. First, the total number of large motile crustaceans and fish captured was usually greater in the very narrow oyster long-line study plot (OLN-1.5 ft) compared to the wide oyster long-line study plot (OLN-5 ft). Second, the body sizes of crabs were generally larger in the low-density wide oyster line plots (OLN-5 ft) in comparison with the very narrow oyster long-line plot (OLN-1.5 ft). These results, although not statistically rigorous, support the understanding that habitat conditions for recruitment of motile crabs, shrimp, and resident demersal fish may be enhanced by dense oyster beds, although these predatory species may attain greater body sizes in low-density oyster beds.

E. Comparisons of Oyster Growth

Shell lengths and widths of living oysters were measured in the experimental oyster long-line plots in May 2002 – May 2003 (Figure 9). Juvenile oysters were out-planted into plots OLN-1.5, OLN-2.5, OLN-5, and OLN-10 as cultch in September 2001, and they attained dimensions of about 50-60 mm in shell length and 38-42 mm in width by May 2002. Shell lengths increased to 102-108 mm and shell widths increased to 70-76 mm by May 2003, about a month before harvest. We did not observe any significant differences in shell lengths ($F_{3,202}$=1.9, p=0.14) or shell widths ($F_{3,202}$=2.6, p=0.05) among the experimental oyster long-line plots.

F. Sedimentation within Oyster Long-Line Plots

Small-scale topographical profiles were constructed for the tideflat surface sediments along representative 100 cm transects in each of the experimental oyster long-line plots (OLN-1.5, OLN-2.5, OLN-5, and OLN-10) and in the adjacent control plot (no oyster long-lines; OLN-CON, see Figure 10). Comparison of surface elevation profiles revealed that fine sediments were deposited and eroded in an inconsistent manner between November 2001 and July 2003. Changes in sediment deposition and erosion were clearly evident in the plots with high densities of oyster lines (OLN-1.5, OLN-2.5, OLN-5, Figure 10A-C), and the seasonal build-up of sediments was particularly evident in May 2003 around the PVC stakes that support the oyster lines. Substantial and rapid sediment deposition was observed in plot OLN-1.5 where tideflat elevations reached their highest point about 70 mm and above the initial profile (Figure 10A). These soft and flocculent sediments were largely eroded away by July 2003. New sediments were also deposited in oyster plot OLN-2.5 to a level of about 62 mm above the initial elevation where they remained through July 2003 (Figure 10B). In study plot OLN-5, w observed substantial deposition of fine sediments to their highest point of 95 mm in May 2003, follwed by erosion in the summer to a level of about 51 mm above the initial elevation by July 2003 (Figure 10C). but they remained along the transect in plot OLN-2.5. Conversely, sediments were deposited more slowly over time within oyster long-line plot OLN-10 where they reached a level of about 40 mm above the initial elevation in July 2003 (Figure 10D). In contrast, tideflat sediments in the control (no oyster) plot OLN-CON remained fairly static along one portion of the transect and eroded to a level of about 20 mm below the initial elevation along the other portion of the transect (Figure 10D-E).

G. Tideflat Light Levels

The intensity of incident light was measured to assess the extent to which suspended oyster long-lines may shade the tideflat surface and impair growth of *Zostera marina*. Light intensity was measured at the sediment surface and at an elevation of 60 cm above the sediment over a period of about 24 hrs within three experimental oyster long-line plots (OLN-2.5, OLN-5, and OLN-CON; Figure 11). The deployment period spanned a single semi-diurnal tidal cycle, beginning at dawn with the lower low tide. Measurements of light intensity decreased rapidly as the meters were covered by the

rising tide, and they were completely immersed by the flooding tidal waters after about 1000 hrs. Ambient light levels stabilized between 1000 and 1200 hrs during the period of maximum tidal flood (lower high tide), and then decreased rapidly again between 1200 – 1500 hrs as the receding ebb tide brought highly turbid waters past the submerged meters. Incident light levels increased sharply between 1500 – 1800 hrs when the meters were exposed to air during the higher of the semi-diurnal low tides. Finally, ambient light levels decreased rapidly between 1800 and 2000 hrs with immersion by the flooding evening tide, and the meters recorded an 8 hr period of darkness that was coincident with night and the higher high tide (Figure 11).

Light intensity measurements recorded at the level of tideflat sediments (0 cm) were generally similar between the OLN-2.5 oyster long-line plot and the adjacent control (OLN-CON) plot, and slightly lower in the OLN-5 oyster plot (Figure 11). Light measurements in in all three plots exhibited nearly identical time-series signatures with the daily ebb and flood of the tidal cycle, and differences between light measurements recorded at the sediment surface (0 cm), directly beneath oyster lines, and at a height of 60 cm above the sediments, were slight. These results suggest that the shading effect of oyster long-lines on the mudflats and *Zostera marina* plants is probably negligible. Measurements of light attenuation within the water column of the turbid Arcata Bay tidal channels (Figure 12) indicate that underwater light levels typically drop to below 100 m moles $m^{-2}s^{-1}$ at a depth of 2.5 m below the surface at low tide, and it is unlikely that eelgrass beds can persist below this depth in Arcata Bay.

In August 2003, we measured incident light profiles along a transect that ran beneath oyster long-lines in a commercial oyster bed located within Coast Seafoods Co. Management Area EB #6-2 (Figure 13). Oyster long-lines in the management area were spaced 2.5 ft. apart with a 5-ft. space every six lines. An Onset HOBO light meter was sealed in a waterproof container and attached to a buoyant sled. The light meter was pulled back and forth six times beneath the oyster lines along an approximately 13-m transect over a period of about 16 minutes (0828-0844 hrs). The light meter was then pulled through an eelgrass bed adjacent to the oyster long-lines for a period of about 9 minutes (0845-0854 hrs). The six passes through the oyster long-line are evident as distinctly different sections on the light profile (Figure 13) where light intensity values alternated between lower and less variable measurements when the sled was pulled toward the east as opposed to higher and more variable values when it was pulled in a westerly direction. The shading effect of oyster long-lines is illustrated by the sharp decreases in light intensity. This erratic pattern was not evident when the light meter was pulled across adjacent eelgrass bed (Figure 13). The ecological importance of these differences in incident light levels between oyster lines and the adjacent eelgrass bed has not yet been determined.

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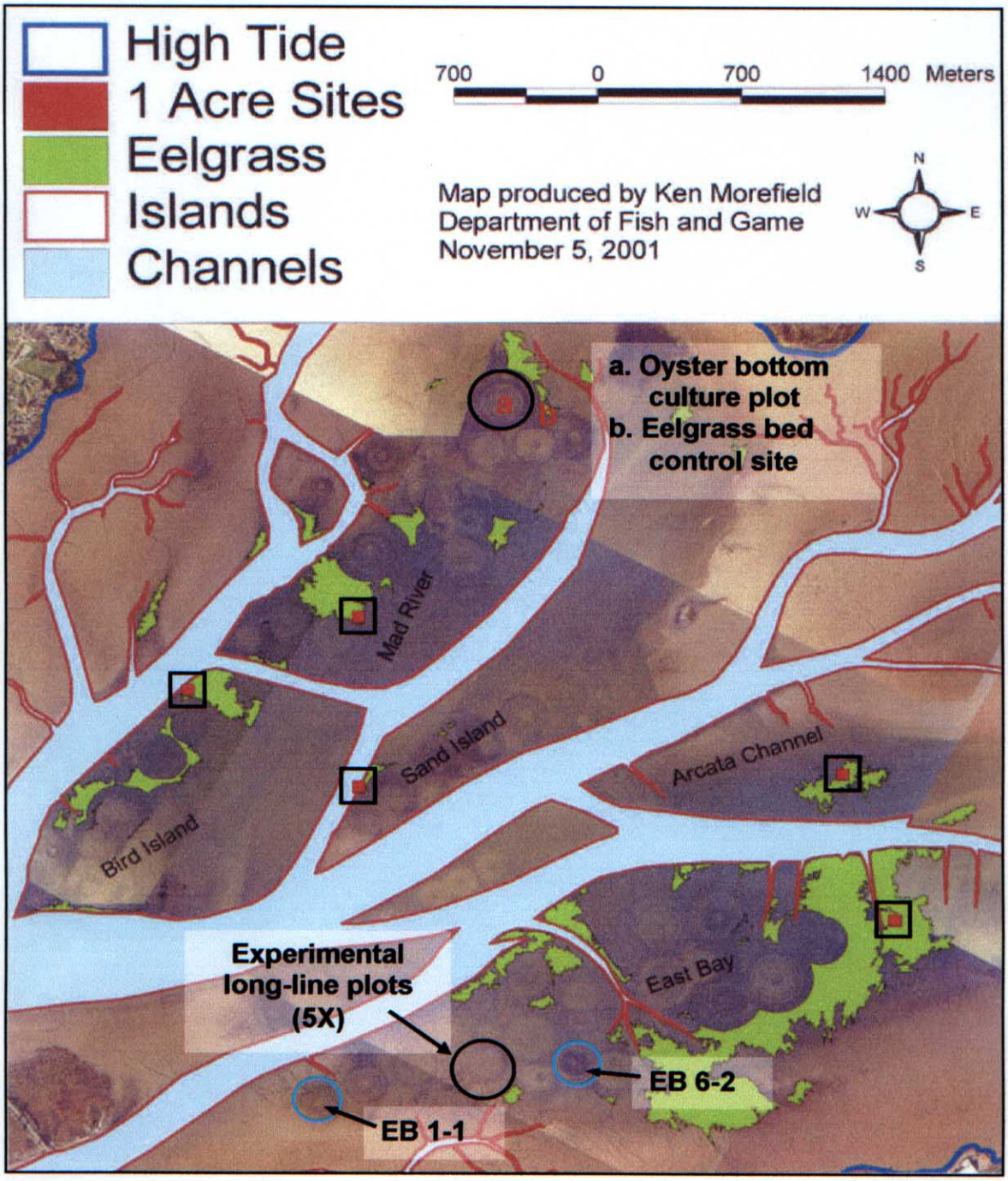


Figure 1. Location of study sites for the assessment of commercial oyster mariculture impacts in eelgrass beds and tideflat communities, Arcata Bay, CA. Map indicates location of 12 study plots monitored Aug 2001 to Aug 2003, and location of sites EB 1-1 and EB 6-2 surveyed in Aug 2003.

Table 1. Summary of sampling activities conducted in Humboldt Bay, CA (August 2001- August 2003).

Aug. 2001	EB-CON	OGC-CON	OLN-1.5	OLN-2.5	OLN-5	OLN-10	OLN-CON	OLE-2.5
Plot description	Eelgrass bed	Ground culture	1.5-ft. long-line	2.5-ft. long-line	5-ft. long-line	10-ft. long-line	control (no lines)	2.5-ft. commercial long-line
Sample date	20 Aug	20 Aug	18 Aug	18 Aug	19 Aug	18 Aug	19 Aug	21 Aug
Temp. TidbiT	initiated	initiated		initiated			initiated	
Photo / Spatial cover / density quadrats	10	10	10	10	10	10	10	site visit
Sediment core	2	2		2			2	
Infauna core	5	5	5	5	5	5	5	
Box core	1	1	1	1	1	1	1	
Zostera $1m^2$							10	
Zostera biomass	30 plants						30 plants	
Nov. 2001	**EB-CON**	**OGC-CON**	**OLN-1.5**	**OLN-2.5**	**OLN-5**	**OLN-10**	**OLN-CON**	
Plot description	Eelgrass bed	Ground culture	1.5-ft. long-line	2.5-ft. long-line	5-ft. long-line	10-ft. long-line	control (no lines)	
Sample pattern	30-m transect	30-m transect	30x30-m grid	30x30-m grid	30x30-m grid	30x30-m grid	30x30-m grid	
Temp. TidbiT	X	X				X	X	
Photo / Spatial cover / density quadrats	10	10	10	10	10	25	10	
Infauna core	10	10	10	10	10	25	10	
Sediment contour			X	X	X	X	X	

Table 1. Continued.

May 2002	EB-CON	OGC-CON	OLN-1.5	OLN-2.5	OLN-5	OLN-10	OLN-CON	Mad River	Bird Island	Sand Island	East Bay	Arcata Channel
Plot description	Eelgrass bed	Ground culture	1.5-ft. long-line	2.5-ft. long-line	5-ft. long-line	10-ft. long-line	control (no lines)	reference site	reference site	reference site	reference site	reference site
Sample date	27 May	27 May	25-26 May	25 May	26 May	25 May	25-26 May	28 May	28 May	29 May	29 May	30 May
Sample pattern	30-m transect	30-m transect	30x30-m grid	30x30-m grid	30x30-m grid	30x30-m grid	30x30-m grid	30x30-m x- tran	30x30-m x- tran	30x30-m x- tran	30x30-m x-tran	30x30-m x- tran
Temp. TidbiT	X	X		X		X			initiated			initiated
Photo / Spatial cover / density quadrats	12	12	12	12	12	12	12	12	12	12	12	12
Infauna core	12	12	12	12	12	12	12	12	12	12	12	12
Sediment contour			X	X	X	X	X					
Sweep net	5	6	5	6	6	6	4	2		3	2	2
Fish Traps			2		2							

August 2002	EB-CON	OGC-CON	OLN-1.5	OLN-2.5	OLN-5	OLN-10	OLN-CON	Mad River	Bird Island	Sand Island	East Bay	Arcata Channel
Plot description	Eelgrass bed	Ground culture	1.5-ft. long-line	2.5-ft. long-line	5-ft. long-line	10-ft. long-line	control (no lines)	reference site	reference site	reference site	reference site	reference site
Sample date	9 Aug	9 Aug	7 Aug	8 Aug	7 Aug	7 Aug	8 Aug	11 Aug	9 Aug	11 Aug	10 Aug	10 Aug
Sample pattern	30-m transect	30-m transect	30x30-m grid	30x30-m grid	30x30-m grid	30x30-m grid	30x30-m grid	30x30-m x- tran	30x30-m x- tran	30x30-m x- tran	30x30-m x-tran	30x30-m x- tran
Temp. TidbiT	X	X		X		X			X			X
Photo / Spatial cover / density quadrats	12	12	12	12	12	12	12	12	12	12	12	12
Infauna core	12	12	12	12	12	12	12	12	12	12	12	12
Sediment contour			X	X	X	X	X					
Sweep net			5		6	6						
Fish Traps			3		3							
Light meters			2		2							

Table 1. Continued.

Dec 2002	EB-CON	OGC-CON	OLN-1.5	OLN-2.5	OLN-5	OLN-10	OLN-CON	Mad River	Bird Island	Sand Island	East Bay	Arcata Channel
Plot description	Eelgrass bed	Ground culture	1.5-ft. long-line	2.5-ft. long-line	5-ft. long-line	10-ft. long-line	control (no lines)	reference site	reference site	reference site	reference site	reference site
Sample date	4 Dec	4 Dec	2 Dec	3 Dec	3 Dec	2 Dec	2 Dec	5 Dec	5 Dec	4 Dec	6 Dec	6 Dec
Sample pattern	30-m transect	30-m transect	30x30-m grid	30x30-m grid	30x30-m grid	30x30-m grid	30x30-m grid	30x30-m x- tran	30x30-m x- tran	30x30-m x- tran	30x30-m x-tran	30x30-m x- tran
Temp. TidbiT	X	X		X		X			X			X
Photo / Spatial cover / density quadrats	12	12	12	12	12	12	12	12	12	12	12	12
Infauna core	12	12	12	12	12	12	12	12	12	12	12	12
Sediment contour			X	X	X	X	X					
Fish Traps			3		3							

May 2003	EB-CON	OGC-CON	OLN-1.5	OLN-2.5	OLN-5	OLN-10	OLN-CON	Mad River	Bird Island	Sand Island	East Bay	Arcata Channel
Plot description	Eelgrass bed	Ground culture	1.5-ft. long-line	2.5-ft. long-line	5-ft. long-line	10-ft. long-line	control (no lines)	reference site	reference site	reference site	reference site	reference site
Sample date	17 May	17 May	15 May	15 May	16 May	15 May	16 May	17 May	19 May	19 May	18 May	18 May
Sample pattern	30-m transect	30-m transect	30x30-m grid	30x30-m grid	30x30-m grid	30x30-m grid	30x30-m grid	30x30-m x- tran	30x30-m x- tran	30x30-m x- tran	30x30-m x-tran	30x30-m x- tran
Temp. TidbiT	X	X		X		X			X			X
Photo / Spatial cover / density quadrats	12	12	12	12	12	12	12	12	12	12	12	12
Infauna core	12	12	12	12	12	12	12	12	12	12	12	12
Sediment contour			X	X	X	X	X					
Fish Traps			3		3							
Light meters				2	2		2					

Table 1. Continued.

July 2003	EB-CON	OGC-CON	OLN-1.5	OLN-2.5	OLN-5	OLN-10	OLN-CON	Mad River	Bird Island	Sand Island	East Bay	Arcata Channel
Plot description	Eelgrass bed	Ground culture	1.5-ft. long-line	2.5-ft. long-line	5-ft. long-line	10-ft. long-line	control (no lines)	reference site	reference site	reference site	reference site	reference site
Sample date	13 Jul	13 Jul	12 Jul	11 Jul	12 Jul	12 Jul	11 Jul	14 Jul	13 Jul	14 Jul	15 Jul	15 Jul
Sample pattern	30-m transect	30-m transect	30x30-m grid	30x30-m grid	30x30-m grid	30x30-m grid	30x30-m grid	30x30-m x- tran	30x30-m x- tran	30x30-m x- tran	30x30-m x-tran	30x30-m x- tran
Temp. TidbiT	removed	removed		removed		removed			removed			removed
Photo / Spatial cover / density quadrats	12	12	12	12	12	12	12	12	12	12	12	12
Infauna core	12	12	12	12	12	12	12	12	12	12	12	12
Sediment contour			X	X	X	X	X					
Fish Traps			3		3							

								Commercial Long-line Areas		
Aug 2003			OLN-1.5	OLN-2.5	OLN-5	OLN-10	OLN-CON	EB 6-2 (7 sites)	EB 1-1 (4 sites)	EB 1-1 (north)
Plot description			1.5-ft. long-line	2.5-ft. long-line	5-ft. long-line	10-ft. long-line	control (no lines)	long-line reference site	long-line reference site	long-line reference site
Sample date			10 Aug	10 Aug	10 Aug	10 Aug	11 Aug	11-12 Aug	13 Aug	13 Aug
Sample pattern			30x30-m grid	30x30-m grid	30x30-m grid	30x30-m grid	30x30-m grid	30-m transect	30-m transect	30-m transect
Photo / Spatial cover / density quadrats			12	12	12	12	12	12	12	12
Zostera biomass/size			12	12	12	12	12	12	12	
Long-line light profile								X		

Figure 2. Experimental Pacific oyster long-line spacing plots in Arcata Bay, CA
A) 30 x 30-m oyster long-line plot
B) Plots OLN-2.5 and OLN-1.5 before harvest
C) Plots OLN-2.5 and OLN-1.5 after harvest

Table 2. Description of commercial oyster long-line plots sampled within Coast Seafood Co. management areas East Bay 1-1 and East Bay 6-2 during 11-13 August 2003. Table indicates long-ling spacing arrangement (distance between oyster lines) and number of 30 m transect lines sampled; value in parentheses indicates sample size (number of photoquadrats and number of *Zostera marina* plants collected for measurement).

Oyster Long-line spacing	**EB 6-2**	**EB 1-1**
Control (no lines)	1 (12)	1 (12)
2.5 ft. (with 5-ft. break every 5-6 lines)	2[a] (12)	1 (north side) (12)[b]
2.5-5 ft. (2.5-ft. pairs spaced 5 ft. apart)	1 (12)	1 (12)
5 ft.	1 (12)	1 (12)
2.5-10 (2.5-ft. pairs spaced 10 ft. apart)	1 (12)	Not Available
10 ft.	1 (12)	1 (12)

[a] Light profile measured.

[b] Eelgrass plants not collected.

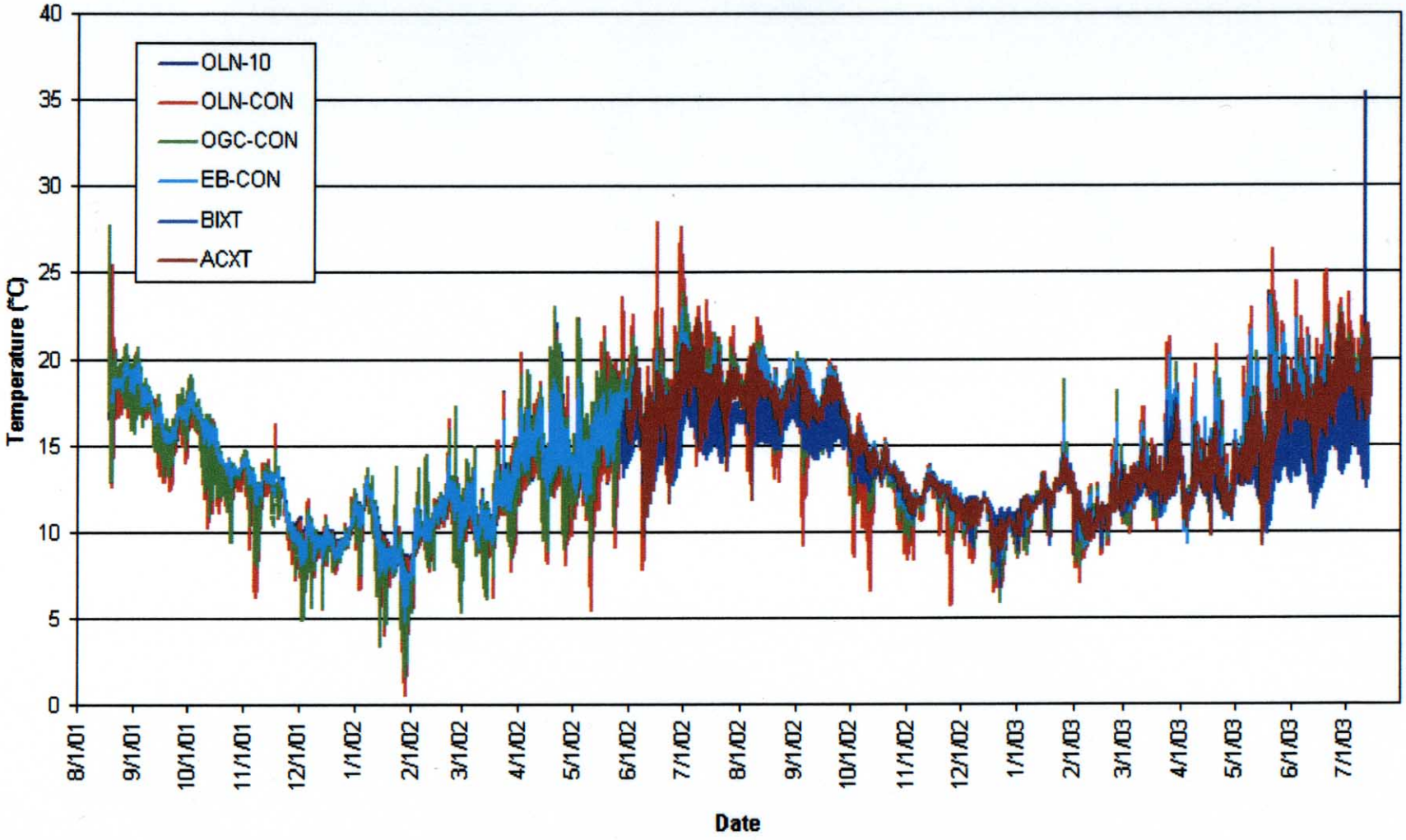


Figure 3. Tideflat temperatures measured at six study sites around Arcata Bay, CA. Temperature (*C) measurements at the mud/water interface recorded at one-hour intervals from August 2001 - July 2003. Legend indicates plot code for the six study sites (see Figure 1 and Table 1 for plot descriptions and locations).

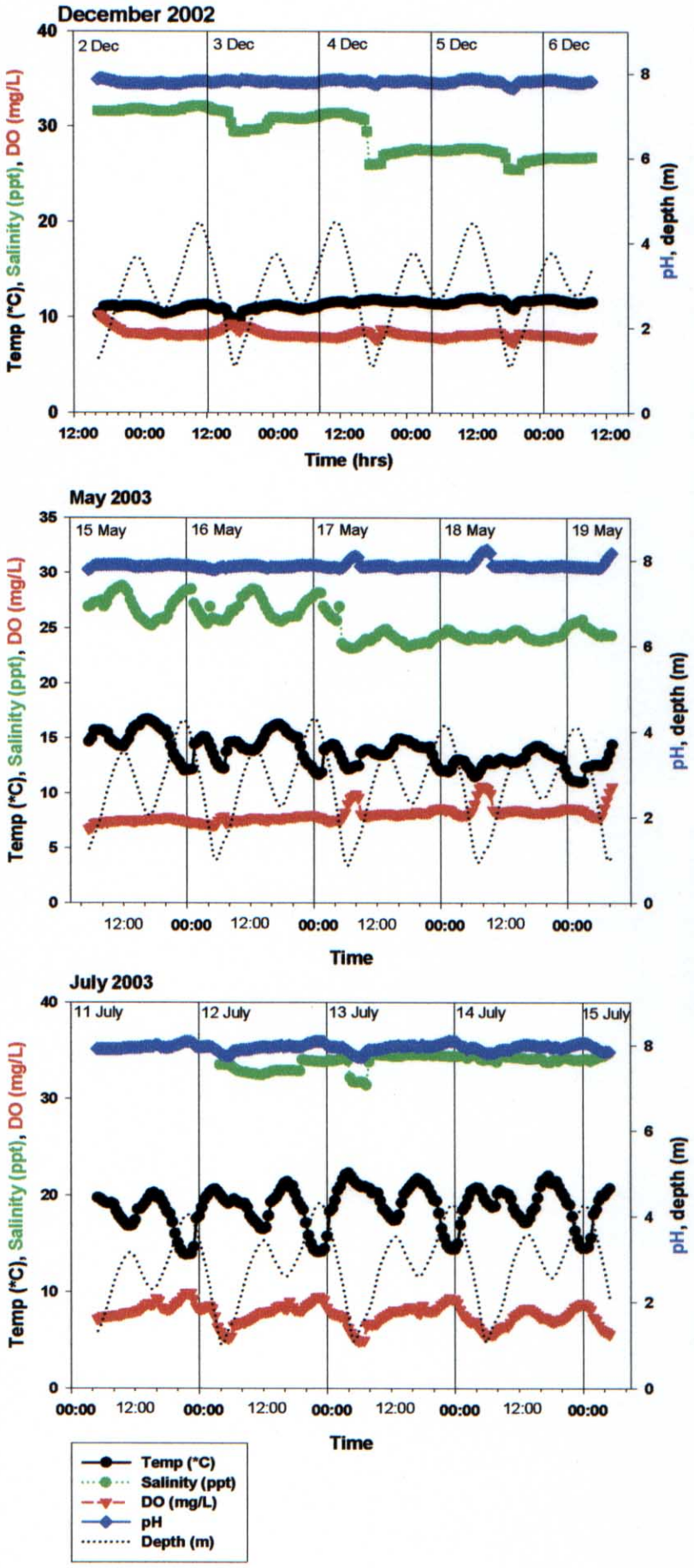
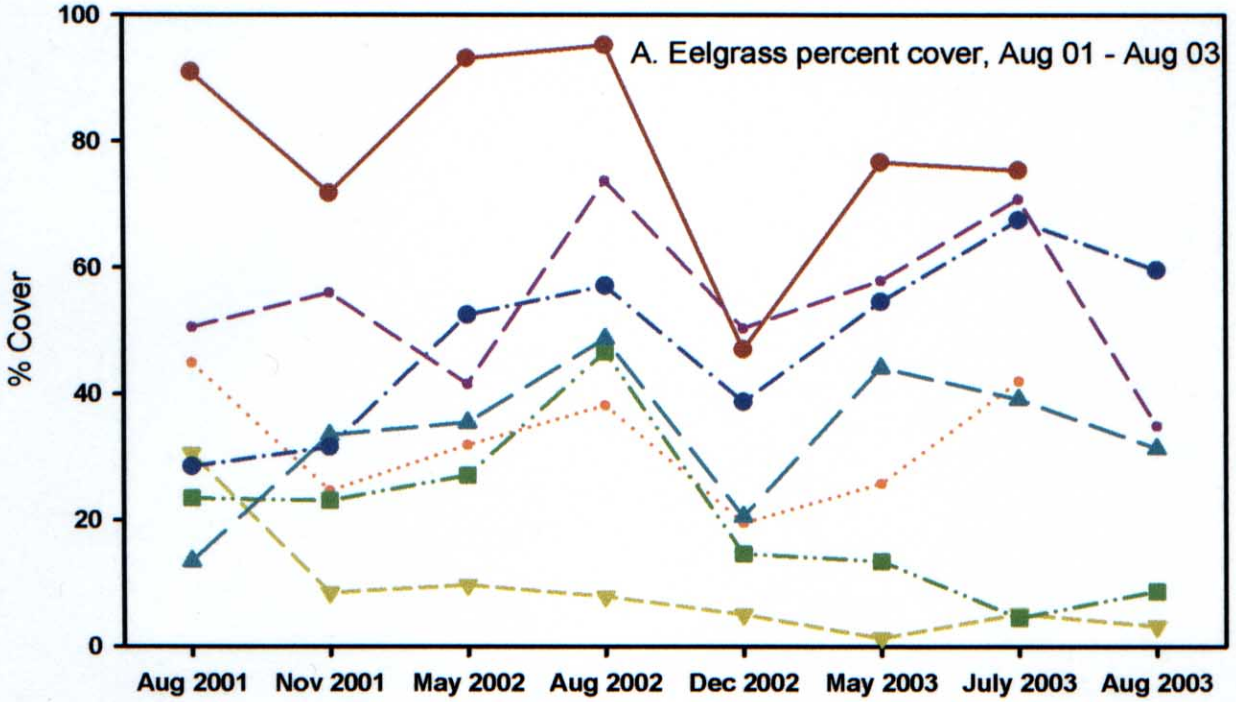
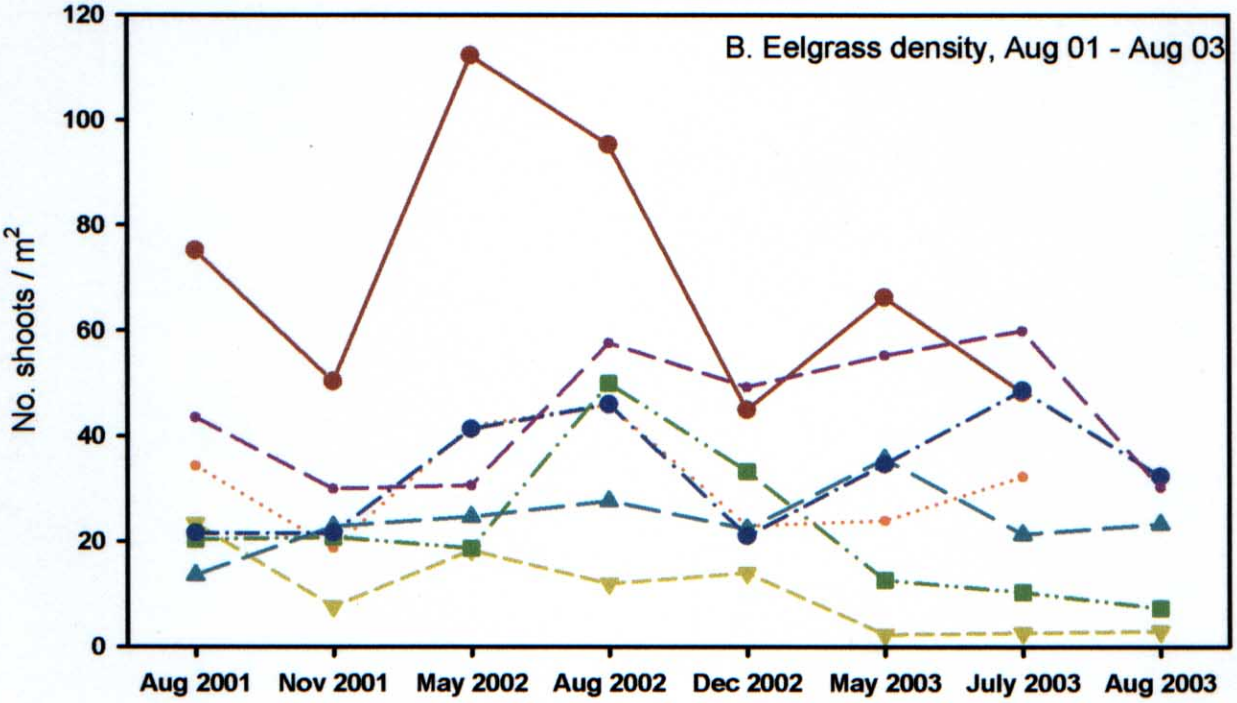


Figure 4. Water quality characteristics within the East Bay Slough tidal channel during sampling periods in Dec 2002 and May and July 2003. Note seasonal increase in estuarine water temperatures from winter through spring and summer.





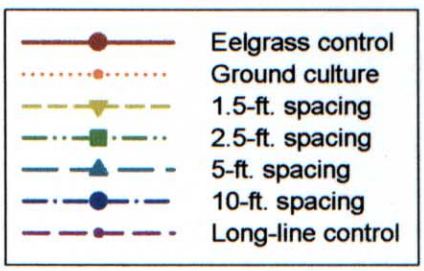


Figure 5. *Z. marina* percent cover (A) and shoot density (B) at the experimental long-line spacing plots, an oyster ground culture site, and an eelgrass control site, August 2001 - August

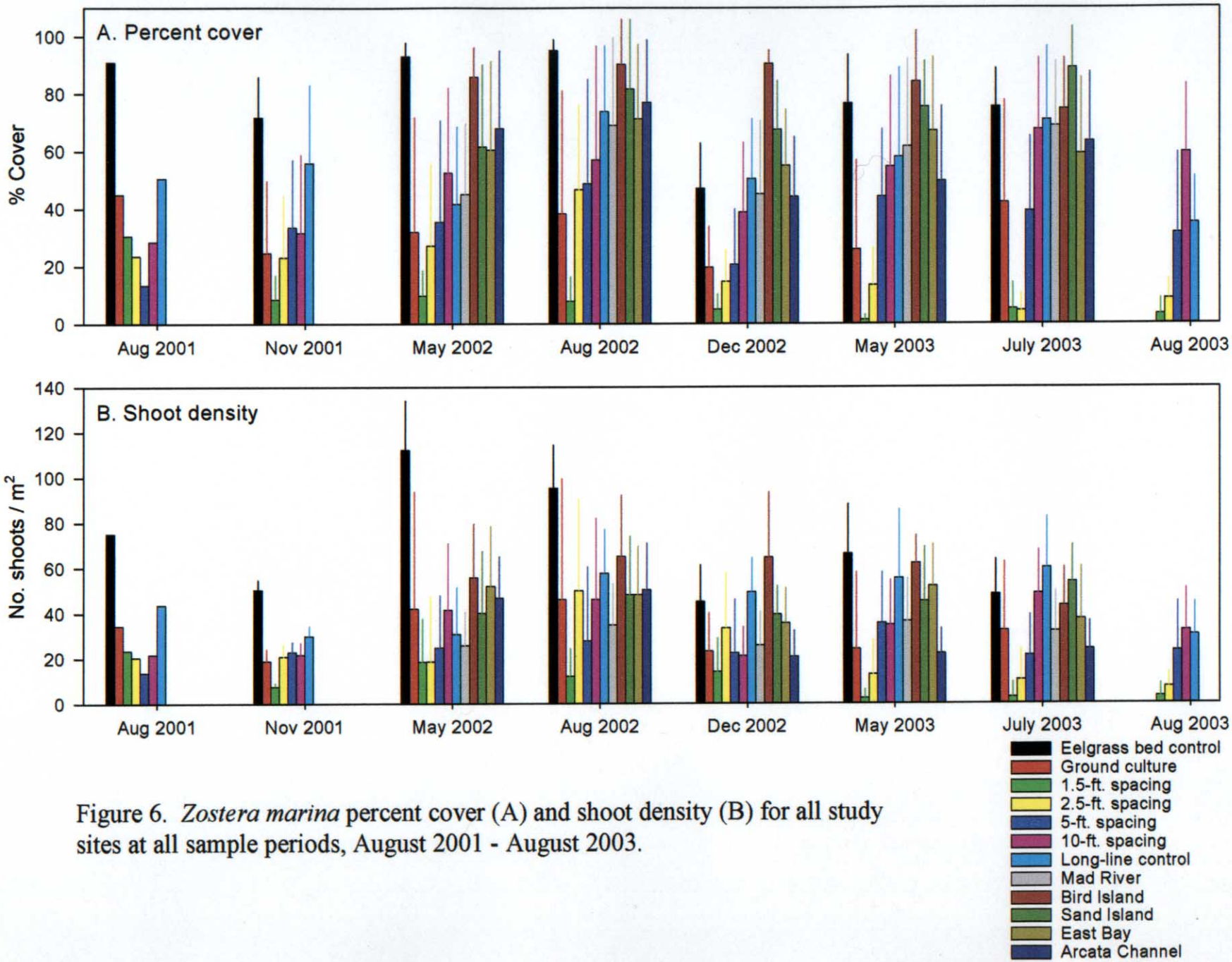
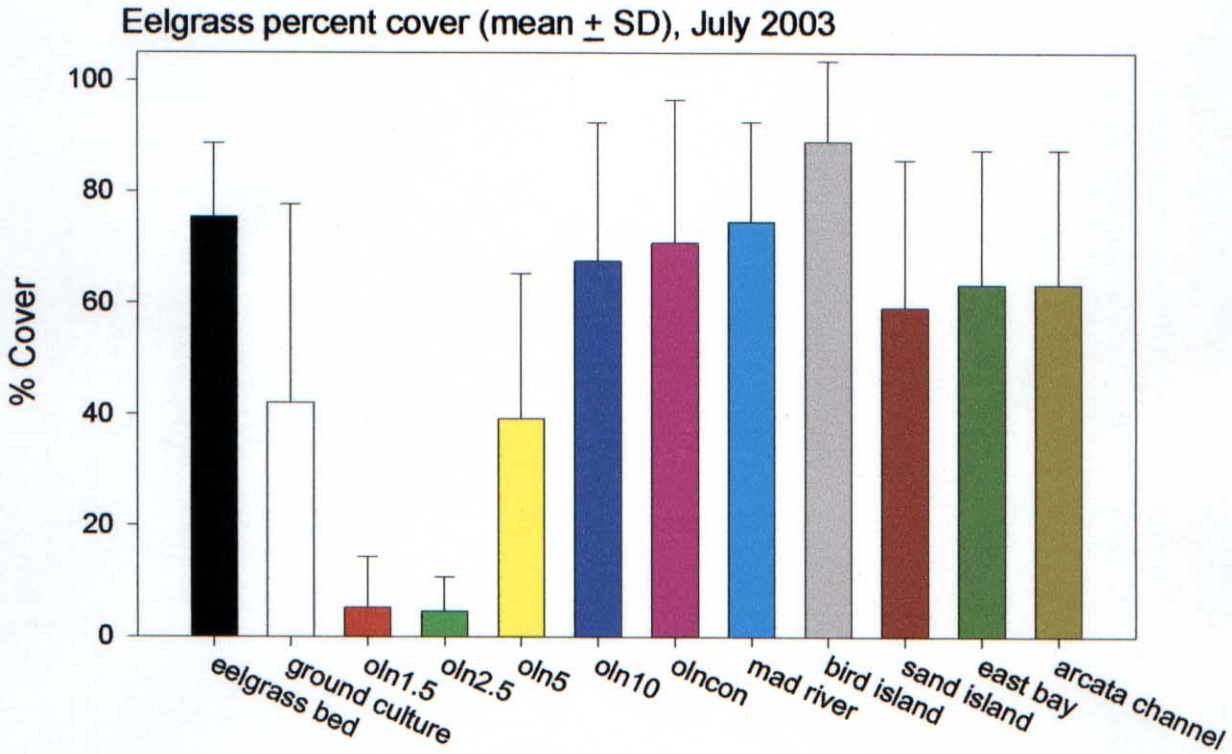


Figure 6. *Zostera marina* percent cover (A) and shoot density (B) for all study sites at all sample periods, August 2001 - August 2003.



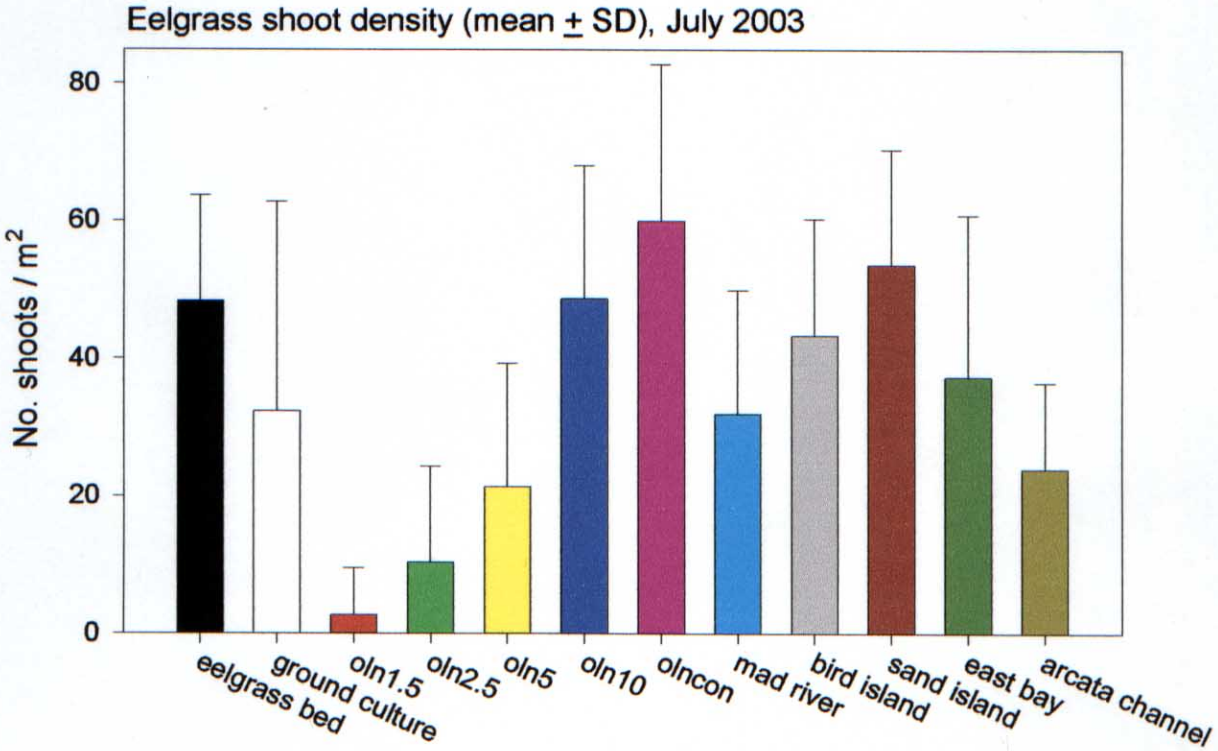


Figure 7. Comparison of eelgrass metrics among the experimental oyster line plots and Arcata Bay eelgrass reference sites immediately after oyster harvest and removal of the oyster lines (July 2003).

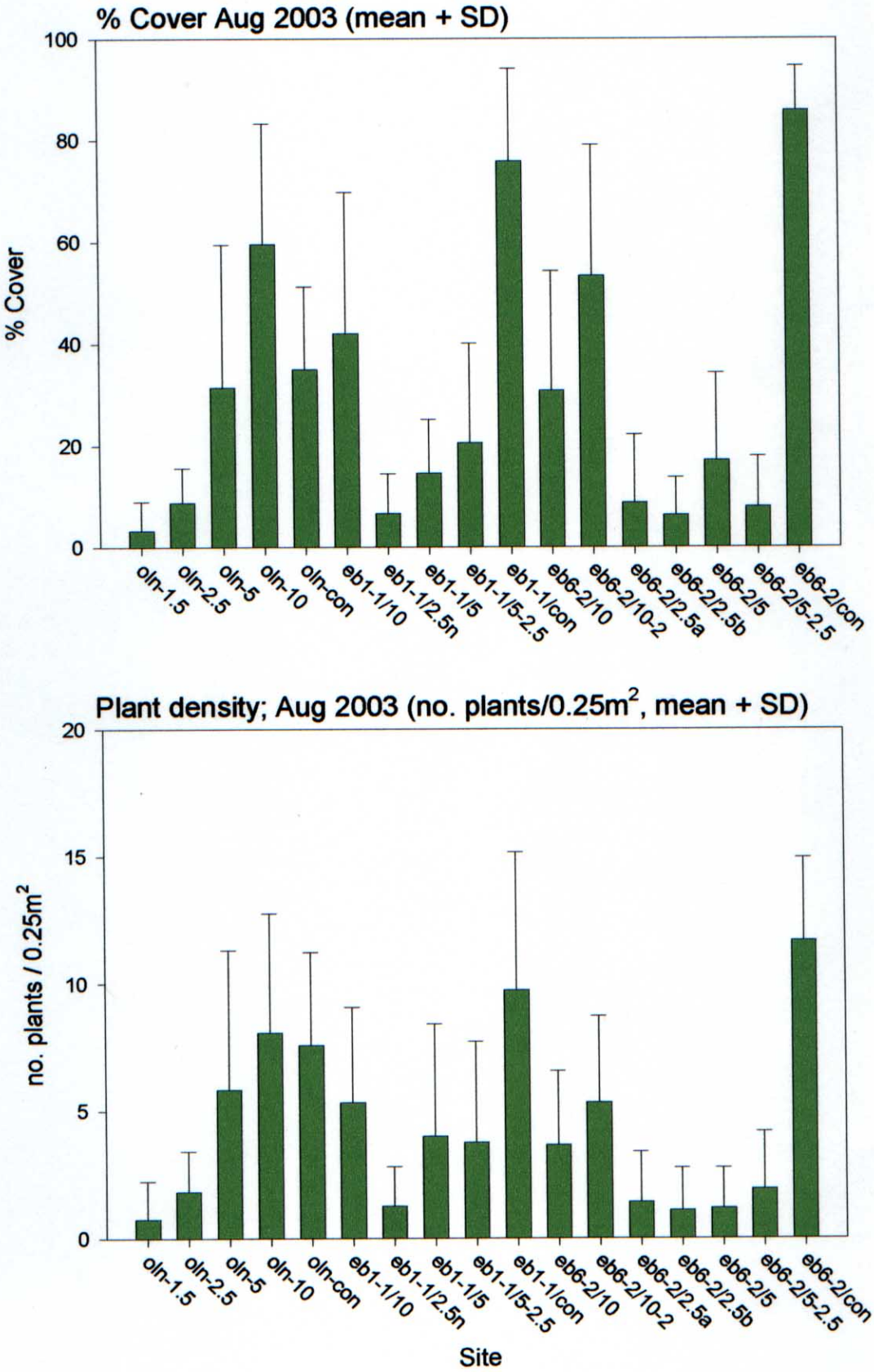


Figure 8. Comparison of eelgrass spatial cover and density among experimental oyster line spacing plots and commercial oyster mariculture areas in Arcata Bay, CA.

Table 3. Summary of 5 most abundant invertebrate taxa in benthic cores collected in August and November 2001 and May 2002.

Site	No. of Cores	Avg. Biomass	Sp. 1	no.	Sp. 2	no.	Sp. 3	no.	Sp. 4	no.	Sp. 5	no.
Aug 2001												
oln-1.5	5	0.108	*Exogone lourei*	269	*Photis* sp. juv.	94	*Aphelochaeta* sp.	73	oligochaetes	59	*Leptochelia savignyi*	56
oln-2.5	5	0.125	*Exogone lourei*	209	oligochaetes	99	*Aphelochaeta* sp.	71	*Leptochelia savignyi*	68	*Sphaerosyllis californiensis*	59
oln-5	5	0.494	*Exogone lourei*	139	*Eudorella pacifica*	69	*Aphelochaeta* sp.	60	*Leptochelia savignyi*	58	*Polydora pygidialis*	48
oln-10	5	0.354	*Exogone lourei*	187	*Leptochelia savignyi*	98	*Aphelochaeta* sp.	92	*Polydora pygidialis*	61	oligochaetes	60
oln-con	5	0.224	*Exogone lourei*	264	oligochaetes	92	*Leptochelia savignyi*	80	Maldanidae sp.	74	*Aphelochaeta* sp.	73
eb-con	5	0.104	*Exogone lourei*	235	*Leptochelia savignyi*	188	*Photis* sp. juv.	143	oligochaetes	96	*Grandidierella japonica*	65
ogc-con	5	0.106	*Leptochelia savignyi*	321	*Exogone lourei*	292	oligochaetes	59	*Grandidierella japonica*	57	*Photis* sp. juv.	49
November 2001												
oln-1.5	10	0.212	*Exogone lourei*	806	*Photis* sp. juv.	536	*Leptochelia savignyi*	427	oligochaetes	391	*Aphelochaeta* sp.	160
oln-2.5	10	0.143	*Photis* sp. juv.	433	oligochaetes	193	*Leptochelia savignyi*	160	*Aphelochaeta* sp.	137	*Exogone lourei*	126
oln-5	10	0.313	*Leptochelia savignyi*	581	*Exogone lourei*	516	*Photis* sp. juv.	502	oligochaetes	285	*Exogone sp.*	245
oln-10	25	0.254	*Exogone sp.*	1256	*Leptochelia savignyi*	946	*Photis* sp. juv.	705	Cirratulidae sp.	466	oligochaetes	465
oln-con	10	0.533	*Leptochelia savignyi*	285	*Photis* sp. juv.	285	*Exogone lourei*	248	oligochaetes	248	*Exogone sp.*	226
eb-con	10	0.212	*Leptochelia savignyi*	931	*Exogone sp.*	825	oligochaetes	448	*Zeuxo normani*	210	*Grandidierella japonica*	159
ogc-con	10	0.185	*Leptochelia savignyi*	514	*Paramicrodeutopus schmitti*	402	*Zeuxo normani*	270	oligochaetes	209	*Photis* sp. juv.	166

Table 3. Continued.

Site	No. of Cores	Avg. Biomass	Sp. 1	no.	Sp. 2	no.	Sp. 3	no.	Sp. 4	no.	Sp. 5	no.
May 2002												
oln-1.5	12	0.113	*Aphelochaeta* sp.	298	*Capitella* sp.	186	oligochaetes	133	*Photis* sp. juv.	96	*Exogone lourei*	74
oln-2.5	12	0.284	*Aphelochaeta* sp.	284	oligochaetes	155	*Capitella* sp.	130	*Exogone lourei*	98	Maldanidae sp.	72
oln-5	12	0.104	*Aphelochaeta* sp.	174	*Capitella* sp.	96	*Exogone lourei*	65	oligochaetes	64	Maldanidae sp.	55
oln-10	12	0.466	*Aphelochaeta* sp.	319	*Exogone lourei*	129	*Idotea* juv.	129*	*Capitella* sp.	97	oligochaetes	95
oln-con	12	0.180	*Protomedeia sp.*	502	*Exogone lourei*	291	*Aphelochaeta* sp.	229	Maldanidae sp.	146	*Leptochelia savignyi*	90
eb-con	11	0.108	*Leptochelia savignyi*	572	*Exogone lourei*	363	oligochaetes	305	*Aphelochaeta* sp.	264	copepods	120
ogc-con	12	0.080	*Leptochelia savignyi*	590	*Exogone lourei*	257	oligochaetes	206	*Aphelochaeta* sp.	167	nematodes	132
Arc. Ch.	12	0.354	oligochaetes	267	*Aphelochaeta* sp.	205	*Eudorella pacifica*	30	*Leitoscoloplos pugettensis*	25	Maldanidae sp.	22
Bird Is.	12	0.229	*Capitella* sp.	273	*Aphelochaeta* sp.	137	nematodes	60	oligochaetes	32	Maldanidae sp.	32
E.Bay	12	0.424	*Exogone lourei*	153	*Aphelochaeta* sp.	145	*Capitella* sp.	105	*Photis* sp. juv.	93	oligochaetes	89
Mad R.	12	0.113	*Capitella capitata*	282	*Aphelochaeta* sp.	168	oligochaetes	80	*Exogone lourei*	62	*Eudorella pacifica*	39
Sand Is.	12	0.199	*Aphelochaeta* sp.	300	*Capitella* sp.	283	*Idotea* juv.	121*	oligochaetes	93	Maldanidae sp.	54

Table 4. Summary of motile invertebrates and fish captured by baited minnow traps deployed in experimental oyster long-line plots (May 2002 – July 2003). Three traps were deployed per site during each sample period (2 traps per site in May 2002).

Sample date	Plot code	Organism	Number of individuals	Mean size (mm)*
May 02				
	OLN-1.5	*Cancer magister*	3	21.5
		Leptcottus armatus	10	75.6
	OLN-5	*Cancer productus*	3	64.7
		Leptocottus armatus	2	121.6
Aug 02				
	OLN-1.5	*Cancer magister*	10	34.3
		Cancer productus	1	67.5
		Leptocottus armatus	4	28.4
	OLN-5	*Cancer magister*	5	62.4
Dec 02				
	OLN-1.5	*Cancer magister*	1	63.6
		shrimp	5	10.7
	OLN-2.5	gammarid amphipod	1	8.4
May 03				
	OLN-1.5	*Cancer magister*	1	57.1
		Cancer productus	2	65.9
		Leptocottus armatus	4	12.4
	OLN-5	*Cancer magister*	4	63.0
		Cancer productus	3	71.6
		Leptocottus armatus	1	9.3
		shrimp	2	10.7
Jul 03				
	OLN-1.5	*Cancer productus*	1	42.4
		Crangon franciscorum	1	9.0
		Idotea resecata	1	20.0
		Leptocottus armatus	6	80.6
	OLN-5	*Crangon franciscorum*	4	9.3
		Leptocottus armatus	2	87.0

* Size measurements indicate mean fish length or carapace width for crabs and shrimp.

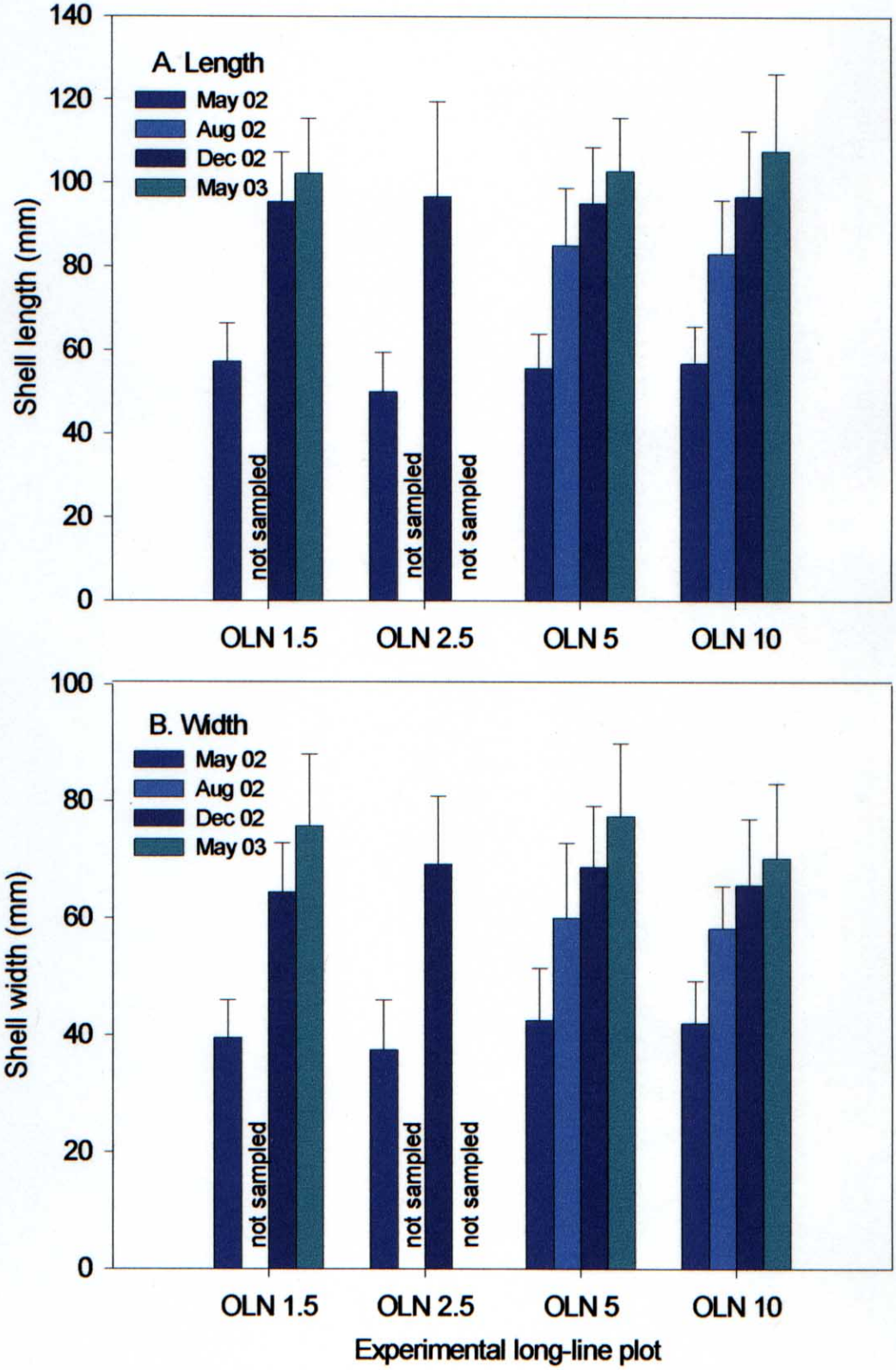


Figure 9. Seasonal growth of *Crassostrea gigas* within different oyster long-line spacing plots (Arcata Bay, CA). Shell dimensions indicate average length and width (± s.d.) for marked clusters of oysters.

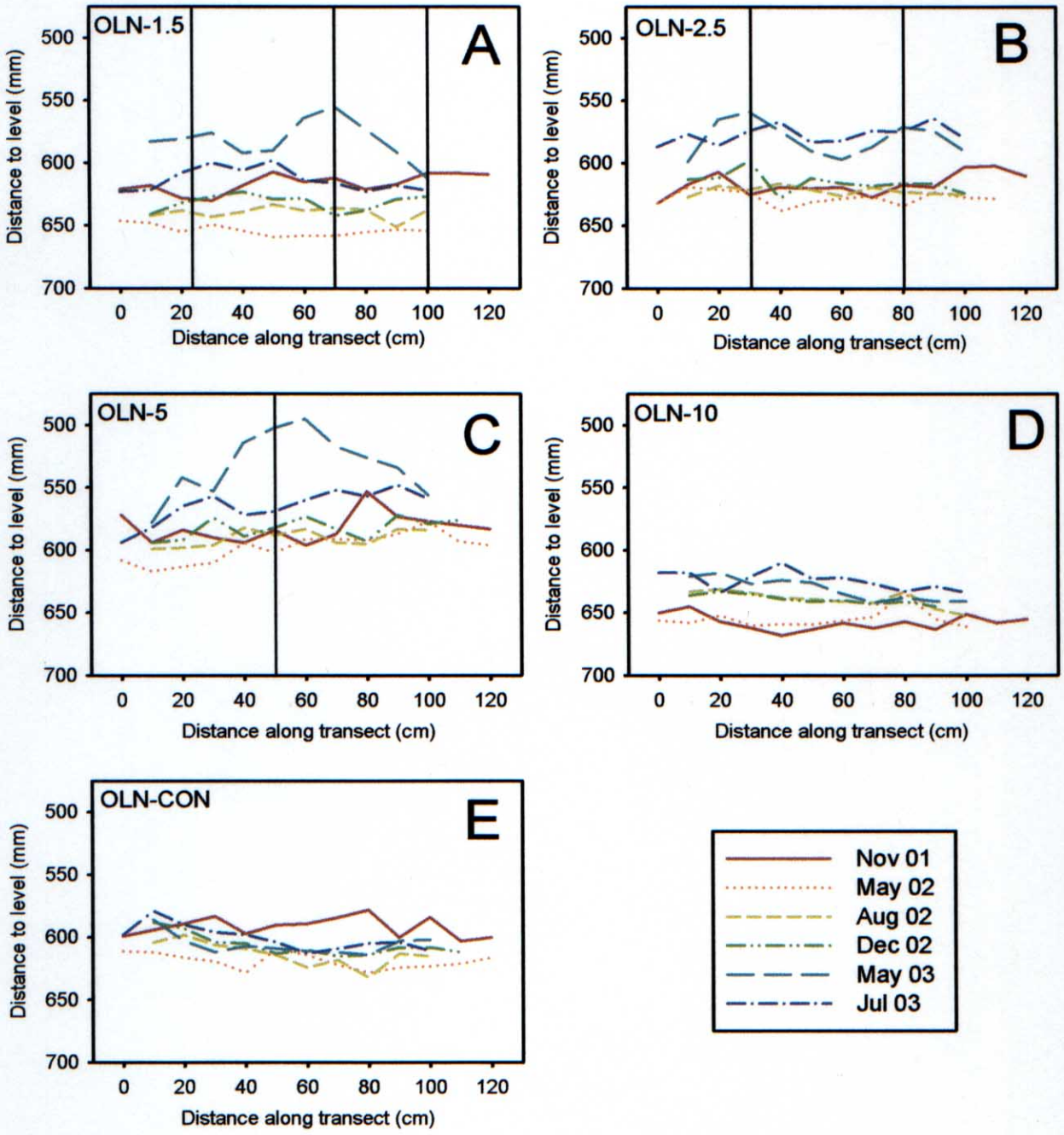


Figure 10. Seasonal changes in tideflat sediment elevation profiles within four experimental oyster line-spacing plots (A-D) and an adjacent control (no oyster) plot (E). Distance measurements indicate distance from sediment surface to a horizontal level located a fixed height above the sediment.

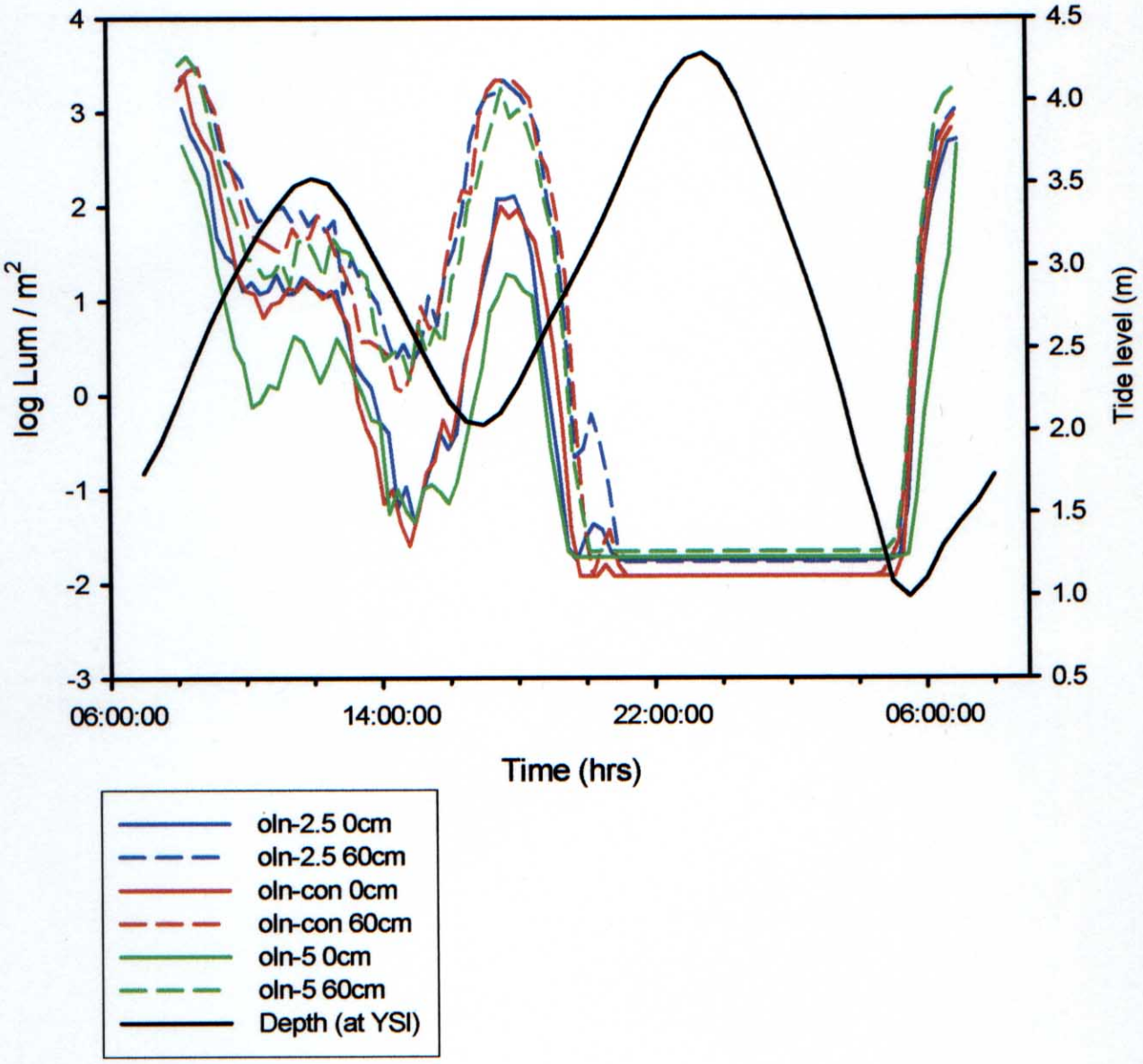


Figure 11. Time-series of incident light intensity measurements in 2 experimental oyster long-line plots and an adjacent control (no oyster) plot (15-16 May 2003). Light meters were placed in each plot at the level of the sediment surface (0 cm) and at a height of 60 cm above the sediment.

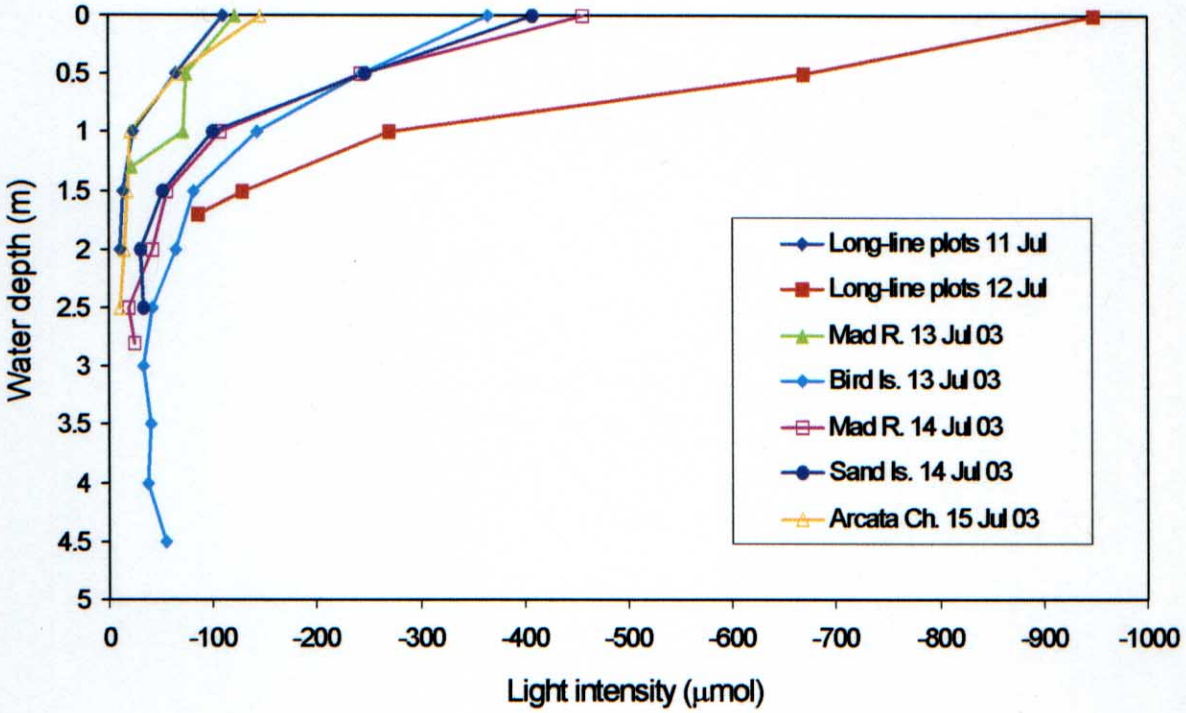


Figure 12. Light attenuation curves measured in primary tidal channels of Arcata Bay, CA (11-15 July 2003).

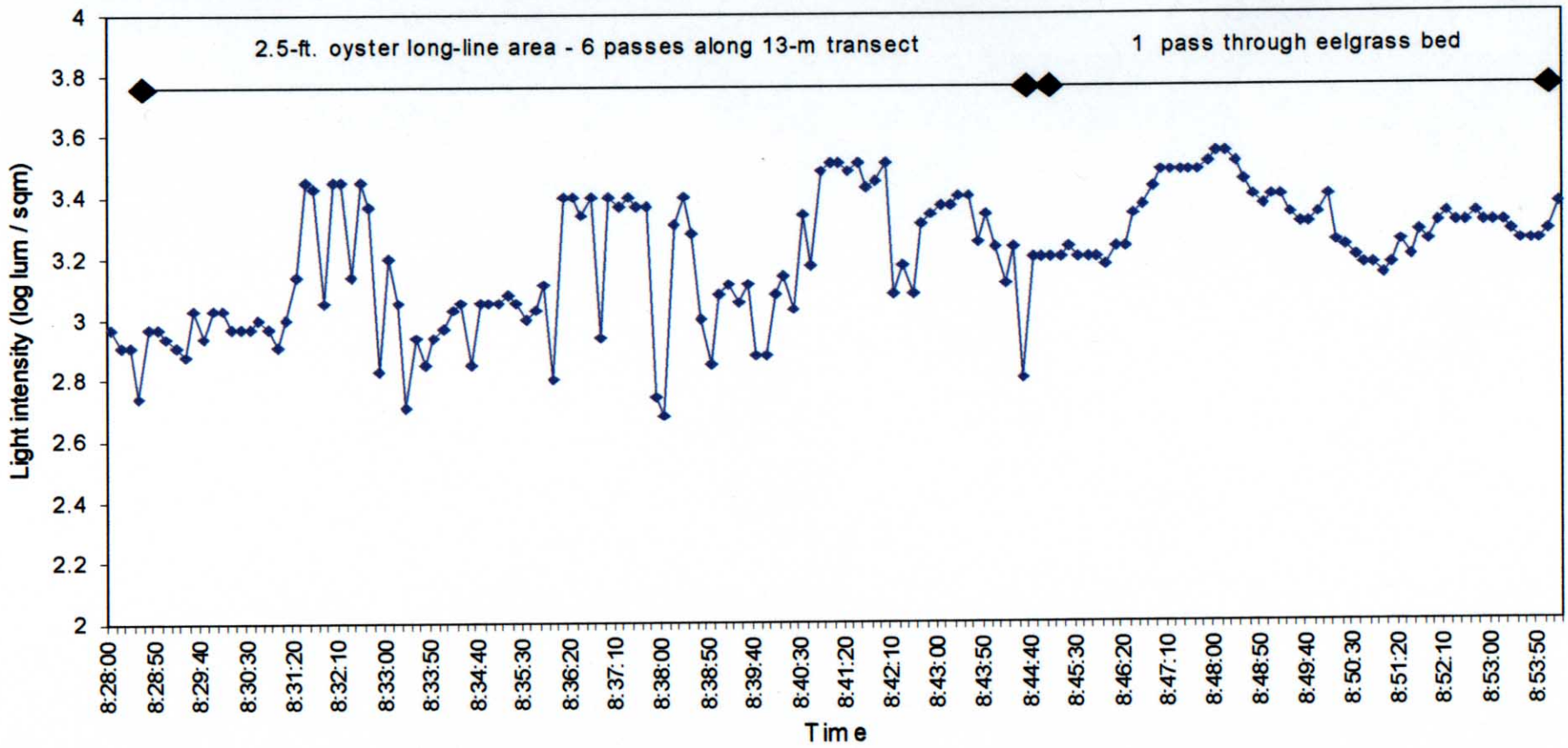


Figure 13. Profiles of incident light levels measured beneath oyster long-lines (2.5-ft. spacing; 0828-0845 hrs) and in an adjacent eelgrass bed (0845-0853 hrs; plot EB 6-2, 12 Aug 2003).

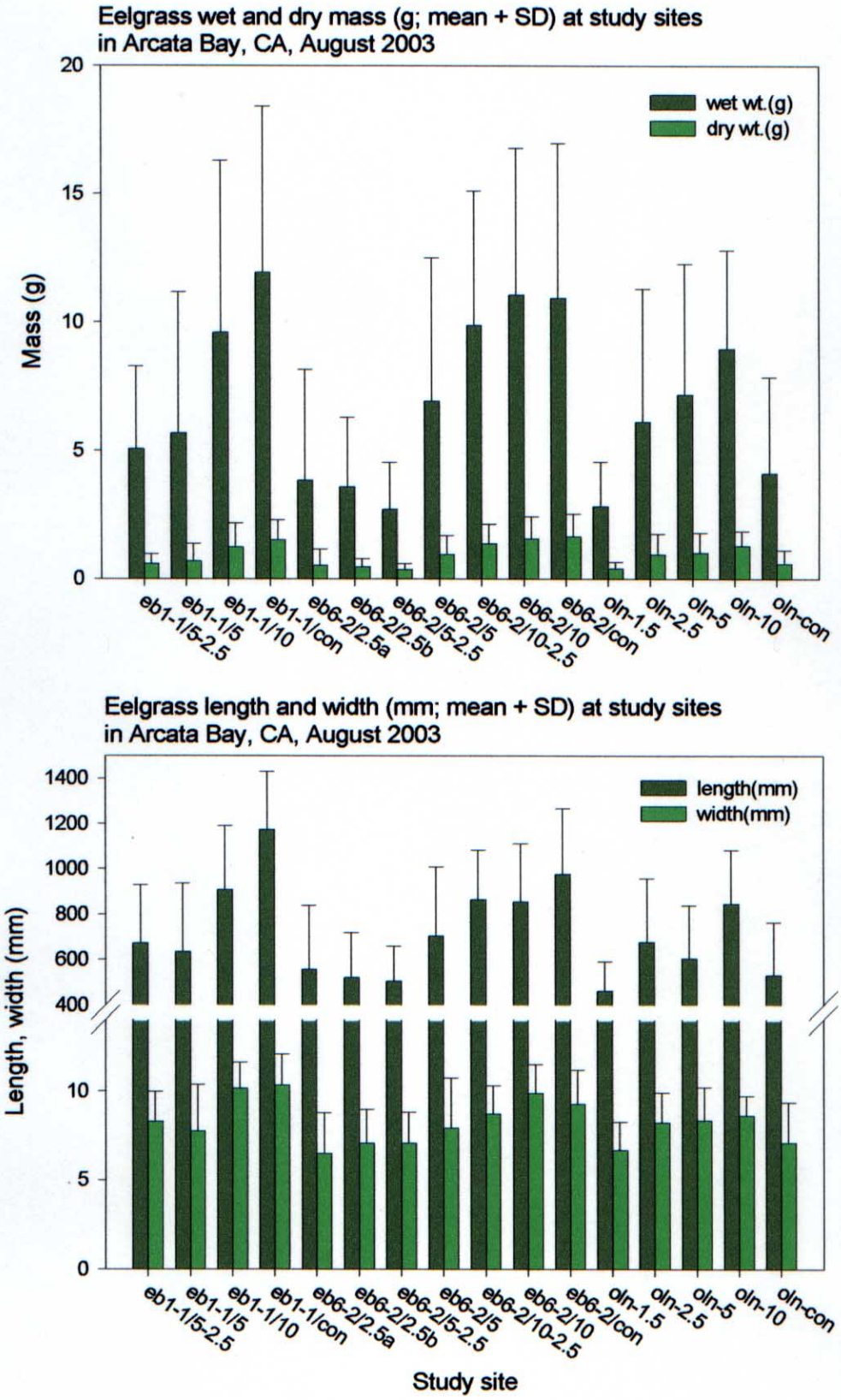


Figure 14. Average (+ SD) *Zostera marina* wet and dry biomass and maximum blade dimensions (length and width) for eelgrass plants collected from study plots in Arcata Bay, CA (August 2003). Sample size is 12 *Z. marina* plants for each study plot.

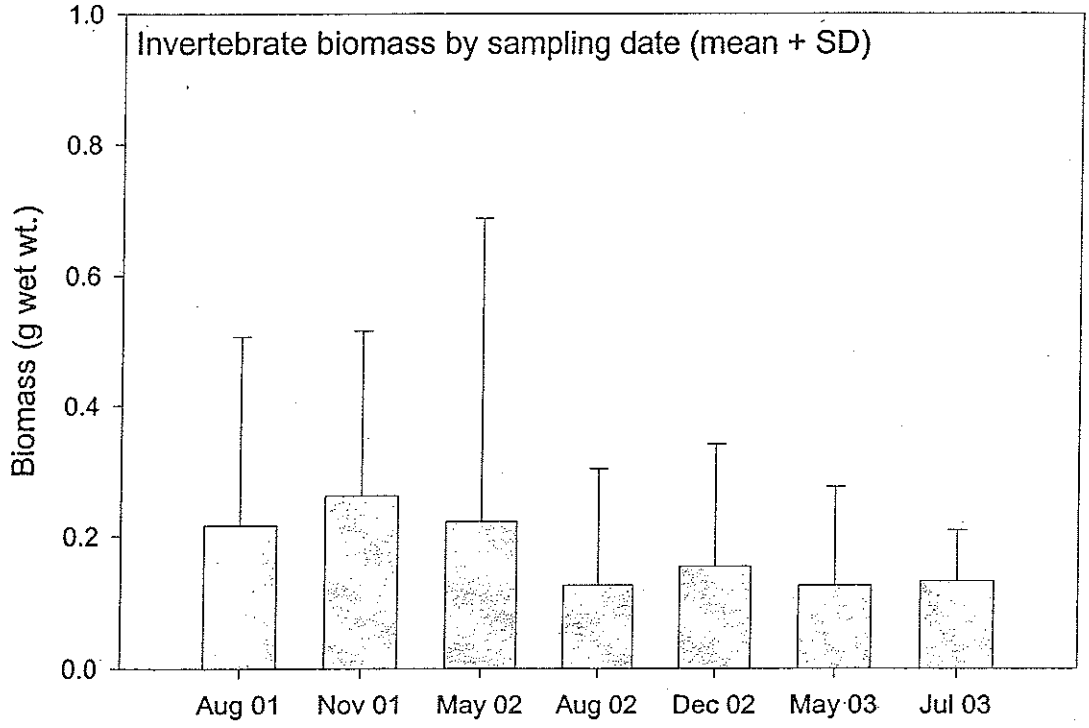
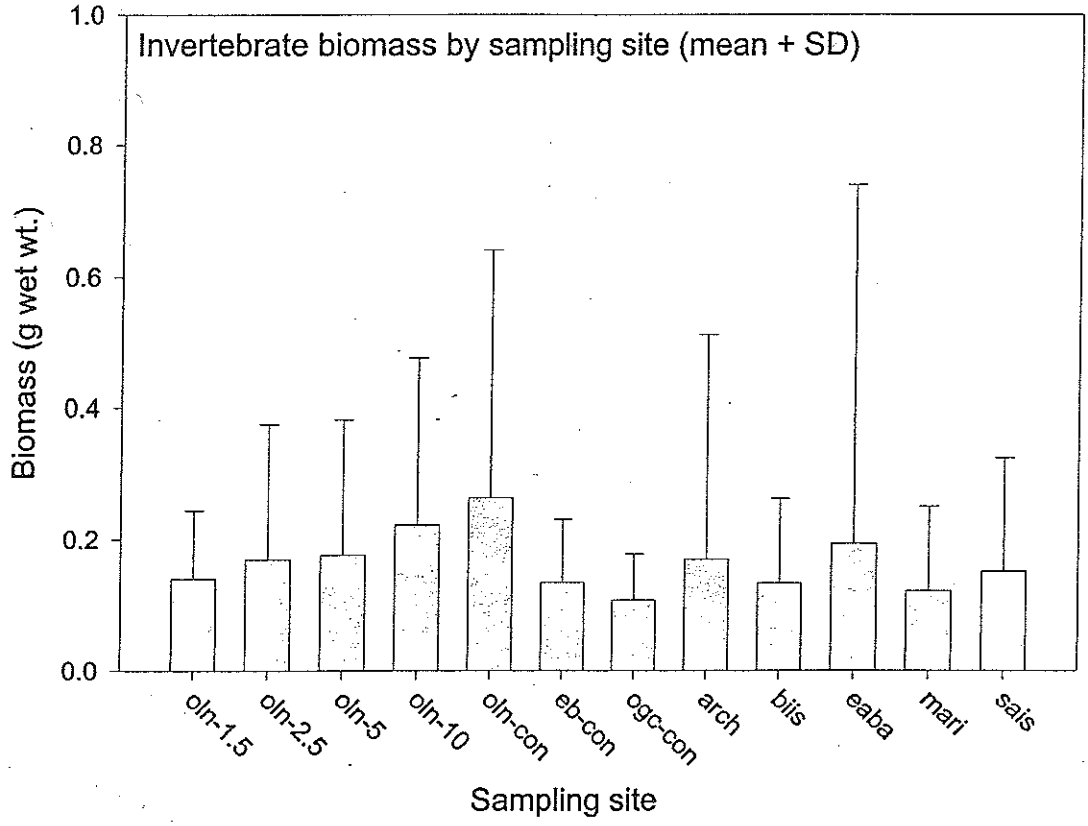



Figure 15. Comparisons of invertebrate biomass among seasons and among sampling sites within Arcata Bay, CA.