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Submerged Vegetation Monitoring Project:
2000 - 2002 Monitoring Report

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WASHINGTON STATE DEPARTMENT OF
Natural Resources
Doug Sutherland - Commissioner of Public Lands

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Submerged Vegetation Monitoring Project:
2000 - 2002 Monitoring Report

by

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EXECUTIVE SUMMARY

Project Overview

The purpose of the Submerged Vegetation Monitoring Project (SVMP) is to monitor status and trends in submerged aquatic vegetation in Puget Sound, Washington, USA. The project is part of the Puget Sound Ambient Monitoring Program, a multi-agency research effort that tracks indicators of ecosystem health. The SVMP has a broad scope with multiple phases, we are currently in phase one of the project:

Phase 1: Develop methods to monitor broad scale status and trends of submerged aquatic vegetation. Focus methodology development on *Zostera marina* L. (eelgrass). Conduct sampling and refine methods. Phase one objectives are to:

1. Assess status of vegetation abundance and distribution;
2. Summarize temporal trends over Puget Sound and subareas, with the ability to detect a 20% change in a 10 year period over Puget Sound;
3. Monitor vegetation parameters that are strong indicators of *Z. marina* bed distribution and health;
4. Consider stressors.

Phase 2: Expand monitoring to include other submerged vegetation types and monitor across gradients of stressors (e.g., shoreline development). Investigate long-term historical changes.

Phase 3: Develop programs that monitor submerged habitat at higher spatial and temporal resolutions. Gather experimental evidence on cause-effect interactions to build cause and effect models. Address functionality, habitat quality, and wildlife usage.

This report summarizes the first three years of research in the Submerged Vegetation Monitoring Project (SVMP). It reviews project objectives, methods, and results for three years of monitoring (2000 – 2002). It presents findings with respect to project objectives, recommends changes to program methods, and discusses potential future project directions.

To monitor *Z. marina* abundance and measure change over time, we adopted a sampling design that extrapolates results from randomly selected sites over geomorphological strata, regions, and the Puget Sound study area. Most sites are randomly selected and sampled for five consecutive years. This design optimizes the joint goals to accurately estimate the correct status of the population and accurately and precisely estimate changes over time. In addition to randomly selected sites, six core sites were hand picked for long term monitoring.

We measured a series of parameters which are recognized to be important indicators of *Z. marina* plant and bed condition: abundance (*Z. marina* area), minimum and maximum depth, and plant characteristics (density, leaf width and leaf length). Data on bed patchiness and water quality were also collected, these results will be discussed in subsequent reports.

We surveyed *Z. marina* beds using towed underwater videography. At each site, line transect sampling methods were employed to estimate total *Z. marina* area with quantified confidence intervals. We adopted underwater videography because vegetation communities in Puget Sound occur at depths beyond the range of conventional aerial photography and the large study area precludes more intensive methods such as diver transects. Additionally, the diversity of submerged vegetation species requires methodology with high species discrimination capability.

In order to optimize the Sound-wide estimate of *Z. marina* area, the study area was divided into strata based on geomorphological characteristics using a Geographical Information System (GIS). The flats stratum includes large embayments and small pocket beaches. The fringe stratum includes areas with relatively linear shorelines and encompasses most of the study area shoreline. Narrow fringe sites and wide fringe sites are differentiated by a width threshold of 305 m (1000 ft) separating ordinary high water and the –20 ft depth contour.

The study area was divided into five regions that grouped sites based on oceanographic similarities in order to evaluate status and trends in sub-areas of Puget Sound.

In an initial effort to link stressors to *Z. marina* distributions, we simulated *Z. marina* distribution at one site, Dumas Bay using a biophysical model (Zimmerman 2001 Appendix M). The model focuses on two parameters that affect submarine light availability: Total Suspended Solids (TSS) and Chlorophyll (Chl).

Results

Between 2000 and 2002, we sampled 66-76 sites per year in 47-56 field days per year. This sampling effort represents approximately 15% of the flats stratum population and 2% of the fringe stratum population. We collected benthic grab samples at approximately 40% of the sites to census plant characteristics.

There are approximately 200 km^2 of *Z. marina* in Puget Sound. *Z. marina* is not evenly distributed; slightly more than half of the *Z. marina* resource is in flats sites, the remainder occurs in narrow and wide fringe beds. One large embayment, Padilla Bay, contains approximately 20% of the *Z. marina* in Puget Sound.

Between 2000 and 2002, total *Z. marina* area in Puget Sound remained stable. No significant change was found between 2000-2001 (+3% SE 3.5%) or 2001-2002 (+1% SE 3%). Changes over time were observed at the regional scale. *Z. marina* area in *Hood Canal* and *San Juan Island/Strait of Juan de Fuca Regions* increased between 2000-2001, and decreased between 2001 and 2002. *North Puget Sound Region* had insufficient samples to detect change in the 2000-2001 and increased in 2001-2002. The *Saratoga/Whidbey Region* remained stable in both time periods. *Central Puget Sound Region* had insufficient samples to detect change.

Z. marina area changed at 13 sites (80% confidence interval). Between 2000 and 2001, *Z. marina* area increased at six sites and decreased at two sites. Between 2001 and 2002, it increased at two sites and decreased at three sites. No geographic patterns were evident among sites that changed. One of the sites, Westcott Bay, has also been identified by other research to be undergoing losses. Sites where change over time is documented are strong candidates for future monitoring.

Our goal was to detect as little as a 20% change in abundance of *Z. marina* over a ten year period. We predicted our ability to detect change by calculating the coefficient of variation (CV) necessary to meet this objective. We determined that the annual adjusted estimates have sufficiently low CVs to capture a 20% to 25% Sound-wide reduction in 10 years. In contrast, many monitoring programs can only reliably detect losses of 50-80%, which does not allow for management actions to be taken before a huge loss of the resource occurs.

Z. marina bed depth ranged from an absolute minimum of +1.8 m to a maximum of –8.8 m (MLLW). Mean minimum and mean maximum bed depth varied broadly within regions. These results reflect the wide range in physical parameters throughout the study area that are known to affect *Z. marina* distribution, including water turbidity, sediment characteristics, wave action, and tidal amplitude (Koch 2001).

Between 2000 and 2001, significant changes were observed in mean minimum depth at four sites and in mean maximum depth at seven sites. Between 2001 and 2002, significant changes were observed in mean minimum depth at seven sites, no changes were observed in mean maximum depth. Given the average sampling effort and average standard deviation during the first three years of sampling, we estimate that we can detect an approximately 1.2 m (4 ft) difference in mean maximum *Z. marina* depth and a 0.9 m (3 ft) difference in mean minimum bed depth at individual sites.

We collected plant characteristics data to contribute to our ability to detect changes over time at the site level. We hypothesized that some plant characteristics might be more sensitive to change than abundance and, therefore, be a precursor to decline in *Z. marina* abundance. We found that at our current level of sampling effort, we could only detect catastrophic changes using plant characteristics data. Therefore, we recommend discontinuing plant characteristics sampling for Sound-wide monitoring.

While the plant characteristics sampling did not meet our monitoring goals, they illustrate the wide variability of plant characteristics of *Zostera marina* over the study area. These results provide a range of values for comparison to smaller scale studies throughout Puget Sound, parameterization data for modeling studies, and can also be useful for restoration, inventory, and monitoring.

Sound-wide, mean shoot density per grab station ranged from 0 to 3,050 shoots m^{-2}. Shoot densities were greatest between 0 and –2 m (MLLW). Shoot density at sites averaged 194.4 shoots m^{-2} in 2000, 163.0 shoots m^{-2} in 2001, and 90.6 shoots m^{-2} in 2002. Over the study period, mean and maximum shoot density increased at some sites and decreased at others. Mean and maximum shoot density was lower in 2002 than in 2000 and 2001. This change over time can be explained in part by site rotation, some sites with high densities rotated out of the sampling pool.

Shoot density is often negatively correlated with depth. Our data supports this relationship with a weak but statistically significant correlation. Shoot density is also dependant on many interrelated factors at a site such as habitat type, substrate type, and wave exposure. *Z. marina* was found most often in sandy substrates in our study and other studies in Puget Sound (Gayaldo 2002, Phillips 1984). Density and leaf characteristics varied by region. The *Hood Canal Region* and *Central Puget Sound Region* had higher densities and smaller plants, while northern regions had lower densities and larger plants. Mean density, leaf length and leaf width were significantly different between the flats and fringe geomorphological strata.

The biophysical model simulations at Dumas Bay identified total suspended sediment (TSS) as a more important water quality variable controlling seagrass distributions than chlorophyll concentration. This finding is similar to results in San Francisco Bay, where light limitation caused by high water column sediment loads can prevent phytoplankton growth and limit *Z. marina* distribution in this eutrophic estuary (Alpine and Cloern 1988, Zimmerman et al. 1991, Zimmerman et al. 1995). In Puget Sound, sediment levels are elevated near glacially-fed river mouths in the spring and early summer. Additionally, anthropogenic activities such as alteration of the shore, dredging and upland land use practices could elevate the natural levels of TSS in streams and rivers. The biophysical model may be useful in future studies to predict potential impacts of these activities on *Z. marina* distribution.

Generally, underwater videography survey technology worked well in a range of environmental conditions. It discriminated *Z. marina* with a high degree of certainty from all species except *Z. japonica* and *Phyllospadix* spp. We would like to increase the accuracy and precision of the depth measurements in future sampling. However, both environmental and technological factors are known to introduce uncertainty to depth measurement, especially in shallow water environments with complex tidal regimes.

We compared our Z. marina area estimates to other data sets. While a rigorous comparison is not possible because other data are sparse and were derived during different time periods with different methods, our results are generally consistent. We believe our estimate has relatively high accuracy because it is based on high resolution data and has greater species discrimination capability.

Concluding Remarks

Results from the first three years of research suggest that the SVMP design meets our project objectives to monitor status and trends in *Z. marina* in Puget Sound. Some improvements are identified to refine current monitoring methods. Additionally, a series of key research issues emerged that are beyond the scope of the current project. We identified the following priorities for future research, if funding becomes available:

- Focus on "hotspots". Conduct further research at sites where significant changes in bed coverage or distribution have been documented. Also consider particular habitat types and regions that are at risk.
- Conduct higher resolution studies of *Z. marina* plant parameters, bed characteristics and environmental conditions. Higher resolution studies will help us understand natural variability, identify parameters that can serve as "early warning" indicators of *Z. marina* bed decline, and link to stressors at specific sites.
- Document long-term historical changes through analysis of available historical data or modeling.
- Develop a rigorous conceptual model of *Z. marina* distribution to focus long term monitoring efforts. A conceptual model is needed that considers environmental conditions in Puget Sound and dynamics at the scale of the bed and landscape.
- Advance the development of predictive measures of *Z. marina* decline in order to anticipate potential losses and avoid future declines.

While documenting trends in Puget Sound's *Z. marina* resource is important, it is only a first step toward a fully developed monitoring program. When it is most effective, monitoring also tracks specific natural and anthropogenic stressors and measures the success of management actions. Our ultimate goal is to develop such an adaptive management framework to help guide best management of the *Z. marina* resource.

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Notice

1 INTRODUCTION

> *"Seagrasses are among the most productive ecosystems in the world and perform a number of irreplaceable ecological functions which range from chemical cycling and physical modification of the water column and sediments to providing food and shelter for commercial, recreational as well as ecologically important organisms". (Thayer et al. 1997).*

1.1 Project Objectives

Puget Sound is a large, fjord-type estuarine complex located in the northeast Pacific, USA. Documented resource losses in this highly productive ecosystem have led to increased interest in understanding how natural and anthropogenic stressors are affecting Puget Sound's health (Wilson et al. 1994, West 1997, PSAT 2002). Nearshore vegetation communities are a focus of interest because of their recognized functions and high rates of loss associated with human activities (Short and Wyllie-Echeverria 1996). While historical losses of tidal salt marshes in the region are fairly well understood (Bortelson et al. 1980, Thom and Hallum 1991), little is known about historical or current trends in submerged vegetation. Given the recognized importance of these habitats to ecosystem health, more information is needed on status and trends of submerged vegetated habitats to guide management and research.

In 2000, The Washington State Department of Natural Resources (DNR) initiated a program to monitor the status and trends of submerged, vegetated habitats. The Submerged Vegetation Monitoring Project (SVMP) draws insight and methods from similar programs in the eastern and southern regions of the United States but is adapted to special features associated with Puget Sound. This relatively unique body of water demands an approach that can: (1) sample vegetation communities at depths beyond the range of conventional aerial photography or hyperspectral technology, (2) allow for species discrimination in diverse vegetation communities, and (3) survey extensive areas with more rapid and less expensive methods than diver transects.

The SVMP is part of the Puget Sound Ambient Monitoring Program (Puget Sound Action Team 2000, Puget Sound Action Team 2002) with an annual budget of approximately $200,000. The project is divided into three phases:

Phase 1: Develop methods to monitor broad scale status and trends of submerged aquatic vegetation. Focus methodology development on *Zostera marina* L. (eelgrass). Conduct sampling and refine methods.

Phase 2: Expand monitoring to include other submerged vegetation types and monitor across gradients of stressors (e.g., shoreline development). Investigate long-term historical changes.

Phase 3: Develop programs that monitor submerged habitat at higher spatial and temporal resolutions. Gather experimental evidence on cause-effect interactions to build cause and effect models. Address functionality, habitat quality, and wildlife usage.

We are currently in the first phase of the monitoring program, which targets the seagrass, *Zostera marina* L. (eelgrass). The objectives of phase one are to:

1. Assess status of vegetation abundance and distribution;
2. Capture temporal trends over Puget Sound and subareas, with the ability to detect a 20% change over 10 years;
3. Monitor vegetation parameters that are strong indicators of *Z. marina* bed distribution and health;
4. Consider stressors.

This report summarizes the program design and presents results from the first three years of sampling. It reviews project objectives, methods, and results for three years of monitoring (2000, 2001 and 2002). It discusses findings with respect to the project objectives and recommends changes to program methods. Finally, it discusses potential future project directions.

1.2 Why *Z. marina*?

Puget Sound's diverse environment supports six seagrass species and over 625 marine alga taxa that sustain nearshore systems (Gabrielson, et al. 1990, Dethier 1990, Wyllie-Echeverria and Ackerman 2003). However, the combined attributes of *Z. marina* as a vital nearshore resource (e.g., Phillips 1984) and a bio-indicator of ecosystem change (e.g., Dennison et al. 1993) made this plant the logical choice to initiate the program. *Z. marina* has an extensive worldwide literature. It is one of the best understood marine benthic plants, both in terms of its basic biology and also as a bio-indicator. Other species of seagrasses, especially the introduced *Zostera japonica* (Harrison and Bigley 1983, aka *Nanozostera japonica* see Tomlinson and Posluzney 2001), and most marine algae are not as well understood.

As a nearshore resource in Puget Sound, *Z. marina* annual productivity can be high, with values ranging between 84 and 480 g C m-2 yr^{-1}, associated epiphytes can nearly double this NPP output (Phillips 1984). Depending on environmental conditions, standing stocks can cover many hectares of the seafloor (Phillips 1972, Thom 1990). The carbon export from this system strongly contributes to secondary nearshore productivity in this region. For example, in the Hood Canal, Simenstad and Wissmar (1985) found that the contribution of *Z. marina* to organic carbon transport to nearshore food webs was as high as 25%. These plants also stabilize the sediment and attenuate wave energy preventing erosion of benthic habitats and shorelines, entrap and recycle nutrients, supply oxygen to the water column and sediment, sequester carbon in below ground rhizomes, and export carbon to adjacent ecosystems (Duarte 2002).

Moreover, *Z. marina* meadows provide habitat and feeding areas for important species including juvenile salmonids (*Oncorhynchus* spp.), Pacific herring (*Clupea harengus pallasi*), Black Brant (*Branta bernicla nigricans*) and great blue heron (*Ardea herodias*) (Simenstad 1994, Wilson and Atkinson 1995, Butler 1995). The diversity of invertebrate, fish and waterfowl species that depend on *Z. marina* resources for shelter, substrate and foraging habitat (Table 1) implies that the species abundance and richness associated with these biomes may be without parallel in the nearshore region of Puget Sound (Phillips 1984, Simenstad 1994). The ecosystem functions provided by *Z. marina* and other seagrasses are valuable enough to encourage coastal states to adopt strict protection measures. Washington State is no exception: the Washington State Department of Fish and Wildlife (WDFW) enforces a "no-net-loss" policy (Fresh 1994).

Table 1. Number of species that feed, forage and find shelter in a typical Puget Sound *Z. marina* meadow (adapted from Phillips 1984). Based on observations of multiple meadows.

Group	Total number observed	Number commonly found
Invertebrates	165	132
Fish	76	38
Waterfowl	80	47*

* Seasonally dependent.

Loss of *Z. marina* can signal a decline in water quality conditions (Dennison et al. 1993, Short and Burdick 1996, Short and Wyllie-Echeverria 1996, Duarte 2002). Reduced water clarity is the most serious water quality condition affecting *Z. marina* and other seagrasses globally (Short and Wyllie-Echeverria 1996) as studies show that the quality and quantity of submarine light controls *in situ* patch densities as well as the lower depth limit of distribution (Zimmerman et al. 1991, Duarte 1991, Zimmerman et al. 1995). Water clarity can be compromised by a number of factors such as eutrophication, suspended sediment and shading associated with overwater structures and each of these conditions can result from industrial, agricultural and residential practices that either modify the watershed or shoreline (Short and Wyllie-Echeverria 1996; Duarte 2002).

Z. marina is also sensitive to a number of other factors easily altered by anthropogenic forces (Prange and Dennison 2000, Koch 2001, Duarte 2002, Moore et al. 2002). For example direct physical impacts may result from prop scour or aquaculture practices such as harrowing and waves or boat wakes can change the energy regime and destroy plants or prevent recruitment (Rich Passage Wave Action Study Team 2001). In addition, the release of trace metals into coastal waters or the uptake of heavy metal contaminants from the sediment can threaten the physiological health of *Z. marina* and other seagrasses (Ward 1989, Lyngby and Brix 1984, Prange and Dennison 2000). Consequently, monitoring changes in cover and patch size within the *Z. marina* zone or the maximum depth of *Z. marina* growth can identify areas that are degenerating and in danger of environmental collapse, as witnessed in the Chesapeake Bay in the latter half of the 1900's (Orth and Moore 1983)

Either patchy or continuous meadows of *Z. marina* have been mapped along 1,935 km or 43% of Puget Sound's shoreline from an aerial platform (Nearshore Habitat Program 2000). These line segment data are useful for delineating intertidal and shallow subtidal distribution, however, because of large tidal amplitudes (4.8 – 6.9 m) and limited water clarity at some sites, the lower limit of growth and the associated configuration of patches remains largely unknown. Consequently, in Puget Sound it has not been possible to estimate either the total amount of *Z. marina* within the sound or lower limit of growth. This is troublesome given that losses have been found in small-urbanized embayments such as Eagle Harbor, Westcott Bay, and Quartermaster Harbor (Mumford, unpubl. data) and because the relatively few studies documenting historical change to *Z. marina* abundance found that cover has decreased in some areas and increased in others (Thom and Hallum 1991).

Z. marina is ecologically "in the middle". It provides important ecosystem functions, and it is impacted by a wide variety of anthropogenic stressors. Populations of this rooted benthic organism - reproducing both asexually via rhizome elongation and sexually with a yearly seed rain - can persist over hundreds of years at the same location if the conditions that support growth are relatively stable (Reusch et al. 1999). Populations also respond to seasonal and yearly variation in environmental conditions such as temperature, salinity and submarine light that may result in the increase or decrease of patch-size and placement within the *Z. marina* zone (Fonseca 1992, Nelson 1997, Thom et al. 2000). However, once a population is established in a location, its reduction or displacement can be, and often is, related to a human caused disturbance (Short and Wyllie-Echeverria 1996, Short and Burdick 1996, Duarte 2002). Monitoring changes in abundance and the depth limit of growth can provide estimates of habitat availability as well as signal ecosystem change in the nearshore region.

Z. marina is also "in the middle" in a geographic sense as it occupies the margin between the terrestrial and marine environments and responds to forces forming that margin. Although plants and animals are well adapted to natural disturbance vectors impacting this region, increased human development in the watershed and along the shoreline threatens many nearshore environments in Puget Sound.

1.3 *Z. marina* Monitoring

Monitoring can be defined as the repeated collection of data to evaluate changes in the condition or status of a species identified as ecologically important or indicative of ecosystem health (after Elizinga et al. 2001). The purpose of a monitoring program is not to provide maps depicting distribution but to evaluate both the status and trends of target species using a statistically valid protocol (Monitoring Oversight Committee 2002). The objective of the SVMP is to provide valid inferences relative to the Puget Sound wide population of *Z. marina* on an annual basis (status) and over time (trends). Because this monitoring project makes statistically rigorous statements about the status and trends of *Z. marina* on a Sound-wide basis, we will be able to assess the success of the "no net loss" policy, the only existing performance measure in Washington State. In the future, this monitoring data can contribute to the definition and assessment of more robust performance measures.

1.4 Parameters Measured

Natural and anthropogenic disturbance regimes can singularly, or in concert, influence geographic distribution and *in situ* patch size of *Z. marina* at local and regional scales (Short and Wyllie-Echeverria 1996). Because the goals of this monitoring program are to (1) estimate the amount of *Z. marina* habitat and (2) detect a change in *Z. marina* metrics that signify potential population decline, we chose parameters that would be cost effective to measure without compromising our ability to detect sound-wide status and trends. To satisfy these criteria, a series of parameters were selected as indicators of *Z. marina* plant and bed condition at a variety of spatial scales (Table 2).

1.4.1 Z. marina *Area*

Seagrass monitoring programs commonly utilize abundance estimates to determine whether the resource is expanding or contracting over time (Kurtz et al. 2000, Moore et al. 2000, Virnstein and Morris 2000). For this study, *Z. marina* area is defined as the area of benthic habitat covered by one or more shoots m^{-2} of *Z. marina* (Norris et al. 1997).

Table 2. Parameters measured at different spatial scales.

Scale	Parameter
Study Area	*Z. marina* Area
Region	*Z. marina* Area
Site	*Z. marina* Area Minimum and maximum bed depth Patchiness index Shoot density Leaf length and width

1.4.2 Maximum/Minimum Depth

The maximum depth of *Z. marina* growth can be directly related to the submarine light environment (Dennison and Alberte 1985, Zimmerman et al. 1991, Moore et al. 1997). Accordingly, tracking the deep edge of growth can provide information on the quality of the estuarine light environment over time relative to local and regional water quality standards.

At the upper limit or shallow edge of *Z. marina* growth is controlled by desiccation and temperature stress (Koch and Beer 1996) but can also be locally influenced by activities such as shellfish harvest and reflective energy from shoreline armoring (Short and Wyllie-Echeverria 1996).

1.4.3 Patchiness Index

While *Z. marina* area parameter describes how much of the substrate is covered by *Z. marina*, it does not provide information on distribution within the bed. In order to improve the *Z. marina* area descriptor, we developed a patchiness index to describe distribution within a site. This metric can be used to compare the same site over time or separate sites. It can also be used to address habitat value of single large or several small (SLOSS) vegetation patches (e.g. Robbins 1997).

1.4.4 Shoot Density

Z. marina density declines as environmental quality deteriorates (Kentula and McIntire 1986, Olesen and Sand-Jensen 1994). Consequently, time series evaluation of this metric at the same site and season can provide an assessment of ecosystem health.

1.4.5 Leaf Length and Leaf Width

Leaf morphometric measurements can used to signal environmental changes in populations of seagrasses (Neckles et al. 1994, Short and Cole 2002). In conjunction with shoot density, they provide an indication of the size of the plants and the habitat available to organisms within the seagrass canopy.

2 METHODS

2.1 Study Area Description

For the purpose of this study, the Puget Sound study area is defined to include saltwater areas in Washington State, USA that are east of Cape Flattery and south of the Canadian border (Figure 1). The study area comprises approximately 4,115 km of shoreline (Nearshore Habitat Program 2001). It includes portions of the Strait of Juan de Fuca and the Strait of Georgia, the San Juan Archipelago, the Saratoga/Whidbey Basin, and waters south of Admiralty Inlet. The extreme reaches of southern Puget Sound are excluded from the study area because *Z. marina* is not known to occur there (Nearshore Habitat Program 2001).

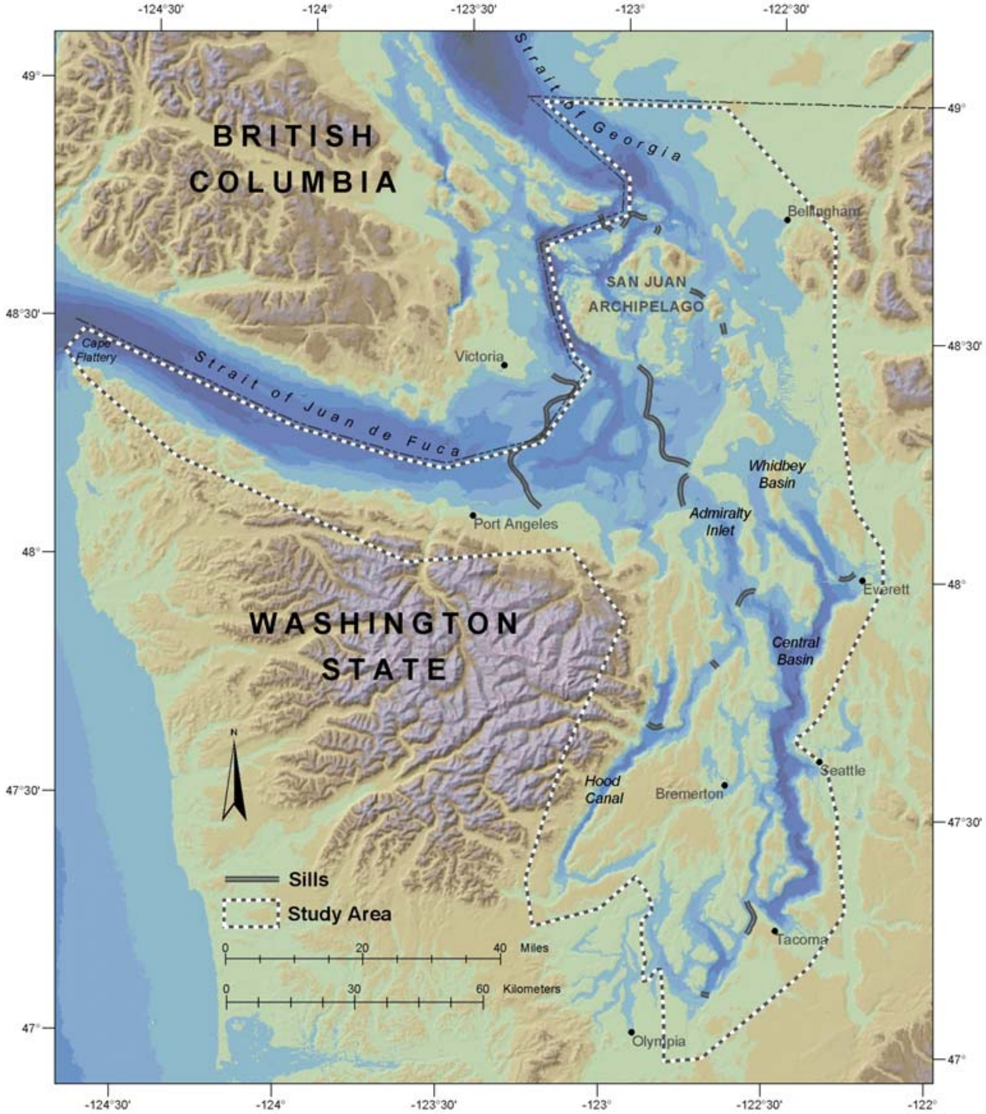

Figure 1. Map of study area (Puget Sound, WA, USA).
Sills based on Ebbesmeyer et al. (1984).

Puget Sound is a semi-enclosed, glacial fjord where saltwater from the ocean is mixed with fresh water draining from the surrounding watersheds. The average depth of Puget Sound is 140 m. Deep channels, typical of fjord estuaries, are common in the sound, along with major river deltas, small "pocket" estuaries, lagoons, sand, cobble and gravel beaches, and short stretches of rocky intertidal shoreline (Downing 1983). Strong gradients exist in wave energy, salinity, temperature, and other characteristics. These gradients are related primarily to distance from the open ocean and secondarily to local features such as oceanic sill location, fetch, currents, and fresh water input. A series of oceanic sills influence water circulation, stratification, currents, and water quality, creating unique habitat characteristics in each oceanographic basin.

The maximum tidal range increases from north to south from 4.8 m at Cape Flattery, the entrance to the Strait of Juan de Fuca, to 6.9 m at Olympia, in southern Puget Sound. Tidal range affects the amount of water present over the *Z. marina* beds during a given tidal cycle and can, depending on local conditions, affect submarine light quality.

Anthropogenic influences are abundant and spatially variable throughout the study area. Approximately one-third of the shoreline is modified (Nearshore Habitat Program 2001). This alteration can either eliminate the shallow subtidal habitat available for *Z. marina* (dredging, deep piers, filling of natural shorelines) or alter the intensity of the wave energy in the intertidal and shallow subtidal habitats. Anthropogenic impacts to water quality, sediment quality, wave energy, and other physical and chemical characteristics are extensive and spatially variable.

Diverse intertidal and subtidal vegetation communities occur along Puget Sound's shorelines. Seagrasses occur along approximately 43% of the Puget Sound's shorelines (Nearshore Habitat Program 2001). There are six species of seagrasses in the region: *Phyllospadix torreyi, P. scouleri, P serrulatus*, *Ruppia maritima*, *Zostera marina*, and *Z. japonica* (Phillips 1984, Wyllie-Echeverria and Ackerman 2003). Algal species intermix with seagrasses. Ulvoids commonly grow in the upper portions of the *Zostera marina* zone, brown and red algae commonly occur in the lower intertidal and shallow subtidal zones.

2.2 Sampling Design

2.2.1 Random Sampling with Partial Replacement Design

The objective of our sampling design is to provide valid inferences about the Sound-wide population of *Z. marina* on an annual basis (status) and over time (trends). Our protocol uses sampling with partial replacement (SPR) to balance these conflicting goals of status and trends estimation (Skalski 1990). SPR optimizes the joint desires to accurately estimate the correct status of the population and accurately and precisely estimate changes over time. In SPR designs, a fixed fraction of the sampling sites is replaced annually with a new random selection. The precision of *Z. marina* abundance estimates is improved over time as subsequent years of data are used to update site-specific estimates. Consequently, each sampling year has an initial estimate of *Z. marina* area based on data from that year and an adjusted estimate that is made when data from the following year is available.

We instituted a random rotational design with 20% of the sites replaced yearly. Using this approach, sites are randomly chosen, sampled for five years, then replaced by new randomly chosen sites. A waiting period of five years is imposed before a site can be chosen again for sampling. This repetition of sites for a five year period allows us to match sites from year to year and partition the variance due to yearly changes separately from between site variances when we calculate trend analysis.

2.2.2 Stratification and Site Definition

In order to randomly select sampling sites and to extrapolate sampling results over the entire study area, we delineated all potential *Z. marina* habitat and defined sites using a Geographic Information System (GIS). We defined the boundaries of potential *Z. marina* habitat using the best available state-wide digital data that approximate the minimum and maximum depth of *Z. marina* occurrence. The minimum depth boundary was defined using an approximate Mean High Tide line, which was digitized from 1:12,000 orthophotos (Washington Department of Natural Resources 1999). The maximum depth boundary was defined using a –20 foot depth contour, which was interpolated from NOAA soundings (Washington Department of Fish and Wildlife 2000). The minimum and maximum depth lines do not constitute ideal depth boundaries for *Z. marina* habitat, and their accuracy is limited by age and resolution. Despite these weaknesses, the boundaries successfully narrowed the survey area to include only shallow littoral areas where *Z. marina* might occur.

All potential *Z. marina* habitat was stratified based on geomorphological characteristics. The primary purpose of the stratification was to produce the most precise extrapolation of *Z. marina* from the sampled sites over the study area as a whole. The statistical framework for extrapolating *Z. marina* area estimates over each stratum is discussed in detail in Appendix L. The secondary purpose of the stratification was to compare different bed types. We defined two broad strata:

Flats
Areas with extensive broad shallows, such as river deltas, and pocket beaches (Figure 2). We identified 71 flats sites. Large embayments were divided into multiple flats sites in order to facilitate sampling each site in one day or less.

The area of potential *Z. marina* habitat for each flat site was calculated as the area between the shoreline and the –20 ft depth contour. The total area of all flats sites was used to produce sound-wide area estimates by extrapolating the ratio of habitat with *Z. marina* to total habitat at sampled sites over the area of unsampled flats.

Fringes
Areas with relatively linear shorelines where potential *Z. marina* habitat is limited to a narrow band by bathymetry (Figure 2). Fringe sites were defined to include a 1000 m segment of a –20 ft depth contour. A segment length of 1000 m was chosen because it could be easily sampled in half of a day and because it includes a large enough stretch of shoreline to represent bed characteristics in most areas. The abundance of *Z. marina* at all fringe sites was estimated by extrapolating the mean area of *Z. marina* at sampled sites over the total linear amount of fringe habitat.

Fringe sites were further divided into narrow and wide categories. A threshold width of 305 m (1000 ft) was used to differentiate narrow and wide sites. We delineated 2,019 narrow fringe sites and 351 wide fringe sites in Puget Sound.

Due to islands, river mouths, and other shoreline discontinuities, approximately 2% of the line segments were less than 1000 m long. These areas were excluded from the sampling pool. However, they were included in the overall estimation of *Z. marina* in fringe sites.

The wide fringe stratum was defined following our year 2000 sampling based on analysis of the sources of variance in our estimate of *Z. marina* area. We found that wide fringe sites have a much larger range in the amount of *Z. marina* than regular fringe sites. Partitioning the fringe strata into regular and wide fringes greatly improved the precision of the overall estimate.

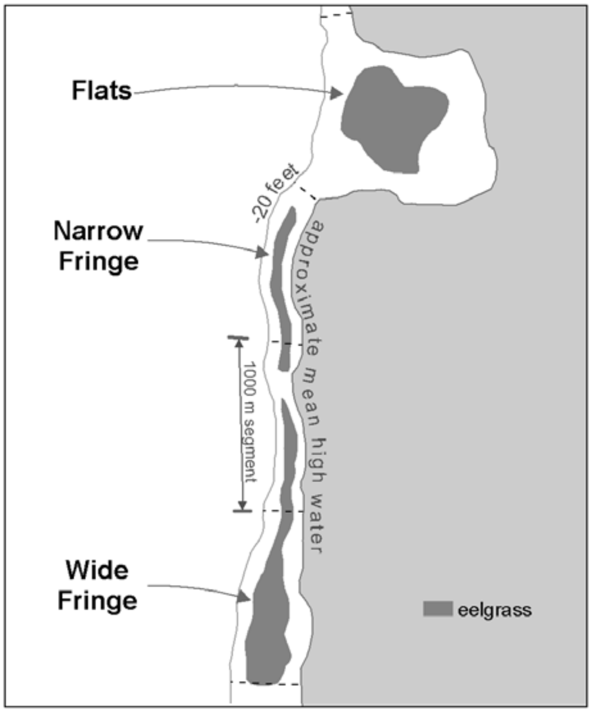

Figure 2. Schematic drawing of the geomorphological strata: flats, narrow fringe, and wide fringe.

We used a GIS to delineate the total areal and linear extent of potential *Z. marina* habitat in Puget Sound in each geomorphological stratum (Table 3).

Table 3. Amount of habitat in Puget Sound by geomorphological strata. Fringe sites represented by linear measure along the –20 ft bathymetry contour. Flats sites represented by areal measure between approximate Mean High Water and –20 ft bathymetry contour.

Region	Number of Sites	Extent (area or length)
Flats	71	444 km^2
Fringe	2,370	2,424 km
Narrow	2,019	2,067 km
Wide	351	357 km

2.2.3 Sampling Allocation and Sample Selection

While the majority of sites were selected randomly for five year sampling rotations, six core sites were hand picked for long term sampling (Table 4). Core sites will provide continuous monitoring data to compare with shorter time series (5 years) at randomly selected sites. The core sites were chosen after informal consultation with a group of Puget Sound scientists familiar with *Z. marina* distribution throughout the state. We selected these sites to represent a range of geographical locations, management concerns, research interests, and habitat types.

Table 4. Core sites chosen for the Submerged Vegetation Monitoring Project.

Name	Region	County	Type
Padilla Bay	North Puget Sound	Skagit	Flat
Picnic Cove	San Juan/Strait of Juan de Fuca	San Juan	Flat
Jamestown	San Juan/Strait of Juan de Fuca	Clallum	Flat
Lynch Cove	Hood Canal	Mason	Flat
Dumas Bay	Central Puget Sound	King	Wide Fringe
Burley Spit	Central Puget Sound	Kitsap	Narrow Fringe

In the first year of sampling, we randomly selected nine flats sites, 45 narrow fringe sites, and six wide fringe sites for sampling. A larger relative proportion of sites were allocated to the flats stratum based on the assumption that within site variation is larger among flats sites. Following the first year of sampling, we calculated the optimal sampling allocation among strata by considering variance associated with each stratum, desired CV, and sampling time required for each stratum (Cochran 1977). We found that a 3:1 ratio of narrow to wide fringes was optimal. Thus, we chose 15 wide fringe sites to sample in 2001. In 2002, we began rotation of sites by selecting 20% of the sites for replacement with newly selected random sites in each stratum.

Random site selection was completed with one criterion, that at least three fringe sites would be represented in each region (see section 2.2.4). If the random draw contained less than three fringe sites per region a new random draw was selected.

2.2.4 Regional Stratification

We created regions for post hoc analysis of the data over smaller geographic areas. We defined five regions based on oceanographic basins and habitat characteristics (Figure 3). Boundaries were placed along oceanographic sills as delineated by Ebbesmeyer et al. (1984). Regions were selected to balance two competing goals: to define sufficiently discrete geographic areas to capture smaller scale trends and yet maintain enough sites per region to attain acceptable statistical power.

The *San Juan Islands and Straits of Juan de Fuca Region* is the most influenced by oceanic waters. *North Puget Sound Region* encompasses the marine waters south from the Canadian border to Anacortes on Fidalgo Island, including the large shallow flats of Samish and Padilla Bays. The largest and deepest of the basins in Puget Sound proper, the *Central Puget Sound Region*, consists of two sub-basins and extends some from Admiralty Inlet to the Tacoma Narrows. Near the Tacoma Narrows, a shallow sill divides the main portion of the basin from the Southern Basin. The east half of the Southern basin from Johnson Point to Hartstene Island does not contain *Z. marina* and was excluded from the study (Nearshore Habitat Program 2000). *The*

Saratoga/Whidbey Island Region includes the shallow, more protected waters of Possession Sound, Port Susan, Saratoga Passage, and Skagit Bay. The smallest of the four basins, in terms of area, is the *Hood Canal Region,* a long, narrow channel branching from the Admiralty Inlet. The amount of habitat per region and the number of sites per region are summarized in Table 5. For regional analysis, core sites were placed in their respective geomorphological stratum (flats, narrow fringe, wide fringe).

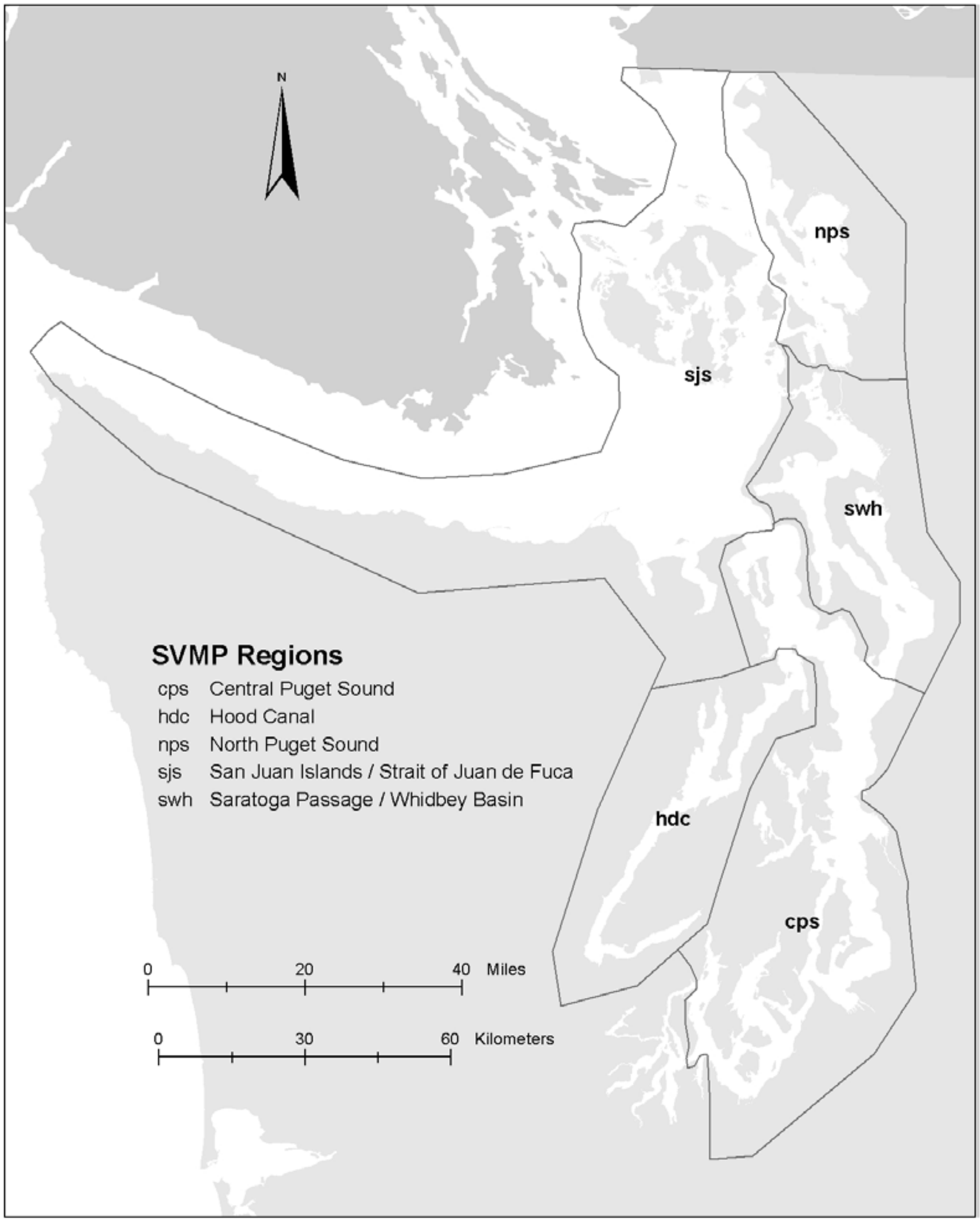

Figure 3. Regions defined for summarizing *Z. marina* data.

Table 5. Total amount of habitat and number of sites by region.

Region	Number of Sites Flats	 Narrow Fringe	 Wide Fringe	Total Area or Length in Study Area Flats (m^2)	 Narrow Fringe (m)	 Wide Fringe (m)
Central Puget Sound	8	749	91	21,142,852	758,927	92,528
Hood Canal	6	253	31	16,543,549	254,553	31,000
North Puget Sound	15	124	52	162,219,358	127,573	55,088
San Juan/Straits	27	684	133	38,699,811	708,895	134,330
Saratoga/Whidbey	15	209	44	205,099,061	216,882	44,001

2.3 Sampling Window

Samples were collected between June and October, the period of maximum vegetative biomass (Phillips 1984). This broad sampling window provides sufficient time to visit many sites over a large geographic area with a single vessel. In order to maximize the comparability of individual sites over multiple years, sites were sampled as closely as possible to the same date among years.

2.4 Data Collection

Sampling was conducted from the 11-m (36-ft) R/V Brendan D II manned by a helmsman, technician, and scientist. Table 6 lists the survey equipment used. Each site survey consisted of a series of sequential tasks that are described in detail the sections that follow:

- Line transect sampling using a towed underwater video camera to collect data on *Z. marina* presence, minimum depth and maximum depth.
- Benthic grabs to estimate plant parameters.
- Water quality sampling.
- Shoreline videography.

Table 6. Equipment used during the 2000-2002 surveys.

Equipment	Manufacturer/Model
Differential GPS Unit	Trimble AgGPS 132 Leica MX200 GPS Navigator
Depth Sounder	Garmin Fishfinder 240 200 KHz 11^o single-beam transducer with temperature sensor
Echosounder	Biosonics DT Series Echosounder (or DE) 420 KHz 6^o single-beam transducer
Water Quality Sensor	HydroLab DataSonde 4
PAR Sensor	Licor LI-192 underwater quantum sensor
Bottom Grab	Kohl Scientific Stainless Steel 0.1 m^2 van Veen Grab
Underwater Camera	Deep Sea Power & Light SeaCam 2000
Lasers	Deep Sea Power & Light
Underwater Light	Deep Sea Power & Light RiteLite (250 watt)
Image Recording	General Electric VG4043 VHS 4-Head Zenith TV/VCR Combo 4-Head Sony 930 Digital8 Camcorder

2.4.1 Z. marina *Area, Minimum Depth, and Maximum Depth Data Collection*

Line transect sampling was used to survey *Z. marina* area, minimum depth, and maximum depth (Norris and Wyllie-Echeverria 1997, Norris et al. 1997). Transects were surveyed using an underwater video camera mounted in a downward-looking orientation on a weighted towfish. The towfish was deployed directly off the stern of the vessel using the cargo boom and boom winch. During transect sampling, a technician lowered and raised the towfish using a winch to keep the camera just above the *Z. marina* canopy. Parallel lasers mounted 10 cm apart on the towfish provided a scaling reference in the video image. A 250 watt underwater light provided illumination when needed.

Survey equipment simultaneously recorded *Z. marina* presence/absence, position, depth and time of day. Time and position data were acquired using a differential global positioning system (DGPS) processor with the antenna located at the tip of the cargo boom used to deploy the camera. The weight of the towfish kept the camera positioned beneath the DGPS antenna, ensuring that the position data reflected the geographic location of the camera. Differential corrections were received from the United States Coast Guard public DGPS network.

In 2000, 2001 and 2002, we measured depth (distance between the seabed and the transducer) along all underwater video transects using a Garmin Fishfinder 240. For a portion of 2001 and all of 2002, we collected additional depth data using a BioSonics echosounder.

A laptop computer equipped with a video overlay controller and data logger software integrated the DGPS data, user supplied transect information (transect number and site code), and the video signal at one second intervals. Video images with overlain DGPS data and transect information were recorded on one master and two backup recorders. Date, time, position, and transect information were also stored on the computer at one second intervals. A real-time plotting system used a multiplexer to integrate National Marine Electronic Association 0132 standard sentences produced by the DGPS, two depth sounders, and a user-controlled toggle switch to indicate *Z. marina* presence/absence.

Transects were randomly placed along the depth gradient, the observed axis of greatest variation in *Z. marina* occurrence (Figure 4). A general goal of 11 transects per site was set to attain a CV less than 20%, this rule of thumb was varied based on site size, heterogeneity, and previous sampling results. We collected more than 11 random transects at sites that had large within-transect variance the previous year, spanned large areas, or appeared to have patchy *Z. marina* area.

Figure 4. Example of random transect placement at a fringe site
(Photo: WA Department of Ecology, Oblique Shoreline Photos 2000-2002).

In 2000 and 2001, systematic straight-line transect samples covering the entire site were employed at sites sampled for the first time. Often, a coarse grid pattern was used followed by a fine grid pattern over any observed *Z. marina*. The actual pattern and berthing (i.e., distance) between transects was determined by the size and shape of the site and the amount of effort allocated to the site. At previously sampled sites, transects were surveyed at randomly selected angles through the shallow and deep edge of the bed. If *Z. marina* was observed only on a portion of the site, additional transects were surveyed through the *Z. marina* zone until the bed was adequately delimited.

In 2002, line transect sampling methods changed based on our analysis of data collected in 2000 and 2001. The sampling area was defined *a priori* using reconnaissance surveys and data from previous sampling seasons. Line transects were selected randomly within the sampling area. All transects were oriented perpendicular to the shoreline to cross the shallow and deep edge of the *Z. marina* bed.

2.4.2 Plant Characteristics

We sampled whole plants using a 0.10 m^2 van Veen benthic grab (Long et al. 1994). Samples were collected at all sites in the flats and core strata. Due to time constraints in the field, grab samples were collected at a random selection of 30% of sites in the fringe stratum.

At each site, benthic grab stations were chosen randomly from all *Z. marina* observations along underwater videography transects. In 2000, we selected 10 random stations per site. We increased the number of stations to 25 in 2001 and 2002 to improve statistical power. At each grab station, we recorded depth, visual assessment of substrate type (e.g. mud, sand, gravel). Samples were rinsed, bagged, and stored on ice for processing in the lab within one week.

2.4.3 Other Parameters Measured

At each site, we sampled water quality near the deep-water edge of the observed *Z. marina* bed. At sites with no *Z. marina*, we chose a site at approximately -6 m (MLLW), or outside the existing kelp bed or other obstacles such as boulders. We recorded temperature, salinity, dissolved oxygen, conductivity, and photosynthetically active radiation (PAR). At each sampling site, a record of the shoreline characteristics was captured on digital video by panning the shore.

2.5 Data Processing and Analysis

2.5.1 Z. marina *Area*

2.5.1.1 Video processing

All videotapes were post-processed for *Z. marina* presence/absence at one second intervals. We defined "*Z. marina* presence" as any part of a single rooted plant that was visible in one of the video frames stamped with a specific time/position (approximately 30 video frames are recorded per second). Information on *Z. marina* presence was recorded with corresponding spatial information. This data was then analyzed to estimate the fraction of *Z. marina* along each survey transect.

2.5.1.2 *Z. marina* Area Estimation at a Site

Z. marina area was calculated at each site using methods based on Norris et al. (1997):

1. Delineate a polygon around the area within the site with *Z. marina*;
2. Calculate the fraction of *Z. marina* along each line transect and associated variance;
3. Estimate the overall area with *Z. marina* at the site by extrapolating the fraction of *Z. marina* along transects over the total polygon area (Appendix L, pg 1-3).

Z. marina area estimation methods varied slightly among years to accommodate changes in data collection methods. In 2002, area was estimated using the sampling polygon defined in the field from a reconnaissance survey. Only random transects were used to calculate the fraction of *Z. marina*. In 2000 and 2001, sampling polygons were not defined *a priori*. Sampling polygons were delineated in the office based on referencing field notes regarding the expected location of the *Z. marina* bed.

2.5.1.3 Area Status and Trends Estimation Over Larger Areas

Site area estimates were extrapolated within strata and over the study area as a whole. Statistical extrapolation methods are described in Appendix L for status calculation for each stratum, trend detection, retrospective adjustment, fractional change, areal change, 5-year and 10-year trends, and power analysis.

Because sites were randomly selected from the study area, sites can be aggregated in any manner desired to estimate regional *Z. marina* area (provided there are a sufficient number of samples per region). This approach was adopted to estimate regional trends over time. For each region, relative change was calculated within each stratum by comparing sites that were sampled during both time periods. Fractional change in *Z. marina* area was calculated using regression analysis and then extrapolated over each stratum in the region (Appendix L).

The spatial extent of one site (*core 01-Padilla Bay*) changed significantly between 2000 and 2001 due to site boundary re-definition. In order to avoid a false change in status and trends associated with the site boundary movement, the area estimate from 2001was substituted for the 2000 data for status and trends analysis. This substitution may have dampened the estimate of trends. However, based on similarities between the 2001 and 2002 data for the areas measured, we assumed that the actual *Z. marina* area in 2000 was not dissimilar.

2.5.2 Depth Data

Underwater video transects were used for maximum and minimum depth estimation if they were randomly selected, had *Z. marina* observed along them, were oriented perpendicular to the bathymetry contours (i.e., running shallow to deep or visa versa) and extended beyond the deep and shallow extent of the bed.

During post-processing, depths were corrected to the MLLW datum by adding the transducer-offset, subtracting the predicted tidal height for the site and adding the tide prediction error (calculated using measured tide data from the National Oceanic and Atmospheric Administration website http://co-ops.nos.noaa.gov/data_res.html). These final corrected depth data were then merged with *Z. marina* presence/absence data so each *Z. marina* observation had an associated depth measurement corrected to MLLW datum.

We summarized minimum and maximum *Z. marina* depth characteristics for each site using descriptive statistics (means, ranges, and standard deviations). We compared each site that was sampled in consecutive years for significant change in mean maximum and minimum *Z. marina* depth using 80% confidence intervals (CI). Overlapping intervals were considered statistically similar. At sites where 80% CI's did not overlap between years, we used field notes and a GIS to determine if the randomly selected transects adequately represented the full extent of the *Z. marina* bed. At a subset of sites, we also tested for significant difference using Milton and Arnold's (1990) methods for comparing two means, this test produced the same results.

To optimize sampling in future years and to quantify the amount of change we are able to detect, we calculated the change detection capability at different magnitudes and standard deviations (e.g. Zar 1984; eq. 9.24; pg 134).

2.5.3 Plant Characteristics

Shoot density at each sampling station was determined by counting all vegetative shoots from each grab sample. The number of generative shoots was recorded but was not included in the shoot density estimate. Shoot density is reported as mean density for all stations and at various spatial scales (site, region, study area).

Shoot leaf and length measurements were recorded for a random selection from a pooled sample of plants from each site. In 2000, 30 plants per site were measured; the number was reduced to 25 in 2001 after determining that a reduction in effort did not affect our power to detect change. Leaf width was measured at the distal end of the sheath to the nearest millimeter. Leaf length was measured from the leaf base to the distal end of the leaf to the nearest 0.1 centimeter. The longest leaf from each shoot was used to calculate leaf statistics. Leaf characteristics were reported as mean measurements of all randomly selected plants at a site, stratum and region. For analysis, core sites were placed in their respective geomorphological strata.

Plant characteristics data were tested for significant differences using a t-test and the Smith-Satterthwaite procedures for calculating degrees of freedom (Milton and Arnold 1990).

2.5.4 Other Parameters

We collected data on additional parameters that will be analyzed in future reports:

- Patchiness. A quantitative measure of "patchiness" (referred to as "grain" by Pielou 1977) will be computed by considering a *Z. marina* bed as a two-phase mosaic (i.e., a surface composed of two types of polygons—*Z. marina* and no *Z. marina*). We define patchiness to be the number of patch/gap transitions along each underwater video transect.
- Water Quality. Data for each water quality parameter will be averaged on the up and down casts for each depth interval, and the mean of all readings will be reported for each site.

2.5.5 Biophysical Modeling

In an initial effort to link stressors to *Z. marina* distributions, we utilized a biophysical model that relates *Z. marina* distribution to environmental parameters and is particularly sensitive to water quality characteristics (Zimmerman 2003). The overall goal of this effort was to enhance our interpretation of observed *Z. marina* distributions and to help prioritize future sampling efforts.

The biophysical model simulated *Z. marina* distribution by computing the maximum sustainable *Z. marina* density based on daily whole plant carbon balance. Maximum sustainable density was assumed to occur when photosynthesis was balanced by respiration. The model focused on light-canopy interactions and relied on an independent radiative transfer program (HydroLight, Mobley 1989) to derive top-of-canopy radiation and effects of total suspended solids and chlorophyll concentrations Details of the model and the parameterization used for the study can be found in Appendix M.

In 2000, the model was applied to one site in Central Puget Sound, *Core005-Dumas Bay*. Data to model canopy architecture at this site were obtained from the benthic grab samples. Predicted *Z. marina* distribution at the site was compared to an underwater videography survey in 2000 and previous site surveys in 1995 (Norman et al. 1995).

The biophysical model was run at various levels of Total Suspended Solids (TSS) and chlorophyll (Chl) to assess *Z. marina* sensitivity to these parameters. In addition, model sensitivity to shoot:root ratio was assessed. The TSS values used were 0, 10 and 25 mg/L. Results of the TSS analysis at the site were not available but field observations indicated that TSS loads were high. Chl values used were 20, 30, 40, and 50 mg m^{-3}. Chl values were based on ambient conditions of water column on June 20, 2000, when concentration ranged from 24 to 54 mg/m^{-3}

3 RESULTS

3.1 General Results – Sampling Effort

Available funding generally determined the number of sites sampled each year. In 2000, we surveyed 61 sites in 46 days of sampling. In 2001 and 2002, we increased sampling effort and surveyed 74 and 73 sites, respectively in 54 days each year (Table 7). We sampled 100% of all core sites, 13-15% of all flat sites, 2% of all narrow fringe sites, and 4% of all wide fringe sites in Puget Sound (Table 8).

Table 7. Sampling effort in 2000, 2001 and 2002.

Year	Field Season Dates	Sites Visited	Sites Sampled	Sites That Could Not be Sampled Due to Obstructions
2000	July 7 – October 10	66	61	5
2001	July 28 – October 20 (1 site re-sampled 12/27/02)	77	74	3
2002	June 21 – September 29	76	73	3

Sampling took place between June and October. In 2001, we returned to one site that had extensive summer kelp beds and sampled in December (*sjs0819-Point Partridge*). Each year, sampling began in the San Juan Archipelago and moved east and then south into Puget Sound proper. The Strait of Juan de Fuca was sampled last, during early fall when seas are often calm.

Navigation obstructions such as kelp, rocks, or high currents precluded underwater video surveys at five sites in 2000 and three sites in 2001 and 2002. All of the sites that could not be sampled were in the fringe stratum.

Table 8. Proportion of the total population in each stratum sampled in 2000, 2001 and 2002.

Stratum	2000		2001		2002	
	Number	Percentage	Number	Percentage	Number	Percentage
Core	6	100%	6	100%	6	100%
Flat	9	13%	10	15%	10	15%
Narrow Fringe	42	2%	44	2%	44	2%
Wide Fringe	4	1%	13	4%	13	4%

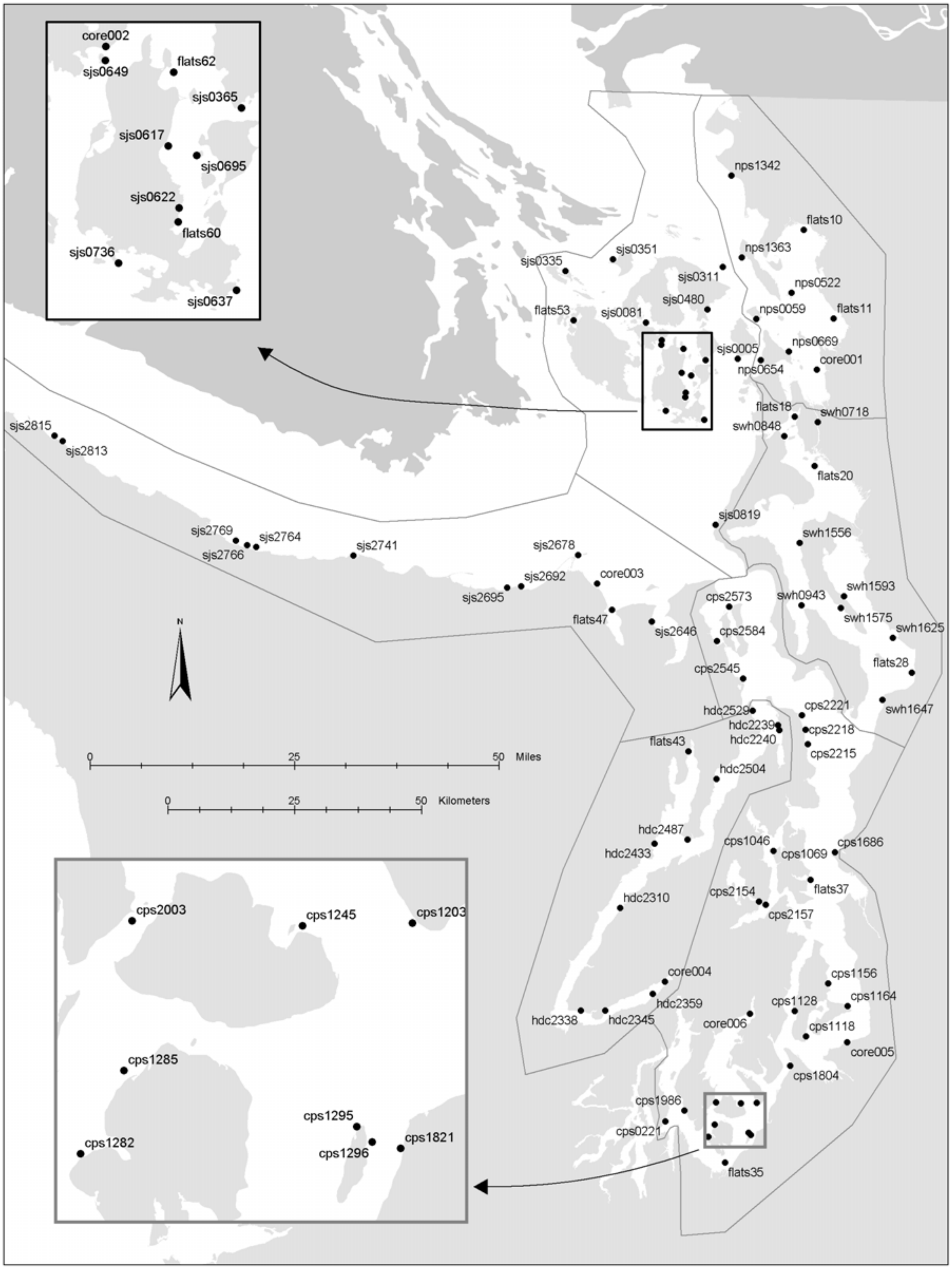

Figure 5. Sites sampled in 2000, 2001 and 2002.

Randomly selected sampling sites were distributed throughout the study area (Figure 5, appendices A-C list approximate latitude and longitude coordinates for each site). Travel time between sites, tidal height and other logistics dictated the sampling schedule. Generally, two narrow fringe or wide fringe sites could be sampled in one day. Sampling time required at flats sites ranged from half a day at small sites to four days at *Core001-Padilla Bay*, the largest site.

The introduced species, *Z. japonica* was found at the following sites: *Core001-Padilla Bay*, *Flats18-Similk Bay*, *Flats20-Skagit Bay S.*, *Flats 11-Samish Bay N.*, *cps2215-So. of Eglon*, *Core004-Lynch Cove*, *Flats 43-Dabob Bay*, *hdc2359-Lynch Cove fringe*, *hdc2239-NE Hood Canal*, and *Core006-Dumas Bay*. Although, no intensive efforts have been made to document the extent or spread of this invasive species, this list added locations to its known extent. Surfgrass, *Phyllospadix serrulatus*, was found at *cps2545-Olele Pt*. *Phyllospadix* spp. was found at *sjs0819-Partridge Point*, *sjs2678-Dungeness Spit Lighthouse Res*., *sjs0637-Watmough Head*, and *sjs2692-East Green Point*. Specimens were not collected at these sites. Based on growth patterns and zonation, we believe these were *P. scouleri* or *P. torreyi*.

3.2 Z. marina Area

3.2.1 Sound-wide Status

Puget Sound has approximately 200 km^2 of *Z. marina* (Table 9). The adjusted year 2001 estimate of 186 km^2 (±23, 90% CI) is most accurate. The adjusted estimate improves precision by considering the positive correlation between measurements in consecutive years. The year 2001 adjusted estimate is similar to the initial estimate; the standard error and coefficient of variation (CV) are approximately 75% smaller.

Table 9. Estimated *Z. marina* area in Puget Sound, 2000-2002.

	2000	2001	2002
Initial Estimate (km^2)	145	207	212
Standard Error	24	57	62
Coefficient of variation	.17	.28	.29
Confidence Interval (90%)	±40	±94	±102
Adjusted Estimate (km^2)	It is not possible to calculate an adjusted estimate because site rotation did not begin until 2002.	186	To be calculated using 2003 data.
Standard Error		14	
Coefficient of variation		.07	
Confidence Interval (90%)		±23	

Slightly more than half of Puget Sound's *Z. marina* area occurs at flats sites (Figure 6); status estimates range from 48% in 2000 to 60% in 2001 and 2002. The remainder of *Z. marina* area occurs in fringe sites, with similar proportions in narrow and wide fringe types. The proportion of *Z. marina* area in flats is similar to the proportion of total shallow water area in the flats stratum (52%) but much greater than the proportion of linear shoreline in the stratum (14%). Narrow and wide fringe sites account for a slightly lower proportion of *Z. marina* area relative to the proportion of total shallow water area and a much lower proportion of *Z. marina* area relative to the proportion of linear shoreline. While it is possible to compare yearly status estimates for trends over time, we compared matched sites for year-to-year trends (next section, Appendix L).

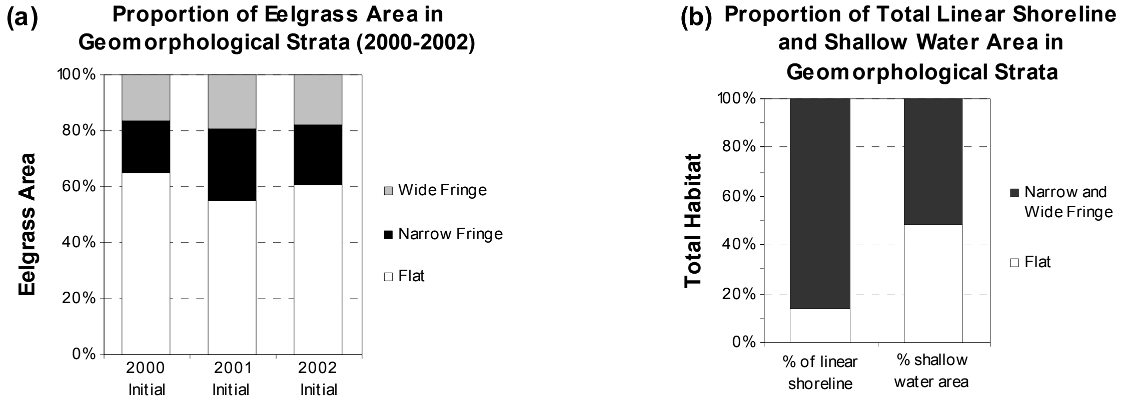

Figure 6. (a) Puget Sound initial estimate of *Z. marina* area in strata in 2000, 2001 and 2002 and (b) linear and areal estimates of total area in each stratum.

3.2.2 *Sound-wide Trends in Z. marina Area*

We estimated year-to-year trends in *Z. marina* area by comparing matched sites between years and extrapolating the results over each stratum and the entire study area. In Puget Sound as a whole, no significant change was found in either time period (Table 10).

Table 10. Yearly trends in *Z. marina* area in Puget Sound (2000-2002).

Stratum	2000-2001		2001-2002	
	% change	Standard error	% change	Standard error
Cores	0%	1.4%	+8%*	0.5%
Flats	-11%*	6.4%	+10%*	2.4%
Narrow Fringe	+11%*	1.6%	-15%*	1.5%
Wide Fringe	+9%	12.5%	-9%*	5.1%
TOTAL	+3%	3.6%	+1%	3.0%

* Statistically significant change (90% confidence level)

Our estimates of trend between 2000 and 2001 indicate a significant change in *Z. marina* area in the flats (-11%, SE 6.38%) and narrow fringe strata (+11%, SE 1.62%). Between 2001 and 2002, our trend estimates indicate a significant change in *Z. marina* area in all four strata including increases in the core (+8%, SE 0.52%) and flats (+10%, SE 2.44%) and decreases in the narrow fringe (-15%, SE 1.49%) and wide fringe (-9%, SE 5.14%) strata.

3.2.3 *Trends by Region in* Z. marina *Area*

No region had a sufficient number of samples to compute status estimates for all strata. A minimum of three sites per stratum per region was required. It was possible to estimate year-to-year trends by region. In order to increase the number of sites per stratum per region, all sites were placed in their respective geomorphological stratum (flat or fringe). We computed change over time by matched comparison of sites and extrapolation over the region.

Saratoga/Whidbey Region showed no significant change in either time period (Table 11 and Table 12). The estimate of *Z. marina* area in *Hood Canal Region* increased by 23% (SE 4%) in 2000-2001 and then decreased by 16% (SE 3.3%) in 2001-2002. In the *San Juan/Straits Region*, estimated *Z. marina* area increased in the first time period by 34% (SE 5%) and decreased in the second time period by 9% (SE 4.6%). Sample number was too low to estimate trends for *North Puget Sound Region* during 2000-2001 and for *Central Puget Sound Region* during both time periods.

Table 11. Trends in *Z. marina* area by region 2000-2001 (cores and wide fringe sites lumped into flats or fringe geomorphological strata).

Region	Flats		Fringes		Total
	Number of sites	% Change (standard error)	Number of sites	% Change (standard error)	% Change (standard error)
Central Puget Sound	1	⓪	18	12%* (2.4%)	⓪
Hood Canal	2	66%* (7.5%)	8	13%* (2.4%)	23%* (4%)
North Puget Sound	1	⓪	3	-22%* (2.8%)	⓪
San Juan/Straits	6	18%* (1.3%)	14	44%* (5.1%)	34%* (5%)
Saratoga /Whidbey	3	-13% (11.4%)	5	0% (2.7%)	-6% (6%)

⓪ = insufficient data * significant change at 90% Confidence interval

Table 12. Trends in *Z. marina* area by region 2001-2002 (cores and wide fringe sites lumped into flats or fringe geomorphological strata).

Region	Flats		Fringes		Total
	Number of sites	% Change (standard error)	Number of sites	% Change (standard error)	% Change (standard error)
Central Puget Sound	1	⓪	19	-14.2%* (5.2%)	⓪
Hood Canal	2	-12%* (1.1%)	5	-16.6%* (4.2%)	-16%* (3.3%)
North Puget Sound	2	8%* (0.6%)	3	-25.3%* (0.6%)	8%* (0.7%)
San Juan/Straits	4	8%* (0.7%)	15	-15.9%* (5.0%)	-9%* (4.5%)
Saratoga /Whidbey	3	18% (25.4%)	8	-1.6% (1.3%)	7% (10.9%)

⓪ = insufficient data * significant change at 90% Confidence interval

3.2.4 Ability to detect change in Z. marina *Area in Puget Sound and Regions*

A primary goal of the SVMP is to detect trends in *Z. marina* area in Puget Sound. We tested our ability to detect trends over time by calculating the CVs required to detect a 25% decline over a five and ten year monitoring period, respectively. We found that a total CV of 8% and 11% would allow detection of a 25% decline over a five and ten year monitoring period, respectively.

3.2.5 Site-level status

Z. marina area estimates for all sites sampled in 2000, 2001 and 2002 are summarized in Appendices A, B, and C, respectively. During the first three years of sampling, sites with *Z. marina* present ranged area from 0.02 hectares to 3,453 hectares of *Z. marina* at *sjs0649-Canoe Island*, 2002 and *core001-Padilla Bay*, 2002, respectively. Approximately 20% of *Z. marina* area in Puget Sound was found in Padilla Bay.

Along each underwater videography transect, we calculated the fraction of each transect with *Z. marina* present. Generally, *Z. marina* fraction was higher at flats sites. However, there were exceptions; the *Z. marina* fraction was highest at *sjs0351-Waldron* (0.9) in 2002. *Z. marina* fraction was lowest at *sjs0049-Crescent Bay* (0.0049) in 2001.

The coefficient of variation (CV) associated with *Z. marina* area estimates at individual sites ranged from 0.05 (*core002-Picnic Cove* in 2000) to 0.78 (*sjs0622-Jasper Cove-Lopez* in 2000). Average annual site CVs were 0.19, 0.16 and 0.12 in 2000, 2001, and 2002, respectively. Site-level CVs generally decreased when more transects were sampled. The average number of transects sampled per site was slightly higher than the original target of 11 transects. An average of 12 transects were surveyed in 2000 and 2002, and an average of 13 transects were surveyed in 2001. Additional transects were surveyed when site CV was expected to be high and when field time allowed for more sampling. In addition to the number of transects surveyed, bed characteristics at a site affected CV. Heterogeneous *Z. marina* beds had inherently higher CVs. Site CV affected the precision of the *Z. marina* area estimate. Sites with CVs above 0.20 had broad ranges in *Z. marina* area at the 80% confidence interval (Appendices A, B, and C).

Approximately 20% of the sites sampled each year did not have *Z. marina* present (Appendices A, B, an C). One flats site (*Flats10-Nooksack Delta East* in 2002) did not have *Z. marina* present, the remaining sites that did not have *Z. marina* were in the fringe stratum. Most of the sites without *Z. marina* were located along steep shorelines with predominantly rocky habitats or high currents.

While it is difficult to assess long term trends from three years of sampling, it is possible to identify sites where short term changes in *Z. marina* area are evident. Sites at which *Z. marina* area changed between years are listed in Tables 13 and 14. This list was produced by review of every site which showed statistically significant changes among years. Sites at which change in *Z. marina* area could be attributed to sampling effects were excluded (Appendix D). Sampling effects that were considered include changes in polygon size and shape between years, random transect placement, and species discrimination difficulty. Two screening levels are included: the more restrictive 95% CI identifies sites that are highly likely to have changed, with a low associated risk of false positives. At the 80% CI, a larger list of sites that may have changed are identified, and this list has a higher chance of false positives. Annual change in *Z. marina* area estimates for all sites are listed in Appendix D.

Table 13. Sites at which *Z. marina* area changed between 2000 and 2001.

Site code	Location	Site Type	Region	2000-2001 Relative % change 80% CI	95% CI
Core002	Picnic Cove	flat	sjs	-26.6 ± 10.6*	-26.6 ± 16.2*
Core004	Lynch Cove	flat	hdc	67.2 ± 33.1*	67.2 ± 50.6*
Flats47	Travis Spit	flat	sjs	37.7 ± 30.9*	37.7 ± 47.2
Flats53	Westcott Bay	flat	sjs	-23.8 ± 21.1*	-23.8 ± 32.3
hdc2359	Lynch Cove	narrow fringe	hdc	11.5 ± 9.7*	11.5 ± 14.8
hdc2529	Tala Point	narrow fringe	hdc	20.3 ± 16.8*	20.3 ± 25.7
sjs2646	Discovery Bay	narrow fringe	sjs	41.3 ± 36.9*	41.3 ± 56.4
swh1593	Cornell, Camano	narrow fringe	swh	40.2 ± 31.9*	40.2 ± 48.7

*significant difference at indicated confidence interval

Table 14. Sites at which *Z. marina* area changed between 2001 and 2002.

Site code	Location	Site Type	Region	2001-2002 Relative % change 80% CI	95% CI
cps2215	S. of Eglon	narrow fringe	cps	-20.6 ± 11.0*	-20.6 ± 16.8*
cps2584	Lower Hadlock	narrow fringe	cps	-26.5 ± 16.2*	-26.5 ± 24.8*
Flats11	Samish Bay N.	flat	swh	10.1 ± 9.0*	10.1 ± 13.8
Flats20	Skagit Bay N.	flat	swh	50.0 ± 31.2*	50.0 ± 47.8*
swh1647	Mukilteo	narrow fringe	swh	-17.2 ± 8.8*	-17.2 ± 13.5*

* significant difference at indicated confidence interval

Between 2000 and 2001, *Z. marina* area changed at two sites at the 95% confidence interval (CI); one site increased and one site decreased. At the 80% CI, *Z. marina* area changed at eight sites; six sites increased and two sites decreased. Between 2001 and 2002, *Z. marina* area changed at four sites at the 95% CI; one site increased and three sites decreased. At the 80% CI, *Z. marina* area changed at five sites; two sites increased and three sites decreased. No sites changed in both time periods. However, some sites were not sampled in all three years due to random site rotation: two sites were removed from the sampling pool prior to 2002 (*flats47-Travis Spit* and *flats53-Westcott Bay*) and two sites rotated into the sampling pool in 2001 (*cps2215-S. of Eglon* and *flats11-Samish Bay*).

3.2.6 Ability to Detect Trends in Z. marina *Area at Sites*

We tested our ability to detect trends at a site by considering the number of transects required to detect changes in *Z. marina* area for various coefficients of variation (CV). An average of 12 transects were surveyed in 2000 and 2002, and an average of 13 transects were surveyed in 2001. *Z. marina* area estimates at sites had average coefficients of variation of 0.19, 0.16 and 0.12 in 2000, 2001, and 2002, respectively. We conclude from this analysis that the sampling design is capable of detecting a 20% change over a five year period at most sites. Ability to detect change varies at individual sites. *Z. marina* area at each site and 80% confidence intervals are listed in Appendices A, B, and C.

3.3 Maximum/Minimum Depth

3.3.1 Minimum and Maximum Bed Depth in Puget Sound and Regions

Absolute minimum, mean minimum, absolute maximum, and mean maximum *Z. marina* depths are summarized in Table 15 by region for all sites sampled from 2000 to 2002 (results for each site are listed in Appendices E, F, and G). Absolute minimum depth was +1.8 m (MLLW). Mean minimum *Z. marina* depth at sites ranged from +1.1 to -4.9 m (MLLW), the average for all sites was –0.7 m (MLLW). Absolute maximum depth was –8.8 m (MLLW). Mean maximum *Z. marina* depth at sites ranged from -0.3 to -7.8 m (MLLW), the average of all sites was -3.5 m (MLLW). Average bed depths were shallowest in *Central Puget Sound Region* and *Hood Canal Region* and deepest in the *San Juan/Straits Region*. While spatial patterns in bed depth were evident among regions, bed depth ranges within regions were broad.

Table 15. Range of maximum and minimum *Z. marina* depth (MLLW)
for all strata by region in 2000-2002.

Region	Minimum Depth (m)		Maximum Depth (m)	
	Absolute	Range in Site Means	Absolute	Range in Site Means
North Puget Sound	+1.4	+0.6 to -2.2	-7.6	-2.6 to -6.6
San Juan/Straits	+1.5	+0.4 to -4.9	-8.8	-0.4 to -7.8
Saratoga/Whidbey	+1.3	+0.5 to -0.9	-8.0	-0.3 to -4.4
Hood Canal	+1.8	+1.1 to -1.4	-6.5	-2.3 to -4.3
Central Puget Sound	+1.6	+1.1 to -1.3	-7.3	-0.5 to -2.7

Absolute maximum bed depths were deepest along the Strait of Juan de Fuca and the San Juan Islands (Figure 7). Generally, absolute maximum bed depths were shallower in the extreme reaches of Puget Sound. Smaller scale gradients in bed depth were also evident along smaller inlets, such as Saratoga Passage.

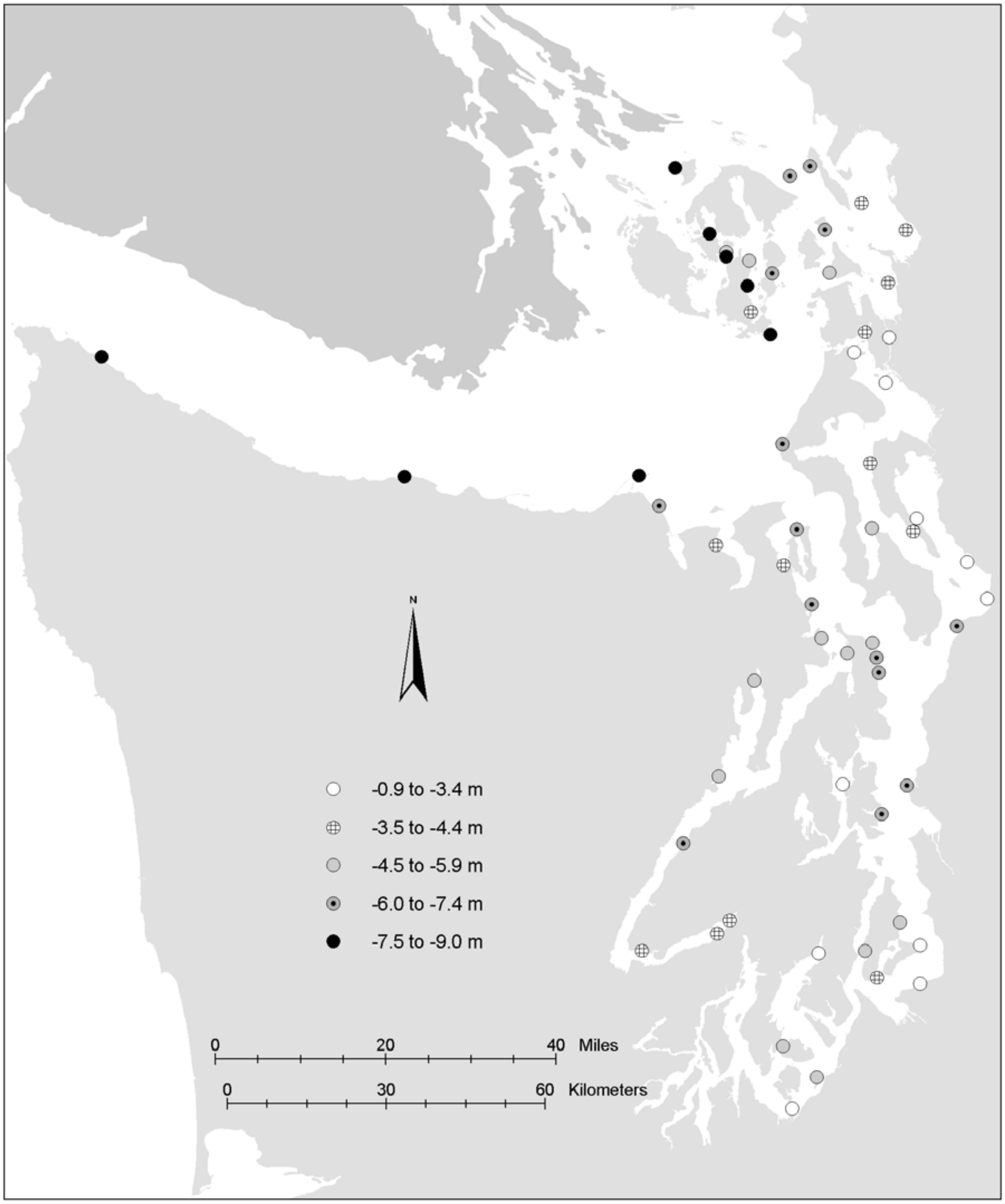

Figure 7. Absolute maximum *Z. marina* depth in 2002.

3.3.2 Trends in Minimum and Maximum Depth at Individual Sites

Maximum and minimum *Z. marina* depth summaries for all sample sites with *Z. marina* in 2000, 2001 and 2002 are listed in Appendices E, F, and G, respectively. Between 2000 and 2001, significant differences in mean maximum *Z. marina* depth were observed at seven sites; all had significantly shallower mean maximum depth observations in 2001 (Table 16). During the same time period, mean minimum *Z. marina* depth changed at four sites; three had significantly shallower mean minimum depths and one had a deeper mean minimum depth. From 2001 to 2002, there were no significant differences in mean maximum *Z. marina* depth observed at any sites. However, there were significant differences in mean minimum *Z. marina* depth at seven sites; all had significantly deeper mean minimum *Z. marina* depths (Table 17).

Table 16. Sites with significant differences in (a) observed mean minimum and (b) observed mean maximum *Z. marina* depth from 2000 to 2001.

			2000			2001	
Site	Location	Mean Minimum Depth (m)	80% Lower Limit (m)	80% Upper Limit (m)	Mean Minimum Depth (m)	80% Lower Limit (m)	80% Upper Limit (m)
Core004	Lynch Cove	-0.5	-0.8	-0.1	+0.8	+0.5	+1.0
Flats20	Skagit Bay N.	-0.4	-0.7	-0.1	+0.2	+0.1	+0.4
Flats28	Snohomish S.	-0.1	-0.4	+0.3	+0.5	+0.4	+0.7
hdc2338	Across from Union	-0.5	-0.7	-0.3	-0.9	-1.1	-0.8

			2000			2001	
Site	Location	Mean Maximum Depth (m)	80% Lower Limit (m)	80% Upper Limit (m)	Mean Maximum Depth (m)	80% Lower Limit (m)	80% Upper Limit (m)
Core005	Dumas Bay	-3.4	-5.1	-1.6	-1.1	-1.2	-0.9
Flats20	Skagit Bay N.	-3.2	-3.9	-2.6	-1.1	-1.4	-0.9
Flats35	Nisqually E.	-1.3	-1.7	-0.9	-0.5	-0.7	-0.3
Flats43	Dabob Bay	-3.2	-3.5	-2.8	-2.3	-2.7	-2.0
Flats53	Westcott Bay	-4.1	-5.7	-2.5	-1.7	-2.0	-1.6
hdc2504	Thorndyke Bay	-3.6	-3.9	-3.3	-2.9	-3.2	-2.6
nps0059	Sinclair Island	-6.6	-7.3	-5.8	-5.2	-5.5	-4.8

Table 17. Sites with significant differences in observed mean minimum *Z. marina* depth between 2001 and 2002.

		2001			2002		
Site	Location	Mean Minimum Depth (m)	80% Lower Limit (m)	80% Upper Limit (m)	Mean Minimum Depth (m)	80% Lower Limit (m)	80% Upper Limit (m)
Core004	Lynch Cove	+0.8	+0.5	+1.0	-0.2	-0.6	+0.1
Flats20	Skagit Bay N.	+0.2	+0.1	+0.4	-0.2	-0.5	0.0
Flats28	Snohomish S.	+0.5	+0.4	+0.7	-0.3	-0.4	-0.2
cps2584	Lower Hadlock	+0.1	-0.1	+0.3	-0.7	-0.7	-0.5
sjs0081	Broken Point	+0.1	-0.2	+0.3	-0.8	-1.0	-0.5
sjs0351	NW Waldron Island	+0.3	+0.2	+0.4	0.0	0.0	+0.1
swh0943	Hackney Island	+0.2	-0.2	+0.5	-0.9	-1.2	-0.5

No sites showed consistent significant changes in *Z. marina* mean minimum or mean maximum depth over both time periods considered (Tables 16 and 17). Three sites had significantly different mean minimum *Z. marina* depths in all years, but the direction of change reversed (*core004-Lynch*, *Flats20-Skagit Bay N* , and *flats28-Snohomish S.*) Only *Flats20-Skagit Bay N* had both a significantly different mean maximum and minimum *Z. marina* depth in the same year, both measures decreased.

3.3.3 Ability to Detect Changes in Depth Over Time

We considered our ability to detect change based on the average sample size and standard deviation for all sites. Site estimates of mean minimum *Z. marina* depth had an average sample size of 10 and standard deviation of 1.8, which enables us to detect a 0.9 m (3 ft) difference in mean minimum *Z. marina* depth from year to year at a site. Site estimates of mean maximum *Z. marina* depth had an average sample size of 12 and standard deviation of 2.8, which enables us to detect an approximately 1.2 m (4 ft) difference in mean maximum *Z. marina* depth from year to year at a site. While estimates based on an average sample size and average standard deviation provide useful general guidelines, the wide range of standard deviations leads to differing change detection capability at individual sites (Appendices E, F, and G).

3.4 Plant Characteristics

3.4.1 General Results

Benthic grab samples were collected at all six core sites, all flats sites, and approximately one-third of the fringe sites with *Z. marina* present (Table 18). At one site (*cps1046-Battle Point*) we did not collect benthic grab samples because there was very little *Z. marina* present. At *Core001-Padilla Bay,* additional samples were collected in 2000. Generative shoots represented 0.5% of all shoots censused in 2000 and 2001. Summaries of all plant characteristics by site for 2000, 2001 and 2002 are listed in Appendices I, J, and K, respectively.

Table 18. Benthic grab sampling effort in 2000, 2001 and 2002.

Year	2000	2001	2002
Total Sites Sampled for *Z. marina* Area	61	73	73
Sites Sampled for Shoot Density and Plant Characteristics	27	31	25
Percent of Total Sites Sampled	44	42	34
Target Number of Stations Sampled Per Site	10	25	25
Total Number of Stations Sampled for Shoot Density	279	775	622
Shoots Measured per Site	30	25	25
Total Number of Shoots Measured	953	797	616

3.4.2 Ability to Detect Change

The ability to detect change in plant characteristics data was low. Given the coefficients of variation (CV) observed during the 2000 survey, several hundred benthic grab samples per site would be necessary to detect a 20% change in mean site shoot density (Table 19).

Table 19. Samples sizes required to detect a 20% decline (or 25% increase) in shoot density between years. Coefficients of variation observed during from 2000 samples were used for the two tailed test using an 80% confidence level.

Stratum	Sample Size Per Site
Core	280
Flats	400
Narrow Fringe	224
Wide Fringe	399

3.4.3 Shoot Density

Shoot density of *Z. marina* at sites averaged 194.4 shoots m^{-2} in 2000, 163.0 shoots m^{-2} in 2001, and 90.6 shoots m^{-2} in 2002 (Table 20). Mean shoot density was significantly higher ($P < 0.05$) at fringe sites than at flats sites in all years. Variability in shoot density was high, standard deviations ranged from 14.4 to 880.5 during the three year period. Maximum shoot density was 3,050 shoots m^{-2} in 2000, 2,790 shoots m^{-2} in 2001 and 650 shoots m^{-2} in 2002. Between 2000 and 2002, mean and maximum shoot density increased at some sites and decreased at others. Over the study area as a whole, mean and maximum shoot density was lower in 2002 than in 2000 and 2001. This can be explained in part by site rotation. In 2002, some sites where the highest densities of *Z. marina* were observed in previous years rotated out of the sampling pool, including *hdc2504-Thorndyke Bay, flats47-Travis Spit, and sjs2646-Discovery Bay* (Appendices I, J, and K). Additionally, one site (C*ore006-Burley Spit*) that had the second highest maximum density in 2000 and 2001 was not sampled due to objections by an intertidal land leaseholder. Some sites that were sampled in all three years showed decreases from high to low maximum shoot densities, including *flats43-Dabob Bay*, *cps1118-Neill Pt*, and *core005-Dumas Bay*.

Table 20. Mean and maximum shoot density for flats and fringe strata based on site averages, 2000-2002.

Year	Stratum	Total Number of Sites	Mean Density (m^{-2}) (Std. Dev.)	Maximum Density (m^{-2})
2000	Flats	12	139.8 (212.5)	1220
	Fringe	15	241.1 (296.4)	3050
	Total	27	194.4 (300.0)	
2001	Flats	14	107.8 (145.1)	1240
	Fringe	17	208.5 (187.1)	2790
	Total	31	163.0 (174.3)	
2002	Flats	13	80.4 (54.4)	650
	Fringe	12	101.1 (62.6)	590
	Total	25	90.6 (58.1)	

Shoot density varied by region (Table 21). *Hood Canal Region* had the highest densities, a maximum of 3,050 m^{-2} and mean of 443.6 m^{-2} for all stations and all years, while *Saratoga/Whidbey Region* had the lowest densities, with a mean 89.2 m^{-2} and maximum of 850 shoots m^{-2}.

Table 21. Mean and maximum shoot densities by region for all stations sampled, 2000-2002.

	Shoot Density (m^{-2})	
Region	Mean (Std. Dev)	Maximum
Central Puget Sound	167.7 (107.8)	1880
Hood Canal	443.6 (347.8)	3050
North Puget Sound	123.8 (60.0)	980
San Juan/Straits	66.8 (56.1)	1150
Saratoga/Whidbey	89.2 (78.1)	850

Shoot density varied with substrate type. Sand supported the highest densities followed by mud and gravel substrates, respectively. Sand was also most common in grab samples (75%), followed by mud (22%) and gravel (3%), respectively.

Shoot density varied with depth, the highest densities were generally found in depths between 0.0 and –2 m relative to MLLW (Figure 8). Shoot density was correlated with depth (Spearman's Rank, $p < 0.001$). While the correlation between density and depth was highly significant, the correlation was not strong (correlation coefficient = -0.311).

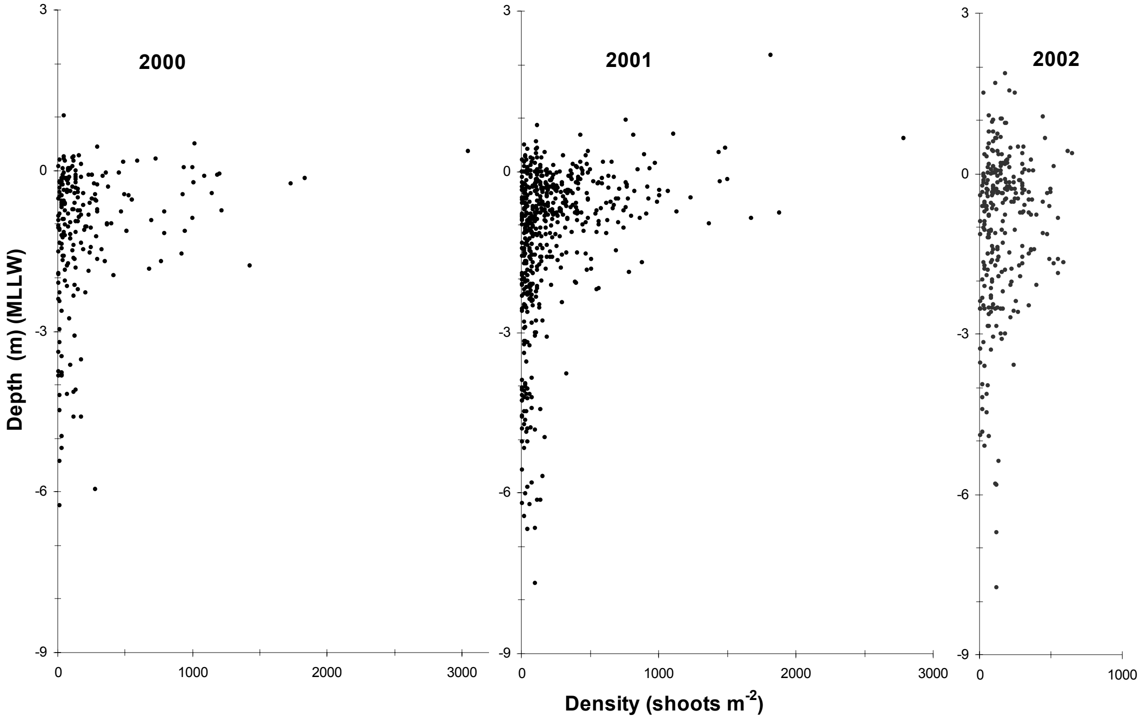

Figure 8. Shoot density and depth for all sampling stations in Puget Sound, 2000–2002 (zero density points not shown).

3.4.4 Leaf Width and Leaf Length

Leaf width varied from 1 mm to 14 mm throughout the study area (Table 22). This range is consistent with previous studies (Phillips 1984). Mean leaf width was consistently wider at flats sites, pooled data in the flats and fringe strata were significantly different ($P<0.00001$).

Table 22. Mean, minimum, and maximum leaf widths for flats and fringe strata based on site averages, 2000-2002.

Year	Strata	Number of Sites	Mean (mm) (Std. Dev.)	Minimum (mm)	Maximum (mm)
2000	Flats	12	7.3 (1.9)	4	14
	Fringe	15	5.1 (1.7)	1	12
2001	Flats	14	7.3 (1.7)	2	13
	Fringe	17	4.8 (1.3)	1	13
2002	Flats	13	7.3 (2.2)	3	14
	Fringe	12	5.8 (2.1)	2	14

Mean leaf length had high variability within and between strata (Table 23). Mean leaf length was longer at flats sites in all three years, and pooled data in the flats and fringe strata were significantly different (P<0.0001). The longest leaf was measured at a fringe site in 2000 and at a flats site in 2001 and 2002.

Table 23. Mean and maximum leaf lengths
for flats and fringe strata based on site averages, 2000-2002.

Year	Strata	Mean (cm) (Std.Dev.)	Maximum (cm)
2000	Flats	64.0 (25.8)	185.2
	Fringe	41.0 (18.8)	196.1
2001	Flats	74.3 (30.3)	227.0
	Fringe	40.2 (12.0)	138.7
2002	Flats	71.3 (27.0)	194.4
	Fringe	55.4 (28.5)	161.6

Leaf width and leaf length varied by region in Puget Sound (Table 24), regions could be clustered into two groups. Mean leaf length and mean leaf width were similar and were relatively high in three regions, *North Puget Sound Region*, *San Juan/Straits Region* and *Saratoga/Whidbey Region*. The longest leaf was measured at *Flats 28-Snohomish Delta South* (Appendix I). Shorter and more narrow leaves were found in *Hood Canal Region* and *Central Puget Sound Region*. The shortest leaves were found in *Hood Canal Region.* The shortest mean site leaf length was at *hdc2405-Thorndyke Bay* mean leaf length was 16.4 cm (Appendix I).

Table 24. Mean, minimum and maximum leaf length and width
by region at all stations, 2000-2002.

	Leaf Length (cm)			Leaf Width (mm)		
Region	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Central Puget Sound	35.2	4	131	4.5	2	10
Hood Canal	38.5	3	164	4.5	2	10
North Puget Sound	80.4	6	177	6.7	3	10
San Juan/Straits	69.8	4	195	8.0	2	14
Saratoga/Whidbey	67.9	4	227	6.7	3	14

3.5 Biophysical Model

Model predictions of eelgrass distributions and plant characteristics were more sensitive to variations in total suspended solids (TSS) than in chlorophyll (Chl). At high TSS, increasing Chl had little effect on either maximum depth or leaf shoot density. For example, when Chl was held constant and TSS was decreased, the predicted eelgrass bed extended from -1.5 m to –3 m in depth (Figure 9). This indicated that suspended sediments, either from terrestrial runoff or re-suspension of tidal mudflats, and not phytoplankton, probably control the submarine light environment, and therefore eelgrass distributions at Dumas Bay.

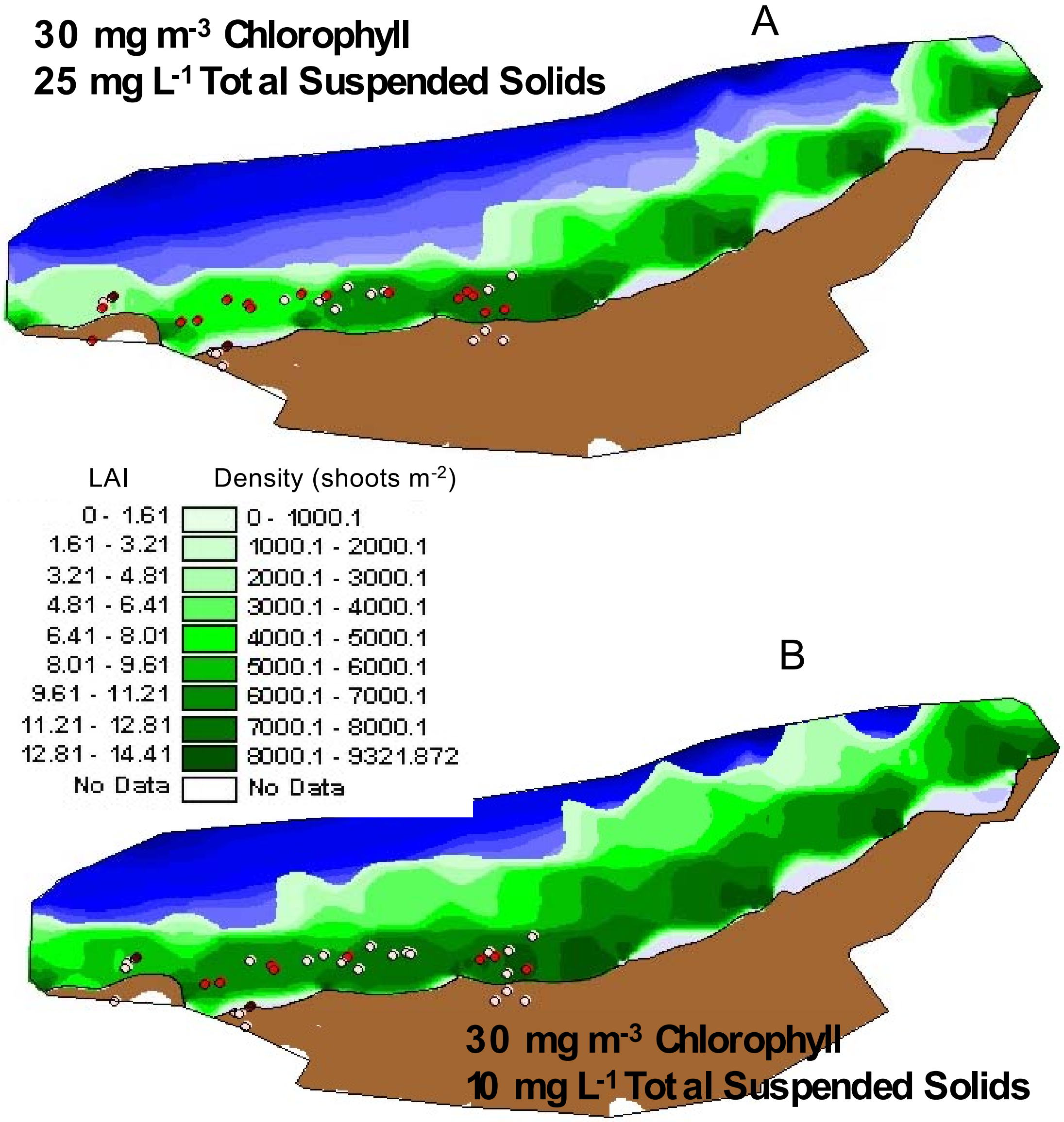

Figure 9. Biophysical model predictions of *Z. marina* distribution at Dumas Bay using two values for total suspended solids (TSS): (a) 25 TSS and (b) 10 TSS. Blue represents bathymetry contours, darker colors are deeper and the green represents *Z. marina*, darker colors represent higher density *Z. marina*. The circles, red (*Z. marina* present) and white (*Z. marina* absent) represent benthic grab samples collected in 2000.

We compared survey data to the model's predicted range in plant and bed characteristics for Dumas Bay. The maximum predicted depth of eelgrass distribution at low TSS and low Chl was below -6 m (MLLW). At high TSS and high Chl, the predicted depth was -1.5 m (MLLW). This was much deeper than our maximum depth survey data which ranged from -1.0 to -1.2 m (MLLW) for all transects. Maximum sustainable leaf shoot density ranged from 8000 shoots m^{-2} in clear water to 3700 shoots m^{-2} at poor water clarity at 0 m (MLLW). Mean and maximum shoot density recorded at Dumas Bay from benthic grab sampling in 2000 were 113.0 shoots m^{-2} and 460 shoots m^{-2}, respectively.

Eelgrass distributions predicted by the biophysical model were qualitatively consistent with eelgrass distributions reported in previous surveys for most of the study area (Norman et al. 1995). However, the 2000 survey of Dumas Bay did not find eelgrass in the eastern part of the bay (Figure 10). This trend continued in 2002; bed patchiness increased and total area decreased.

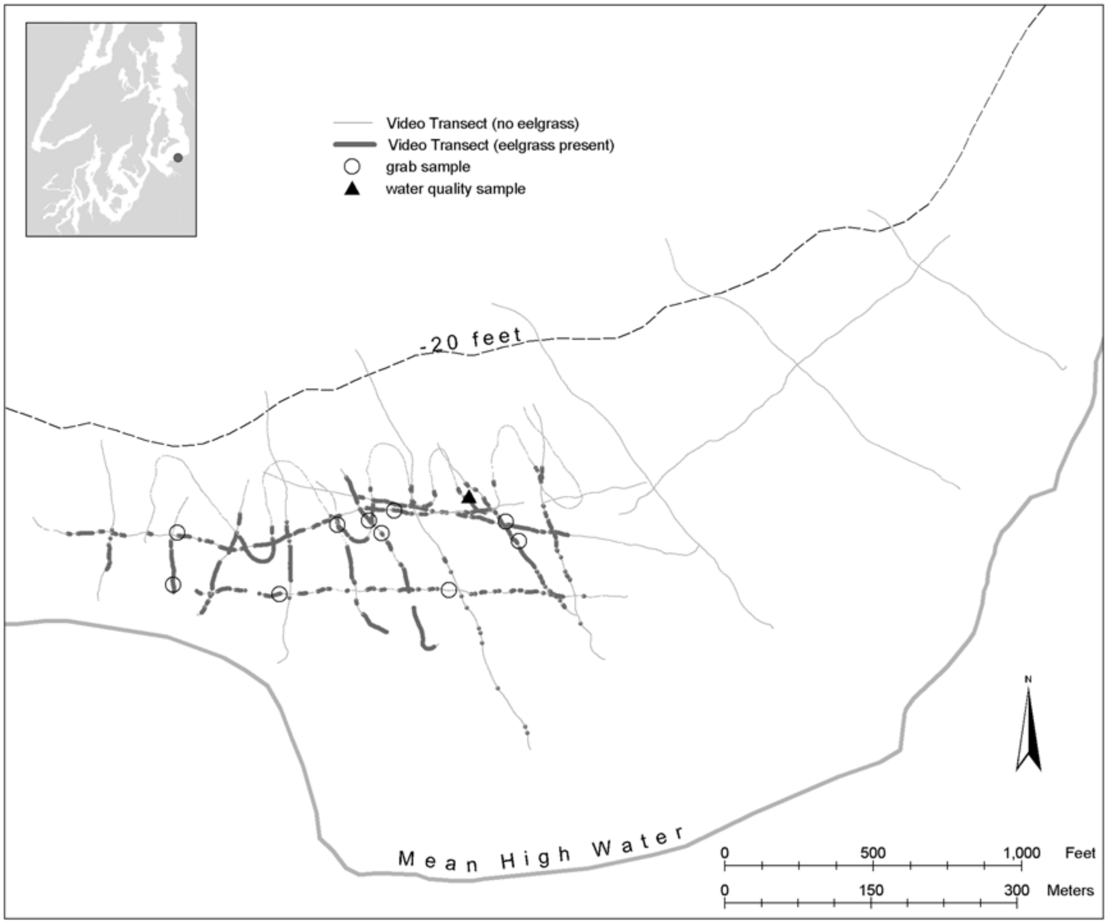

Figure 10. 2000 Survey of *core005-Dumas Bay* showing transects and grab samples.

4 DISCUSSION

4.1 Z. marina Area

4.1.1 *Status of* Z. marina *in Puget Sound and at Individual Sites*

We estimate that there is approximately 200 km^2 of *Z. marina* in Puget Sound. Slightly more than half of the *Z. marina* resource is in flats sites, the remainder occurs in narrow and wide fringe beds. *Z. marina* is not evenly distributed. For example, the Padilla Bay National Estuarine Research Reserve contains approximately 20% of the *Z. marina* resource in Puget Sound.

Few other large area estimates of *Z. marina* extent in Puget Sound exist for comparison to our results, and they all differ greatly in date surveyed, study area extent, methods used, and total estimated *Z. marina* resource (Table 25). Estimates range from 108 km^2 (Department of Ecology 1980) to 450 km^2 (Phillips 1974). We attribute the large differences among the estimates primarily to disparate methods rather than change over time. Uncertainty related to the comparison of historical data sets underscores the need for surveys with consistent methods to monitor for change over time.

Table 25. Estimates of *Z. marina* area in Puget Sound

Source	*Z. marina* Estimate	Study Area	Methods
SVMP (2003)	200 km^2	Inland saltwater areas east of Cape Flattery	Site surveys using Underwater Videography with 1 m^2 resolution, extrapolated using 1:24,000 GIS coverages.
Phillips (1974)	450 km^2	Puget Sound proper (inland waters south of Admiralty Inlet)	Site estimates based on field surveys and transect studies, extrapolated using area-depth data from McLellan (1954).
Coastal Zone Atlas (1980)	108 km^2	Inland saltwater areas east of Dungeness Spit, includes San Juan Archipelago	Interpretation of 1:24,000 aerial photography, survey excludes tribal areas, known edgematching errors.

Mapping resolution is one of the primary differences among methods. The underwater videography-based estimate detects all gaps within *Z. marina* beds of approximately 1 m^2 or greater while many other programs use lower resolution systems. For example, Pulich, Blair and White (1997) note that only features larger than 0.05 ha are distinguishable in aerial photography at a scale of 1:24,000, a recognized vegetation mapping standard. In Puget Sound, low water penetration and diverse submerged vegetation further challenge aerial photography interpretation. The Coastal Zone Atlas was produced using aerial photography interpretation. The Coastal Zone Atlas includes generalized delineations of large *Z. marina* beds. Small beds and fringe beds that are captured by other inventories (e.g. ShoreZone, SVMP) are frequently absent in The Coastal Zone Atlas inventory.

An independent underwater videography-based estimate of *Z. marina* area exists at one site, *core002-Picnic Cove*. Using similar techniques, Norris et al. (1997) estimated that there were 320 hectares of *Z. marina* in 1995. The SVMP *Z. marina* area estimate of 328 hectares in 2000 was similar. In subsequent years, estimated *Z. marina* area in Picnic Cove decreased to 318 hectares in 2001 and to 294 hectares in 2002.

We compared the SVMP underwater videography results at seven sites to previous inventories derived from multispectral data (Berry and Ritter 1997, Ritter and Berry 1999). Multispectral estimates were lower than underwater videography estimates at six sites, ranging from 13 to 66% smaller (Table 26). At one site, *flats20-Skagit Bay N.*, the multispectral estimate was substantially larger. Differences between the data sets could be due to positional accuracy, change over time, or survey methodology. Overall, these results suggest that underwater videography estimates tend to be larger than multispectral estimates.

Table 26. Comparison of *Z. marina* area estimates based on underwater videography and multispectral imagery.

Site Number and Location	Multispectral Inventory (ha)	Line Transect Sampling with Underwater Videography and Statistical Extrapolation (ha)		Size of Multispectral Estimate Relative to Underwater Videography (%)	
	1995 or 1996	2001	2002	2001	2002
core 001-Padilla Bay	2,501	3,193	3,453	-22%	-28%
flats18-Similk Bay	14	40	42	-64%	-66%
flats20-Skagit Bay N	564	152	228	271%	147%
nps0059-Sinclair Is.	0	1	1	-67%	-56%
sjs005-Cypress Is. S.	0	0	0	0	0
nps1363-Village Point	1	1	1	-58%	-58%
swh0848-Ala Spit	22	25	25	-13%	-13%

While *Z. marina* bed location and shape are similar in the multispectral and underwater videography data sets, positional offsets appear to have consistently shifted the data sets at two sites (*nps1363-Village Pt*, *swh0848-Ala Spit*). At the remaining sites, positional offsets potentially explain discrepancies between vegetation classification in portions of the sites.

The underwater videography *Z. marina* transects were generally coincident with the beds in the multispectral inventory or extended beyond them. This result supports known differences in the two systems: the underwater videography has a much lower density detection threshold (1 shoot per m^2) and can detect *Z. marina* deeper in the water column.

At one site, *flats20-Skagit Bay N.*, the multispectral inventory was 147% and 271% larger than the underwater videography estimate in 2001 and 2002, respectively. The substantial difference between estimates at this site was driven primarily by classification of the northeast portion of site; the multispectral inventory classified the area as a dense *Z. marina* bed, the underwater videography line transects recorded few, isolated patches of *Z. marina* and extensive green algal mats. While change over time cannot be ruled out, we believe the discrepancy is most likely due to mis-classification of green algae in the multispectral inventory. It is difficult to differentiate green algae from *Z. marina* because the two species have similar spectral signatures (Aitken et al. 1995).

In summary, available data is highly variable and our results are generally consistent. A rigorous comparison is not possible because other data are sparse and were derived during different time periods, using different methods. We believe our estimate to have relatively high accuracy because it is based on high resolution data and has greater species discrimination capability. Ultimately, successful trend detection depends on repeated surveys with similar methods.

4.1.2 Trends in Z. marina Area Between 2000 and 2002

Z. marina area showed no significant change between 2000 and 2002 in Puget Sound as a whole. This indicates that on a sound-wide scale, *Z. marina* was relatively stable over this time period. Changes were observed within strata and within regions. Observed year-to-year changes could reflect natural variation. Little information exists on interannual variation in Puget Sound for comparison to these data. In several regions, insufficient samples in the flats strata precluded estimation of interannual trends. This is due, in part, to environmental conditions; there are few flats sites in Central Puget Sound.

We tested for trends by comparing matched sites between years and extrapolating the results over geomorphological strata and the study area. Change over time can also be examined by comparison of annual status estimates. These two independent estimates of change allow for results comparison and methods evaluation. In some cases, our estimates of change over time using annual status estimates disagree with our matched sites results. For example, yearly status estimates in *Z. marina* area increased in the flats stratum between 2000 and 2001 (Figure 6, Table 10). Comparison of matched sites shows a decrease over the same time period. We attribute these inconsistencies primarily to the effect of random site rotation; the status estimates were increased in 2001 by the addition of a new flats site (see next section). In contrast, the matched comparison of sites only considers sites sampled in both years. We consider the trend estimate produced by matched site comparison to be more reliable because it is not affected by random site rotation. This finding provides useful early feedback on the performance of the statistics. We are currently planning to test for trends with status estimates over time periods greater than 5 years (Appendix L). While retrospective adjustment is projected to dampen artifacts of site rotation, it will be important to continue comparing both methods in order to identify any apparent trends produced by sampling design or statistical methods.

Change in *Z. marina* area was detected at individual sites. These sites are strong candidates for future monitoring and process studies. No geographic patterns were evident among sites that changed, suggesting that these change may have been driven by local affects. One of these sites, *flats53-Westcott Bay,* has been identified in other research to be threatened (Penttila, 2002 personal communication). Other sites could have experienced change, but the results are uncertain due to potential sampling effects such as polygon delineation, random transect placement or species discrimination issues. For example, we measured significant change over time in *Z. marina* area at *Core005-Dumas Bay*, however, the apparent change is uncertain due to potential confusion between *Z. marina* and *Z. japonica*.

While this project is designed to focus on trends in the study area as a whole, it has potential to yield valuable information at the site level. Dramatic trends, for instance, may be detected at an individual site but not be reflected in regional or study area level results. Information on such local trends may be valuable to resource managers and planners at local jurisdictions.

Westcott Bay (*flats53*) illustrates the potential for local application, as well as its limits due to the sound-wide project focus. The Westcott Bay site was sampled in 2000 and 2001 and then was removed from the sample pool as part of the random site rotation. This rotational design clearly limits the ability to provide ongoing trend information at any particular site. Despite this limitation, site-level information such as this could make an important contribution to local efforts to investigate and manage environmental change in the *Z. marina* resource.

4.1.3 Sampling Methodology Strengths and Weaknesses

4.1.3.1 Stratification

Z. marina area results for each sampling stratum provide information on the relative contribution of each stratum to the overall study area estimate and associated variance (Tables 27, 28, and 29). Overall, the flats stratum performed most poorly of the sampling strata. The 2000 initial estimate for the flats stratum was smaller than the 2001and 2002 estimates. However, it was not significantly different due to the large associated variance. We attribute the change in the magnitude of the flats stratum estimate primarily to the addition of a new, randomly selected flats site in 2001. *Flats 11-Samish Bay* was randomly added to the sampling pool in 2001. It is a large bay with a high *Z. marina* fraction, which raises the overall flats area estimate through the extrapolation. If this site is removed from the 2001 and 2002 results, the initial estimates for those years become more similar to the 2000 initial estimate. The differences in flats stratum estimates among years were mirrored in the Sound-wide estimates. While the Sound-wide estimates from all three years are not significantly different (90% confidence interval), the 2000 estimate is smaller.

Table 27. 2000 initial estimate of *Z. marina* area by stratum.

Stratum	*Z. marina* Area (km^2)	% of Total *Z. marina* Area	Variance	% of Total Variance	Standard Error	CV
Core	37	26%	2	0%	1	0.04
Flats	34	23%	51	9%	7	0.21
Narrow Fringe	40	28%	59	10%	8	0.19
Wide Fringe	34	24%	469	81%	22	0.63
Total	145	100%	580	100%	24	0.17

Table 28. 2001 initial estimate of *Z. marina* area by stratum.

Stratum	*Z. marina* Area (km^2)	% of Total *Z. marina* Area	Variance	% of Total Variance	Standard Error	CV
Core	38	19%	2	0%	1	0.03
Flats	86	42%	3,104	95%	56	0.65
Narrow Fringe	42	20%	69	2%	8	0.20
Wide Fringe	40	19%	93	3%	10	0.24
Total	207	100%	3,268	100%	57	0.28

Table 29. 2002 initial estimate of *Z. marina* area by stratum.

Stratum	*Z. marina* Area (km^2)	% of Total *Z. marina* Area	Variance	% of total variance	Standard Error	CV
Core	41	19%	2	0%	2	0.04
Flats	87	41%	3,686	97%	61	0.70
Narrow Fringe	44	21%	56	1%	8	0.17
Wide Fringe	40	19%	67	2%	8	0.21
Total	212	100%	3,812	100%	62	0.29

The flats stratum contributed the majority of the variance in two of the three monitoring years, 95% and 97% of total variance in 2001 and 2002, respectively. The large variance in the flats stratum is attributed primarily to the wide range in *Z. marina* area at flats sites each year. In 2001, the addition of a randomly selected site with very high *Z. marina* area (*flats11-Samish Bay*) increased within stratum variation. In 2002, random selection of a flats site with no *Z. marina* further increased within stratum variation (*flats10-Nooksack Delta East*).

Retrospective adjustment will compensate, in part, for the influence of random site rotation by correcting estimates with results from subsequent years. Despite this potential improvement, these results suggest that unusual sites in the flats stratum strongly influence the overall estimate. This weakness could be addressed by further partitioning the stratum.

Another potential source of variance in the flats stratum estimate is the flats site definition. Flats sites were delineated using the best digital inventory data available for the entire study area. This consistency requirement led us to define flats sites to include all areas between the approximate Ordinary High Water Line and the –20 foot bathymetry line. This scope exceeds the tidal range of *Z. marina* and introduces uncertainty into the *Z. marina* area estimate. More precise delineation of flat sites would decrease uncertainty. However, to maintain consistency, improved boundary mapping would be required at all 71 flat sites.

The wide fringe stratum had the highest variance in year 2000. We attribute this result to the low number of wide fringe sites sampled in the first year. In subsequent years, we increased the number of wide fringe sites sampled, and the relative contribution of the wide fringe stratum to total variance was reduced. This is an example of increasing sample size can decrease variance.

In all years, the narrow fringe stratum had relatively low CVs for the *Z. marina* area estimates and accounted for a relatively small amount of the total variation in our sound-wide estimate. The core stratum contributed less than 1% of the variance. Variance was consistently lowest in the core stratum because all of the sites were sampled yearly.

The geomorphological stratification was developed primarily to address sampling and extrapolation issues. However, the data suggest that the stratification also captures ecological differences. Most flats sites had greater *Z. marina* area than fringe sites, and all of the sites with *Z. marina* area greater than 100 hectares were flats sites. Flats sites had more shallow water habitat, in part due to total site size and in part due to geomorphological factors such as shoreline shape and bottom slope. The fringe stratum exhibited deeper mean maximum bed depths than the flats stratum. Flats and fringe sites had significantly different mean shoot densities, mean leaf width, and mean leaf length.

Functional differences between flats and fringe sites are suggested by other studies. For example, juvenile salmonids utilize delta flats during freshwater to marine transition and use fringing nearshore beds as migratory corridors and refugia from predators (e.g. Simenstad et al. 1982, Gregory and Levings 1998). Flats sites are vast habitats for congregations of birds (e.g. Baldwin and Lovvorn 1994, Wilson and Atkinson 1995) and nursery areas for crab and fishes (e.g. Phillips 1984, Lemberg et al. 1997). The shape and location of the beds can affect their role as filters for pollutants, sedimentation traps and carbon import and export.

4.1.3.2 Sampling Window

Sampling took place during the summer and early fall (June to October). A single, large sampling window provided sufficient time to visit many sites and produced the best annual estimate. The sampling window conforms to *Z. marina* sampling guidelines in Washington State (Fresh and Williams pers. comm.). However, *Z. marina* shoot density and leaf size are known to vary within the sampling period (Phillips and Lewis 1983, Kentula, 1983, Olesen and Sand-Jensen 1994). Our monitoring fails to capture this seasonal component of growth. A shorter sampling window would span less seasonal variation in the population but would impact project resource allocation.

4.1.3.3 Underwater Videography

Underwater videography generally worked well to detect the presence of *Z. marina* in a range of environments. Overall, we believe that it more reliably discriminates vegetation species than multispectral analysis and airphoto interpretation at this stage of technological development, and it is not limited by depth. It is more rapid than diver surveys, making it a more appropriate large area census tool.

Underwater videography methods did not work well in areas with features that obstruct boat navigation with a dragged towfish. The most problematic obstructions were aquaculture structures, floating kelp beds, mooring buoys, and submerged rocks.

We had a high degree of certainty about the accuracy of species identification and differentiation, with the exception of *Zostera japonica* and *Phyllospadix spp.* Discrimination difficulties among seagrass species re-enforced the need for careful identification of samples and highlights the morphological variation of the species *Z. marina*.

Additional information can be extracted in the future from the underwater videography archive. Rough abundance estimates, such as Braun-Blanquet cover classes (e.g. Fourqurean et al. 2002), could increase the detail of the bed characterization. Identification of other plant and algal species would also enrich the data set without additional sampling.

While underwater videography has methodological advantages, other technologies may supplant it. Alternative data collection methods could emerge that allow for rapid data collection, cover broader areas or differentiate species with a high degree of certainty. Two candidates include the BioSonics vegetation identification algorithm and sidescan sonar.

One weakness related to the *Z. marina* area parameter is that it does not consider *Z. marina* bed density. Each of the samples along a line transect considers *Z. marina* to be present at densities of ≥ 1 shoot m^{-2}. While the resolution of the classification is fairly high, this definition does not consider shoot density. Large decreases in density could go undetected until gaps occurred in the bed of greater than 1 m^2.

4.1.3.4 Line Transect Sampling and Extrapolation Technique

Line transect sampling generally worked well in estimating *Z. marina* area with known statistical accuracy. However, we need a fuller understanding of how random transect placement and polygon edge effects impact *Z. marina* area estimates. Random transects were sometimes located in portions of the bed that were not representative. Differences in the size and shape of the sampling polygon sometimes led to differences in overall *Z. marina* area.

The site definition and extrapolation were based on synoptic GIS inventory data. These data are limited by relatively low resolution, known errors, and change over time. Over time, improving these data will lead to overall improvement in site definition and extrapolation. However, we have not yet determined how best to integrate improvements into the data set. If changes to site delineation are made, the associated cost would be loss of site continuity over time.

4.1.4 Trend detection: are we meeting our goal?

The lower standard errors associated with the adjusted *Z. marina* area estimate improved its precision and ability to detect change. These results suggest that we will meet our trend detection goal. However, additional years of data are needed to provide a more complete picture of our ability to detect change. During this time, we need to continue to fine tune sampling and statistical methods

Retrospective adjustment of the year 2001 initial estimate led to small changes in the relative proportion of *Z. marina* in each stratum and a 74% decrease in overall variation (Table 30, see Table 28 for comparison). The overall decrease in variation was due primarily to improvements in the flats stratum. The flats CV decreased by 82%. Narrow fringe stratum and wide fringe stratum CVs decreased by 20% and 5%, respectively.

Table 30. 2001 adjusted estimate of *Z. marina* area by stratum.

Stratum	*Z. marina* Area (km^2)	% of Total *Z. marina* area	Variance	% of total variance	Standard Error	CV
Core	38	21%	2	1%	1	0.03
Flats	70	37%	73	39%	9	0.12
Narrow Fringe	42	22%	47	25%	7	0.16
Wide Fringe	36	20%	66	35%	8	0.22
Total	186	100%	188	100%	14	0.07

The dramatic improvement in the flats variance is largely due to chance associated with the random rotation of sites. The adjusted variance is a weighted average of the variance for matched and unmatched sites (Appendix L). In 2001, variance for unmatched sites was much smaller than for matched sites. Variance at the unmatched sites was low because the randomly selected sites were rather similar and the sample size was small (two sites). A larger sample size would decrease the impact of individual sites on the overall estimate. If total sample size is held constant, a larger rotational fraction for the flats stratum may provide greater stability between years by maintaining an adequate number of sites in both the matched and unmatched groups. Our relatively high correlation coefficients suggest that a greater rotational fraction would be optimal.

While we can detect general trends in *Z. marina* within some regions, our sample size is too small in some regions for trend detection in all strata. Trend detection over regions is important because different subareas within Puget Sound are subjected to different stressors. However, sampling effort would need to be increased substantially in order to improve trend detection capability in all regions.

Site-level trend analysis provides small scale information on significant changes in abundance. Sites that changed significantly are strong candidates for more detailed monitoring. At the site level, we are able to detect a 20% change over a five year period at most sites. The ability to detect change in the *Z. marina* resource is driven by the number of transects sampled and by within site variability (Table 31).

Table 31. Sample size (number of transects) required to detect a 10%, 20%, 30%, 40%, or 50% change in *Z. marina* area over five sampling periods at a single site with $\alpha = 0.10$ (two tailed) and $1-\beta = 0.80$ for various levels of coefficient of variation. This estimate was derived based on the ideal assumption that the $\sigma^2 = 0$.

Coefficient of Variation	Change in *Z. marina* Area 10%	20%	30%	40%	50%
0.04	3	3	3	3	3
0.06	7	3	3	3	3
0.08	12	3	3	3	3
0.10	18	5	3	3	3
0.12	26	7	3	3	3
0.14	35	9	4	3	3
0.16	46	12	6	3	3
0.18	58	15	7	4	3
0.20	71	18	8	5	3
0.22	86	22	10	6	4
0.24		26	12	7	5
0.26		30	14	8	5

Overall, our change detection capability is generally very good in comparison to other programs. Many programs can only reliably detect losses as high as 50-80% (Duarte 2002). We feel that the ability to detect a 20% change in *Z. marina* Sound-wide over 10 years is reasonable, given natural variation in the resource and limited monitoring funds. Trend detection capability can be improved through increasing our sample size. Management and scientific concerns may require even higher resolution trend detection. For example, Duarte (2002) recommends that programs detect losses of 10% or less, as well as develop early warning indicators of decline.

4.1.5 Recommendations regarding the Z. marina *Area Parameter*

Generally, this methodology meets its objective to monitor status and trends in *Z. marina* given environmental considerations and available funds. We recommend the following changes to existing methods:

- Conduct field and modeling studies to examine the impact of random transect placement, sampling polygon delineation, and line transect extrapolation on the *Z. marina* area estimate at sites.
- In order to decrease variance in the flats stratum, complete a study to further stratify the flats into two groups based on total *Z. marina* area. Develop initial classification categories and model the effects on area estimates and associated variance.
- Evaluate the optimal rotational fraction for each stratum and ramifications of changing rotational fraction.
- Estimates could be improved by increasing the total number of sites sampled, especially at the regional scale. We recommend increasing the number of sites if regional data with greater statistical power is critical to management.
- Develop methods to assess cover class using videography interpretation. Cover class is commonly used by monitoring programs as a surrogate for density.

4.2 Minimum and Maximum *Z. marina* Depth Characteristics

4.2.1 Spatial Patterns in Z. marina *Depth*

Observed patterns in minimum and maximum bed depth generally agree with other findings in Puget Sound (Phillips 1974, Thom et al. 1998). The absolute minimum depth of +1.8 m agrees exactly with values in Phillips (1974). Spatial patterns were observed over the study area as a whole in maximum depth: areas of greater oceanic influence tended to have deeper absolute and mean maximum depths. As expected, minimum and maximum bed depth varied broadly within regions. These results reflect the wide range in physical parameters and disturbance vectors throughout the study area that are known to affect SAV distribution, including water turbidity, sediment characteristics, wave action, and tidal amplitude (Koch 2001, Short and Wyllie-Echeverria 1996). These parameters are likely to drive *Z. marina* bed depth at multiple scales: over the study area as a whole, and also at the local level.

Given the observed diversity of *Z. marina* bed depth in Puget Sound, it would be difficult to determine simple management guidelines for submerged aquatic vegetation habitat depth such as those that have been developed in areas with less variable physical conditions (e.g. Virnstein and Morris 2000). However, regional ranges provide contextual information for other higher resolution *Z. marina* studies and for *Z. marina* restoration efforts (Fonseca *et al* 1998).

4.2.2 Trends in Site Level Z. marina *Depth*

We report no trends in *Z. marina* depth that occurred at individual sites throughout the study period. At sites where *Z. marina* bed depth changed significantly in both years, the direction of change reversed. At some sites, trends in mean minimum and maximum *Z. marina* depth support observed trends in *Z. marina* area. For example, *Z. marina* area at *Flats53-Westcott Bay* decreased significantly from 185,270 m^2 in 2000 to 141,178 m^2 in 2001 (80% CI). The mean maximum *Z. marina* depth at this site decreased significantly over the same time period, from -4.1 m to -1.7 m (MLLW). Following sampling in 2001, the site was randomly removed from the SVMP sampling rotation. However, subsequent investigations found that *Z. marina* abundance in Westcott Bay has continued to decline (Pentilla personal communication, Buffum personal communication). The observed trend in Westcott Bay suggests that maximum depth can be an early indicator of bed loss. Sites where significant changes were observed could be considered as candidates for higher resolution studies.

4.2.3 Ability to Detect Changes in Depth

At the regional scale, mean minimum and maximum *Z. marina* depth ranges were too large to capture moderate trends in depth over time. This finding indicates that trends in depth are most effectively detected at the site scale.

Based on considering average within site CVs and number of transects sampled, we predict that we have the ability to detect a 1.2 m difference in mean maximum *Z. marina* depth and a 0.9 m difference in mean minimum bed depth at individual sites. At many sites, increasing the number of samples would improve our ability to detect changes in depth (Figure 11). At sites where other habitat characteristics produce highly variable minimum and maximum bed depths (Koch 2001), it will be difficult to increase sampling intensity sufficiently to detect moderate changes in bed depth. For example, at *sjs2741-Crescent Bay* there is a strong energy gradient; the site is protected in the west and exposed in the east. Along this exposure gradient, there is a gradient in minimum *Z. marina* depth from 1-2 m to 5-6 m (MLLW).

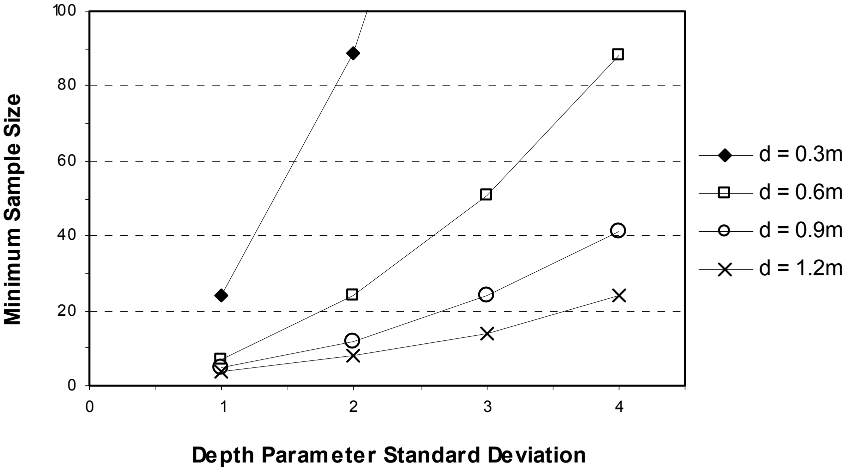

Figure 11. Required sample size to detect changes in depth (m) for four levels of standard deviation in the depth parameter and $\alpha = 0.1$ (two-tailed) and $1-\beta = .80$. Based on 2000 survey data.

4.2.4 Depth Measurement Accuracy and Precision

Both environmental and technological factors are known to introduce uncertainty into the accuracy and precision of depth measurement, especially in shallow water environments with complex tidal regimes. We controlled for these variables to the greatest extent feasible in our equipment selection and data processing. Unfortunately, it is difficult to quantify the precision and accuracy of the depth measurements because multiple factors influence measurement. To evaluate the influence of instrumentation on depth measurement, we collected depth data with two devices in 2002, a Garmin depth sounder and a BioSonics echosounder (Appendices G and H). Out of 59 sites compared, mean maximum depth measurements based on the two instruments were significantly different at four sites (Table 32 and 33). Mean minimum *Z. marina* depth measurements based on the two instruments were significantly different at two sites.

Table 32. Sites with significant differences in mean minimum *Z. marina* depth in 2002 as measured by Garmin and BioSonics depth sounders.

		GARMIN			BIOSONICS		
Site	Location	Mean Minimum Depth (m)	80% Lower Limit	80% Upper Limit	Mean Minimum Depth (m)	80% Lower Limit	80% Upper Limit
Hdc2433	Pleasant Harbor	-0.8	-0.9	-0.8	-1.4	-1.5	-1.3
Swh1647	Mukilteo	-0.9	-1.0	-0.8	-1.3	-1.4	-1.1

Table 33. Sites with significant differences in mean maximum *Z. marina* depth in 2002 as measured by Garmin and BioSonics depth sounders.

		GARMIN			BIOSONICS		
Site	Location	Mean Maximum Depth (m)	80% Lower Limit	80% Upper Limit	Mean Maximum Depth (m)	80% Lower Limit	80% Upper Limit
Core002	Picnic Cove	-4.2	-4.6	-3.8	-4.9	-5.1	-4.7
Cps1164	Maury Island	-1.9	-2.1	-1.7	-2.4	-2.7	-2.2
Hdc2359	Lynch Cove	-3.4	-3.6	-3.2	-3.8	-4.0	-3.7
Swh1593	Camano Island	-1.3	-1.5	-1.2	-1.9	-2.0	-1.8

When the two instrument readings differed significantly, the BioSonics echosounder measurement was deeper than the Garmin depth sounder. The Garmin depth sounder may “ping” off the top of submerged vegetation, unlike the BioSonics echosounder, which has software that helps to discriminate between hard bottom and submerged vegetation. Apparent differences could also be related to data collection methods. The two instruments collect data in different time increments, BioSonics in two-second and Garmin in one-second intervals. The transducers were mounted approximately three meters apart, on opposite sides of the boat’s transom. This positional difference could lead to real differences in depth in areas with steeply sloping shorelines. Additionally, each transducer varies 3-4 inches in response to the boat trim due to fuel on-board.

4.2.5 *Recommendations Regarding* Z. marina *Bed Depth Parameter*

We recommend the following changes to depth measurement methods:

- Increase mean maximum depth sampling to the greatest extent feasible without sacrificing the total number of sites visited. Mean maximum depth is a more important depth parameter to monitor than minimum depth because it responds to changes in water quality, while minimum depth is often controlled by factors such as wave energy and desiccation.
- Evaluate the accuracy and precision of depth measurements through comparisons at various depths in a range of environmental conditions.

4.3 Plant Characteristics

4.3.1 *Ability to Detect Change over Time*

The primary goal of collecting data on plant characteristics was to detect changes over time at the site level. Plant parameters were selected to provide a suite of recognized indicators of *Z. marina* health (Neckles et al. 1984, Hemminga and Duarte 2000, Duarte and Kirkman 2001). We found that the sampling methodology and sampling effort are not effective for change detection. Only extreme changes between years might be detected at a site.

4.3.2 *Plant Characteristics in Puget Sound*

While not appropriate for quantitative assessment of change, the plant characteristics data illustrate the wide variability of *Z. marina* throughout the study area. This is the first study since Phillips (1972) to sample these metrics (density, leaf width and leaf length) throughout Puget Sound from a large number of sites. These data can be useful for comparison to smaller scale studies and to guide restoration, inventory, and other monitoring studies at these sites.

Mean, median, and maximum shoot density values were similar to other studies conducted in the region (Bulthius 1995, Kentula and McIntire 1986, Phillips 1984, Thom et al. 1998, Webber et al., 1987). Shoot density variability was high within and among sites. Measured shoot densities were similar in 2000 and 2001, but declined in 2002 (Appendices I, J, and K). This change over time may be explained by site replacement sampling methodology (see section 4.2.8).

Shoot density is often negatively correlated with depth (Hayashida 2000, Kraus-Jensen et al. 2000). Our data showed a highly significant, yet weak, correlation between depth and shoot density. The weak correlation may reflect that shoot density is dependent on many interrelated factors such as substrate type, and wave exposure (Fonseca and Bell 1998, Koch 2001). Densities were highest in the 0 to –2 m (MLLW) depth range, as found in other Puget Sound surveys (Thom et al. 1998).

Sand was most common substrate type in grab samples. Gayaldo (2002) also observed that sandy substrates were most frequently encountered in North Puget Sound *Z. Marina* beds. Phillips (1984) identified mixed sand and mud as the optimal substrate for *Z. marina.*

Leaf morphometrics varied among regions. The longest leaves were found in the *Saratoga/Whidbey* and *San Juan/Straits Regions* and the shortest leaves were found in *Hood Canal* and *Central Puget Sound Regions*. The widest leaves were found in the northernmost areas (the *San Juan/Straits* and

North Puget Sound Regions), while the narrowest leaves were found in the southernmost areas (*Hood Canal* and *Central Puget Sound Regions*).

Other research suggests that our leaf morphometrics results may reflect genotypic differences in *Z. marina* in Puget Sound. Backman (1991) concluded that observed morphological variation reflected the presence of three varieties of *Z. marina* in Puget Sound, defined primarily by leaf width and tidal depth: var. *typica* var. *Phillipsii*, and var *latifolia*. Genetic analysis revealed different levels of diversity and clone size in intertidal and subtidal populations, suggesting that morphological differences at a site could be related to genetic differences between populations (Ruckelshaus 1995, Ruckelshaus 1996, Ruckelshaus 1998, J.L. Olson, personal communication 2003). The relationship between observed genetic strains and differing genetic responses to stressors is not yet well described or understood in Puget Sound.

4.3.3 Analysis of Methodology

Lower statistical power severely limits the usefulness of the grab sample data for this monitoring program. We attribute the low power in part to limited sampling effort and in part to inherent variability due to habitat heterogeneity. Additionally, the sampling window (June–October) encompasses known variation in the parameters measured (e.g. Kentula and McIntire 1986, Thom 1990).

Random selection and replacement of sites and stations appears to have a large effect on observed plant characteristics. For example, maximum shoot density dropped to 650 in 2002 from 3,050 in 2000 and 2,790 in 2001. This change appears to be due primarily to the random removal of sites with unusually high shoot density measurements (Appendices I, J, and K). A similar effect was observed on *Z. marina* area estimation due to the random selection of *flats11-Samish Bay*. These results highlight tradeoffs related to fixed vs. rotating sampling designs. Habitat heterogeneity in Puget Sound may lead to greater relative influence of random rotation design as compared to seagrass monitoring programs in other regions. Seagrass monitoring programs employ a variety of fixed and rotating designs at the site and at the station scales, these designs exhibit contrasting strengths and weaknesses in terms of their ability to detect trends and to extrapolate results over the study area as a whole (Fourqurean et al. 2002, Durako et al. 2002, Morris et al. 2000).

While plant characteristics are recommended as reliable response variables (Duarte and Kirkman 2002, Neckles et al. 1994, Duarte 2001), their response patterns appear to be complex. In order to qualitatively compare plant characteristics to trends in abundance and depth distribution, we examined plant characteristics collected at similar dates among years at sites where *Z. marina* area changed significantly (Table 34). Changes in bed area did not consistently relate to changes in plant characteristics and bed depth. For example, *Z. marina* area at both *Flats53-Westcott Bay* and *Core 005-Dumas Bay* decreased. But the mean shoot density increased at *Flats53-Westcott Bay* while shoot density decreased at *Core 005-Dumas Bay.* The increase at *Flats53-Westcott Bay* may be attributable to the expansion of the bed at this site to shallower waters. Shoot densities typically are higher in shallower portions of beds (Figure 8). Further, *Z. marina* area increased at both *Core004-Lynch Cove* and *Flats20-Skagit Bay N*. However, the maximum depth of the beds remained the same at each site while the mean minimum depth increased at *Core004-Lynch Cove* and decreased at *Flats20-Skagit Bay North.* Shoot density also showed opposite patterns at the two sites.

Table 34. Sites with significant changes in *Z. marina* bed area and depth compared with a qualitative assessment of the change in density, leaf width and leaf length data. The significance level used for *Z. marina* area and depth was 80% confidence intervals. The magnitude change of the other parameters is shown with arrows: one arrow signifies a 30-100% change; two arrows a 101-200% change; three arrows a 201% to 300% change between years.

Site Code and Location	Bed Area Change	Mean Max. Depth Change	Mean Min. Depth Change	Mean Shoot Density Change	Mean Leaf Width Change
2000-2001					
Core004-Lynch Cove	Increase	No	Shallower	↓↓	No
Flats47-Travis Spit	Increase	No	No	No	No
Flats53-Westcott Bay	Decrease	Shallower	No	↑↑↑	No
Sjs2646-Discovery Bay	Increase	No	No	No	↑
Swh1593-Cornell, Camano	Increase	No	No	↑↑↑	No
2001-2002					
Core005-Dumas Bay	Decrease	No	No	↓	No
Flats11-Samish Bay N	Increase	No	No	No	No
Flats20-Skagit Bay N	Increase	No	Deeper	↑	No

While the grab sample methodology did not provide sufficient statistical power for measuring plant characteristics, it is possible to extract basic information on shoot density from underwater videography. Rough cover classes, commonly used as a surrogate for shoot density, have been used extensively for monitoring (Duarte and Kirkman 2001, Fourqurean et al. 2002), Modified Braun-Blanquet cover classes (eg. Fourqurean et al. 2002) can potentially be extracted from underwater videography during post-processing.

4.3.4 Recommendations Regarding Plant Characteristics Parameters

We recommend the following changes to methods for measuring plant characteristics:

- Discontinue collecting grab samples to monitor plant characteristics.
- Evaluate the feasibility of recording cover class as a surrogate for shoot density during classification of underwater videography.

4.4 Biophysical Model

The biophysical model identified total suspended sediment (TSS) to be more important than chlorophyll (Chl) concentrations in affecting the *Z. marina* distribution in Dumas Bay. This finding is similar to results in San Francisco Bay, where light limitation caused by high water column sediment loads can prevent phytoplankton growth and eelgrass distribution in an otherwise eutrophic estuary (Alpine and Cloern 1988, Zimmerman et al. 1991, Zimmerman et al. 1995). In Puget Sound, elevated sediment levels near river mouths are very common in the spring and early summer. However, anthropogenic activities such as alteration of the shoreline, dredging and upland land use practices could elevate natural levels of TSS in streams and rivers. The biophysical model can be a useful tool to predict impacts these activities might have on eelgrass distribution.

Eelgrass distributions predicted by the biophysical modeling approach employed here were qualitatively consistent with eelgrass distributions from previous 1995 surveys of Dumas Bay where eelgrass was present in the western part of the bay. (Norman et al. 1995). The initial SVMP survey (Figure 12) did not record eelgrass in the western half of the bay and this trend continued in 2001 and 2002 with a decrease of over 60%. If consistently higher turbidity levels have developed since 1995, this could explain the inconsistency of current survey data with model predictions. More water quality data are needed at this site to prove a cause and effect relationship of bed area with water quality.

While the pattern of decline at Dumas Bay was not specifically predicted, the model predictions of supportable shoot density (or leaf area index) must be viewed as the upper bounds for light-limited populations, assuming water column conditions used to create the submarine light environment were representative of the annual mean condition at the site. Additionally, the biophysical model used here did not evaluate other factors that might limit eelgrass density, including nutrient availability, physical disturbances such as dredging operations, burial events or erosive currents. Nor does it include the effects of space competition with macroalgae (e.g. *Ulva* spp., *Enteromorpha* spp., *Gracilaria* spp.) or other seagrasses (e.g. *Zostera japonica*). Thus, disagreement between observed and predicted eelgrass distributions/densities may require investigation into controlling factors other than water column light availability.

The biophysical model provided two important findings for the development of a long-term program monitoring eelgrass resources in Puget Sound:

- Water column turbidity was identified as a major factor determining eelgrass distributions at Dumas Bay. The measurement of water quality parameters, (Chl), and particularly (TSS), especially with regard to accurate resolution of their spatial and temporal variations, should be given high priority in future efforts to monitor and manage eelgrass resources in Puget Sound.
- Uncertainty associated with high variability in shoot:root ratios had a very small (5%) effect on predicted eelgrass density and depth distribution. Insensitivity of the model to large variation in this plant characteristic suggests that extensive field efforts to further refine measurements are unnecessary for this application.

4.4.1 Recommendations Regarding the Biophysical Model

Biophysical modeling at Dumas Bay was a first step toward linking biophysical processes that affect the submarine light environment to eelgrass distribution. A reasonable next step for the modeling effort is to begin testing its utility as a tool for resource management. This may be particularly useful because seagrass declines have historically been of a catastrophic nature (e.g., Chesapeake Bay, Florida Bay, North Sea, Cockburn Sound Australia). Thus, it is important to recognize systems that might easily become vulnerable because it is difficult to reverse seagrass losses once they begin. While monitoring programs focus on status and trend information, the ability to predict changes in the resource is the ultimate goal.

Currently funding is not available for further modeling efforts, however modeling is a crucial tool to allow us to predict change. If funding becomes available, three management applications are recommended:

- Use the model to predict changes in eelgrass cover at a relatively healthy/pristine environment in response to degradation in water quality. For example, how much sediment loading or eutrophication could the system tolerate? Is the current condition close to the threshold for potential eelgrass loss, or is the environment relatively robust?
- Consider a second site in which there is some interest in restoring eelgrass to former habitat. Use the model to predict potential eelgrass distribution/density at that site under present water quality conditions, and determine how much improvement in water quality would be required to obtain a desired level of eelgrass vegetation. Does the model indicate the site to be a reasonable candidate for restoration?
- Consider a site for which an environmental change is anticipated, such as the coastline near the mouth of the Elwha River where two dams are scheduled for demolition. Ask the model to evaluate the impact of changes in water column sediment load brought about by dam removal on eelgrass distributions and habitat potential. By conducting such a study before the impact actually occurs, the model could help guide management activities in restoring and protecting natural resources.

4.5 Concluding Remarks

Results from the first three years of research suggest that the SVMP design meets our project objectives to monitor status and trends in *Z. marina* in Puget Sound. Some improvements are recommended to refine monitoring methods, we will begin implementing these changes during the 2003 sampling season. Additionally, a series of key research issues emerged that are beyond the scope of the current project. We identified the following priorities for future research, if funding becomes available:

- Focus on "hotspots". At individual sites that show a significant decrease or increase in bed coverage or depth distribution, initiate collaborative studies to determine the extent of the change and causes. Work with resource managers to minimize impacts and to restore the site. Consider other scales of impact through focus studies that evaluate specific habitat types, regions, or geomorphological strata that may be at risk. Conduct transboundary research to consider habitat usage and anthropogenic impacts to *Z. marina* over larger scales.
- Conduct higher resolution studies of *Z. marina* plant parameters, bed characteristics, and environmental conditions. Higher resolution studies will help us understand natural variability, identify parameters that can serve as "early warning" indicators of *Z. marina* bed decline, and link to stressors at specific sites. Collaborate with geomorphologists, oceanographers and hydrologists to characterize physical processes. Collaborate with other biologists to investigate usage of *Z. marina* beds by salmonids and other resources, such as herring, crab, birds, and invertebrates. Collaborate with other botanists and phycologists to study interactions between plants and algae. Consider functional differences related to geomorphological characteristics, such as flat and fringe strata.
- Document long-term historical changes. Recent trends in submerged vegetation abundance and distribution do not necessarily reflect historical conditions (e.g. Robbins 1997). Moreover, consideration of compressed temporal scales can lead to

misinterpretation of both resource status and management performance (e.g. Lichatowich 1997). Historical reconstruction can be accomplished through analysis of long term data sets at sites and through biophysical and geomorphological modeling.

- Develop a rigorous conceptual model of *Z. marina* distribution to focus long term monitoring efforts. Existing conceptual models do not fully address conditions in the Puget Sound region. Additionally, most existing models focus on shoot-level dynamics, rather than on dynamics at the scale of the bed or landscape. While some processes scale up from the shoot-level to the bed-level, different dynamics also come into play at the scale of *Z. marina* beds. Because the seagrass landscape is varied and responds to a combination of natural and human-induced stressors (den Hartog 1971, Robbins and Bell 1994, Short and Wyllie-Echeverria 1996, Fonseca and Bell 1998), an important challenge is to determine the connection between changes in patch configuration and the suite of human activities that limit bottom cover and depth distribution. The SVMP effort, coupled with process oriented studies and local and regional stressors, can contribute to a conceptual model that relates stressors to landscape pattern.
- Advance the development of predictive measures of *Z. marina* decline. In the context of natural resource management, a primary objective of a monitoring program is to notify those charged with management that important natural resources are in decline so that corrective actions can be taken (Elzinga et al. 2001). This objective has proven somewhat elusive in monitoring the seagrass biome. Once losses are observed; widespread decline often follows (Hemminga and Duarte 2000). It is, therefore, critically important to develop predictive measures (Duarte 1999).

While documenting trends in Puget Sound's *Z. marina* resource is important, it is only a first step toward a fully developed monitoring program. When it is most effective, monitoring also tracks specific natural and anthropogenic stressors and measures the success of management actions. Our ultimate goal is to develop such an adaptive management framework to help guide best management of the *Z. marina* resource.

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APPENDICES

Appendix A. Summary of *Z. marina* Area Estimates at 2000 SVMP sample sites

Site	Location	Approximate Latitude (decimal degrees)	Approximate Longitude (decimal degrees)	Date Sampled	Number of Transects	Eelgrass Fraction Along Transects	Eelgrass Area at Site (hectares)	Variance	Coefficient of Variation	Estimated Eelgrass Area Confidence Interval (hectares) 80% Lower Limit	80% Upper Limit
Core											
Core001	Padilla Bay	48.52086	-122.50592	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Core002	Picnic Cove	48.56229	-122.92167	14-Jul	14	0.7937	4.33	0.042	0.05	4.06	4.59
Core003	Jamestown	48.13078	-123.07213	20-Sep	9	0.5650	375.02	2,238.450	0.13	314.46	435.58
Core004	Lynch Cove	47.43036	-122.86130	17-Aug	17	0.5544	112.34	201.395	0.13	94.17	130.50
Core005	Dumas Bay	47.33286	-122.37606	18-Jul	8	0.4004	2.65	0.218	0.18	2.05	3.25
Core006	Burley Spit	47.37774	-122.63707	19-Jul	9	0.2446	4.69	0.700	0.18	3.62	5.77
Flats											
Flats18	Similk Bay	48.43667	-122.56061	26-Jul	27	0.4647	43.86	28.394	0.12	37.04	50.68
Flats20	Skagit Bay N.	48.38564	-122.57115	25-Jul	7	0.3702	195.99	1,810.347	0.22	141.52	250.45
Flats28	Snohomish Delta S.	47.98805	-122.23443	7-Jul	8	0.4841	113.89	241.069	0.14	94.01	133.76
Flats35	Nisqually Delta E.	47.11264	-122.69174	20-Jul	9	0.0670	9.12	4.195	0.22	6.50	11.74
Flats43	Dabob Bay	47.83891	-122.81747	17-Sep	12	0.5657	13.38	1.210	0.08	11.97	14.79
Flats47	Travis Spit	48.08536	-123.03089	27-Jun	20	0.3172	35.28	30.744	0.16	28.18	42.38
Flats53	Westcott Bay	48.59509	-123.15827	13-Jul	16	0.2555	18.53	8.134	0.15	14.88	22.18
Flats60	Hunter Bay	48.46520	-122.85394	10-Jul	15	0.1994	1.60	0.100	0.20	1.19	2.00
Flats62	Swifts Bay	48.55140	-122.86195	12-Jul	20	0.2128	12.50	6.045	0.20	9.35	15.65
Narrow Fringe											
cps1046	Battle Point	47.66684	-122.58744	6-Sep	14	0.0587	0.67	0.064	0.38	0.34	0.99
cps1118	Neill Point (Vashon Island)	47.34018	-122.48922	12-Sep	13	0.1780	1.80	0.158	0.22	1.29	2.30
cps1203	Fox Island	47.22021	-122.61290	8-Sep	18	0.1082	0.78	0.094	0.39	0.39	1.17
cps1245	Gertrude Island (by McNeil Island)	47.21872	-122.65472	8-Sep	N/A	N/A	0	N/A	N/A	N/A	N/A
cps1282	NE Anderson Island	47.15803	-122.73662	14-Sep	N/A	N/A	0	N/A	N/A	N/A	N/A
cps1285	NW Anderson Island	47.17988	-122.72100	14-Sep	N/A	N/A	0	N/A	N/A	N/A	N/A
cps1295	NW Ketron Island	47.16711	-122.63191	13-Sep	8	0.1517	0.18	0.004	0.33	0.10	0.26
cps1296	NE Ketron Island	47.16328	-122.62795	13-Sep	N/A	N/A	0	N/A	N/A	N/A	N/A
cps1686	Fort Lawton	47.66715	-122.42635	6-Sep	11	0.4522	7.43	0.548	0.10	6.48	8.37
cps1804	Salmon Beach (S of Pt. Defiance)	47.28700	-122.52856	12-Sep	N/A	N/A	0	N/A	N/A	N/A	N/A
cps1986	S. of Whitman Cove (Case Inlet)	47.20330	-122.80057	13-Sep	N/A	N/A	0	N/A	N/A	N/A	N/A
cps2003	Pitt Passage	47.21870	-122.71950	14-Sep	12	0.3099	2.67	0.323	0.21	1.94	3.39
cps2154	N. of Bremerton	47.57681	-122.62183	7-Sep	N/A	N/A	0	N/A	N/A	N/A	N/A
cps2157	S. of Bremerton	47.57126	-122.60386	7-Sep	N/A	N/A	0	N/A	N/A	N/A	N/A
cps2545	Olele Point	47.97090	-122.67849	15-Aug	14	0.2236	0.74	0.045	0.28	0.47	1.02
cps2584	Lower Hadlock	48.03606	-122.75153	6-Oct	13	0.3298	1.19	0.035	0.16	0.95	1.43
hdc2310	Holly	47.55856	-122.98433	19-Aug	13	0.4008	1.90	0.113	0.18	1.47	2.33
hdc2338	Across from Union	47.37391	-123.07831	18-Aug	15	0.3649	1.99	0.108	0.17	1.57	2.41
hdc2345	Sisters Point	47.37599	-123.01474	19-Aug	12	0.2074	0.77	0.035	0.24	0.53	1.00

Appendix A. Summary of *Z. marina* Area Estimates at 2000 SVMP sample sites

Site	Location	Approximate Latitude (decimal degrees)	Approximate Longitude (decimal degrees)	Date Sampled	Number of Transects	Eelgrass Fraction Along Transects	Eelgrass Area at Site (hectares)	Variance	Coefficient of Variation	Estimated Eelgrass Area Confidence Interval (hectares)	
										80% Lower Limit	80% Upper Limit
hdc2359	Lynch Cove Fringe	47.40760	-122.89194	18-Aug	7	0.7365	10.94	0.367	0.06	10.16	11.72
hdc2433	Pleasant harbor	47.67361	-122.89993	19-Sep	13	0.3363	1.64	0.055	0.14	1.34	1.94
hdc2487	Oak Head	47.68250	-122.81335	17-Aug	16	0.2457	1.44	0.077	0.19	1.09	1.80
hdc2504	Thorndyke Bay	47.79148	-122.74211	16-Aug	11	0.4797	4.87	0.425	0.13	4.04	5.71
hdc2529	S. of Tala Point	47.91407	-122.65129	16-Aug	11	0.5233	6.44	0.265	0.08	5.78	7.10
nps0059	Sinclair Island S.	48.60780	-122.67027	13-Aug	9	0.5813	0.84	0.015	0.15	0.68	1.00
nps0669	SE Guemes Island	48.55147	-122.58155	31-Aug	N/A	N/A	0	N/A	N/A	N/A	N/A
nps1363	Village Pt. (Lummi Island)	48.71571	-122.71381	31-Aug	16	0.2000	1.77	0.184	0.24	1.22	2.32
sjs0081	Broken Point (Shaw Island)	48.59528	-122.96486	12-Aug	10	0.7119	1.66	0.041	0.12	1.40	1.91
sjs0311	Clark Island	48.69796	-122.76405	30-Aug	9	0.5917	1.87	0.033	0.10	1.64	2.10
sjs0335	Sattelite Island (Stuart Island)	48.68227	-123.18447	12-Aug	10	0.2769	0.94	0.120	0.37	0.20	1.39
sjs0365	Thatcher Pass	48.53190	-122.80193	12-Aug	7	0.7494	1.85	0.050	0.12	1.57	2.14
sjs0480	SE Orcas Island	48.62186	-122.80096	13-Aug	10	0.7679	2.83	0.054	0.08	2.53	3.13
sjs0622	Jasper Cove (Lopez Island)	48.47330	-122.85337	11-Aug	3	0.1465	0.06	0.002	0.78	0.00	0.12
sjs0637	Watmough Head (Lopez Island)	48.42688	-122.80167	28-Aug	13	0.5806	3.20	0.251	0.16	2.56	3.85
sjs0695	Trump Island (near Decatur Island)	48.50396	-122.83958	11-Aug	N/A	N/A	0	N/A	N/A	N/A	N/A
sjs0736	Charles Island (S. side)	48.44040	-122.90471	28-Aug	N/A	N/A	0	N/A	N/A	N/A	N/A
sjs2646	Discovery Bay	48.06700	-122.92414	19-Sep	10	0.4432	1.52	0.036	0.13	1.28	1.76
sjs2813	Rasmusson Creek	48.33870	-124.49399	27-Sep	14	0.2872	2.97	0.133	0.12	2.50	3.43
swh1556	NW Camano Island	48.21356	-122.53895	29-Aug	12	0.7185	5.84	0.402	0.11	5.03	6.66
swh1593	Camano Island, Cornell	48.12136	-122.41851	10-Oct	10	0.1815	3.12	0.221	0.15	2.52	3.72
swh1625	So of Tulalip Bay	48.04926	-122.28672	22-Aug	9	0.0357	0.46	0.032	0.39	0.23	0.69
swh1647	Mukilteo	47.93962	-122.31035	23-Aug	12	0.5603	6.64	0.193	0.07	6.07	7.20
Wide Fringe											
sjs2695	W. Green Point	48.11803	-123.31007	28-Sep	N/A	N/A	0	N/A	N/A	N/A	N/A
sjs2741	West of Crescent Bay	48.16444	-123.71955	26-Sep	8	0.2986	12.79	9.111	0.24	8.92	16.65
sjs2766	E. of Deep Creek	48.17797	-124.00035	27-Sep	N/A	N/A	0	N/A	N/A	N/A	N/A
swh0848	Ala Spit	48.40135	-122.58722	30-Aug	8	0.7321	25.47	3.049	0.07	23.23	27.70

Sites that were visited but could not be sampled due to obstructions (i.e. rocks, kelp etc.) - nps1342, sjs0819, swh0718

Sampling at Core001 (Padilla Bay) was not completed in 2000. Therefore, no site coverage estimate is included in this summary

Appendix B. Summary of *Z. marina* Area Estimates at 2001 SVMP Sample Sites

										Estimated Eelgrass Coverage Confidence Interval (hectares)	
Site	Location	Approximate Latitude (decimal degrees)	Approximate Longitude (decimal degrees)	Date Sampled	Number of Transects	Eelgrass Fraction Along Transects	Eelgrass Area at Site (hectares)	Variance	Coefficient of Variation	80% Lower Limit	80% Upper Limit
Core											
Core001	Padilla Bay	48.52086	-122.50592	15-18,29-Aug	10	0.7723	3,193.07	14,607.725	0.04	3,038.37	3,347.78
Core002	Picnic Cove	48.56229	-122.92167	4-Aug	12	0.5965	3.18	0.106	0.10	2.76	3.60
Core003	Jamestown	48.13078	-123.07213	20-Oct	10	0.4908	443.37	2,742.921	0.12	376.34	510.41
Core004	Lynch Cove	47.43036	-122.86130	20,21-Sept	16	0.6131	187.78	279.168	0.09	166.39	209.17
Core005	Dumas Bay	47.33286	-122.37606	5-Oct	9	0.2881	2.88	0.330	0.20	2.15	3.62
Core006	Burley Spit	47.37774	-122.63707	11-Oct	15	0.2428	5.26	0.651	0.15	4.23	6.29
Flats											
Flats11	Samish Bay N.	48.55837	-122.52759	17,18-Aug	8	0.8230	1,150.34	3,326.384	0.05	1,076.51	1,224.16
Flats18	Similk Bay	48.43667	-122.56061	11-Aug	27	0.4900	40.09	17.961	0.11	34.66	45.51
Flats20	Skagit Bay N.	48.38564	-122.57115	12-Aug	17	0.2650	151.94	237.385	0.10	132.22	171.66
Flats28	Snohomish Delta S.	47.98805	-122.23443	28,29-Sep	13	0.5974	131.34	95.838	0.07	118.81	143.87
Flats35	Nisqually Delta E.	47.11264	-122.69174	13-Oct	16	0.1225	16.31	14.804	0.24	11.38	21.23
Flats43	Dabob Bay	47.83891	-122.81747	25-Sep	12	0.4536	13.77	2.431	0.11	11.78	15.77
Flats47	Travis Spit	48.08536	-123.03089	19-Oct	32	0.4872	48.57	13.869	0.08	43.80	53.34
Flats53	Westcott Bay	48.59509	-123.15827	26-Aug	21	0.2389	14.12	4.579	0.15	11.38	16.86
Flats60	Hunter Bay	48.46520	-122.85394	2-Aug	28	0.2103	2.75	0.161	0.15	2.24	3.27
Flats62	Swifts Bay	48.55140	-122.86195	3-Aug	23	0.3741	15.80	3.713	0.12	13.34	18.27
Narrow Fringe											
cps1046	Battle Point	47.66684	-122.58744	18-Oct	9	0.0485	0.16	0.005	0.44	0.07	0.25
cps1118	Neill Point (Vashon Island)	47.34018	-122.48922	9-Oct	14	0.2630	2.68	0.286	0.20	1.99	3.36
cps1203	Fox Island	47.22021	-122.61290	16-Oct	11	0.2	0.78	0.065	0.33	0.45	1.11
cps1245	Gertrude Island (by McNeil)	47.21872	-122.65472	26-Sep	N/A	N/A	0	N/A	N/A	N/A	N/A
cps1282	NE. Anderson Island	47.15803	-122.73662	15-Oct	N/A	N/A	0	N/A	N/A	N/A	N/A
cps1285	NW Anderson Island	47.17988	-122.72100	15-Oct	N/A	N/A	0	N/A	N/A	N/A	N/A
cps1295	NW Ketron Island	47.16711	-122.63191	15-Oct	14	0.2408	0.29	0.002	0.16	0.23	0.35
cps1296	NE Ketron Island	47.16328	-122.62795	15-Oct	N/A	N/A	0	N/A	N/A	N/A	N/A
cps1686	Fort Lawton	47.66715	-122.42635	2-Oct	9	0.6003	8.25	0.300	0.07	7.55	8.95
cps1804	Salmon Beach (S of Pt. Defiance)	47.28700	-122.52856	5-Oct	N/A	N/A	0	N/A	N/A	N/A	N/A
cps1986	S. of Whitman Cove (Case Inlet)	47.20330	-122.80057	15-Oct	N/A	N/A	0	N/A	N/A	N/A	N/A
cps2003	Pitt Passage	47.21870	-122.71950	10,15-Oct	9	0.2233	2.82	1.858	0.48	1.08	4.57
cps2154	N. Bremerton	47.57681	-122.62183	4-Oct	N/A	N/A	0	N/A	N/A	N/A	N/A
cps2157	S. Bremerton	47.57126	-122.60386	4-Oct	N/A	N/A	0	N/A	N/A	N/A	N/A
cps2545	Olele Point	47.97090	-122.67849	26-Sep	11	0.2156	0.67	0.026	0.24	0.46	0.88
cps2584	Lower Hadlock	48.03606	-122.75153	7-Sep	17	0.4199	1.66	0.063	0.15	1.34	1.98
hdc2310	Holly	47.55856	-122.98433	24-Sep	14	0.4010	2.37	0.234	0.20	1.76	2.99
hdc2338	Across from Union	47.37391	-123.07831	19-Sep	15	0.2850	1.94	0.103	0.17	1.53	2.35

Appendix B. Summary of *Z. marina* Area Estimates at 2001 SVMP Sample Sites

Site	Location	Approximate Latitude (decimal degrees)	Approximate Longitude (decimal degrees)	Date Sampled	Number of Transects	Eelgrass Fraction Along Transects	Eelgrass Area at Site (hectares)	Variance	Coefficient of Variation	Estimated Eelgrass Coverage Confidence Interval (hectares)	
										80% Lower Limit	80% Upper Limit
hdc2345	Sisters Point	47.37599	-123.01474	20-Sep	19	0.1616	0.65	0.024	0.24	0.45	8.45
hdc2359	Lynch Cove Fringe	47.40760	-122.89194	20-Sep	10	0.6769	12.20	0.223	0.04	11.59	12.80
hdc2433	Pleasant Harbor	47.67361	-122.89993	24-Sep	13	0.3512	2.09	0.096	0.15	1.69	2.49
hdc2487	Oak Head	47.68250	-122.81335	19-Sep	13	0.3375	1.74	0.068	0.15	1.41	2.08
hdc2504	Thorndyke Bay	47.79148	-122.74211	18-Sep	10	0.4195	5.00	0.301	0.11	4.29	5.70
hdc2529	S. of Tala Point	47.91407	-122.65129	16-Aug	11	0.5168	7.74	0.326	0.07	7.01	8.48
nps0059	Sinclair Island S.	48.60780	-122.67027	10-Aug	17	0.3920	0.73	0.006	0.11	0.63	0.83
nps0669	Guemes Island	48.55147	-122.58155	10-Aug	N/A	N/A	0	N/A	N/A	N/A	N/A
nps1363	Village Pt. (Lummi Island)	48.71571	-122.71381	28-Aug	15	0.1633	1.35	0.120	0.26	0.91	1.80
sjs0081	Broken Point (Shaw Island)	48.59528	-122.96486	4-Aug	12	0.6788	1.69	0.026	0.09	1.48	1.89
sjs0311	Clark Island	48.69796	-122.76405	28-Aug	12	0.4805	1.90	0.012	0.06	1.77	2.04
sjs0335	Sattelite Island (Stuart Island)	48.68227	-123.18447	25-Aug	16	0.2536	0.74	0.024	0.21	0.54	0.94
sjs0365	Thatcher Pass	48.53190	-122.80193	31-Jul	17	0.5950	1.75	0.016	0.07	1.59	1.91
sjs0480	SE Orcas Island	48.62186	-122.80096	25-Aug	12	0.5851	2.64	0.070	0.10	2.30	2.98
sjs0622	Jasper Cove (Lopez Island)	48.47330	-122.85337	2-Aug	6	0.2248	0.12	0.002	0.35	0.07	0.18
sjs0637	Watmough Head (Lopez Island)	48.42688	-122.80167	1-Aug	14	0.5870	3.62	0.200	0.12	3.05	4.19
sjs0695	Trump Island (near Decatur Island)	48.50396	-122.83958	31-Jul	N/A	N/A	0	N/A	N/A	N/A	N/A
sjs0736	Charles Island, south side	48.44040	-122.90471	1-Aug	N/A	N/A	0	N/A	N/A	N/A	N/A
sjs0819	N of Partridge Point	48.24140	-122.76352	27-Dec	5	0.0529	0.45	0.025	0.35	0.25	0.65
sjs2646	Discovery Bay	48.06700	-122.92414	28-Jul	12	0.5958	2.15	0.119	0.16	1.70	2.59
sjs2813	Rasmusson Creek	48.33870	-124.49399	14-Sep	13	0.3270	3.79	0.209	0.12	3.21	4.38
swh0718	Swinomish Channel	48.42820	-122.49960	30-Aug	11	0.0414	0.06	0.000	0.40	0.03	0.08
swh1556	NW Camano Island	48.21356	-122.53895	1-Sep	9	0.5652	5.94	0.921	0.16	4.71	7.17
swh1593	Camano Island, Cornell	48.12136	-122.41851	5-Sep	14	0.3211	4.37	0.166	0.09	3.85	4.90
swh1625	So of Tulalip Bay	48.04926	-122.28672	29-Sep	14	0.0472	0.47	0.017	0.27	0.31	0.64
swh1647	Mukilteo	47.93962	-122.31035	28-Sep	10	0.6236	7.33	0.177	0.06	6.79	7.87
<u>Wide Fringe</u>											
cps2215	Eglon, Kitsap	47.85787	-122.50452	27-Sep	10	0.5195	10.95	0.401	0.06	10.14	11.76
hdc2240	N of Port Gamble	47.88140	-122.58029	26-Sep	10	0.4754	13.32	1.104	0.08	11.98	14.67
sjs0005	Cypress Island, S.	48.53615	-122.71677	24-Aug	N/A	N/A	0	N/A	N/A	N/A	N/A
sjs0351	NW Waldron Island	48.70554	-123.05815	27-Aug	10	0.8720	26.04	0.081	0.01	25.68	26.40
sjs2678	Dungeness Spit Lighthouse Res.	48.18048	-123.12492	11-Sep	10	0.3666	14.98	4.332	0.14	12.31	17.64
sjs2695	W. Green Point	48.11803	-123.31007	11-Sep	N/A	N/A	0	N/A	N/A	N/A	N/A
sjs2741	West of Crescent Bay	48.16444	-123.71955	12-Sep	12	0.0049	19.47	13.049	0.19	3.61	24.09
sjs2766	E of Deep Creek	48.17797	-124.00035	13-Sep	N/A	N/A	0	N/A	N/A	N/A	N/A
sjs2769	Deep Creek	48.18209	-124.03243	13-Sep	7	0.1683	0.84	0.046	0.26	0.56	1.11
swh0848	Ala Spit	48.40135	-122.58722	30-Aug	15	0.6033	25.07	8.463	0.12	21.35	28.79
swh0943	Hackney Island (Whidbey Island)	48.10306	-122.53057	4-Sep	10	0.8155	17.88	0.662	0.05	16.84	18.92
swh1575	Camp Dianna, Camano Island	48.10025	-122.42591	4-Sep	10	0.4826	15.89	0.497	0.04	14.98	16.79

Sites that were visited but could not be sampled due to obstructions (i.e. rocks, kelp etc.) - nps1342, sjs2764, sjs2815

Appendix C. Summary of *Z. marina* Area Estimates at 2002 SVMP Sample Sites

Site	Location	Approximate Latitude (decimal degrees)	Approximate Longitude (decimal degrees)	Date Sampled	Number of Transects	Eelgrass Fraction Along Transects	Eelgrass Area at Site (hectares)	Variance	Coefficient of Variation	Estimated Eelgrass Coverage Confidence Interval (hectares) 80% Lower Limit	80% Upper Limit
Core											
Core001	Padilla Bay	48.52086	-122.50592	22,23-Jul	11	0.7956	3,452.83	21,415.206	0.04	3,265.51	3,640.14
Core002	Picnic Cove	48.56229	-122.92167	8-Jul	14	0.6274	2.94	0.015	0.04	2.79	3.10
Core003	Jamestown	48.13078	-123.07213	17-Sep	10	0.6196	476.81	1,122.600	0.07	433.93	519.70
Core004	Lynch Cove	47.43036	-122.86130	14-Aug	12	0.7119	165.44	170.625	0.08	148.72	182.16
Core005	Dumas Bay	47.33286	-122.37606	6-Sep	11	0.2651	1.00	0.065	0.26	0.67	1.32
Core006	Burley Spit	47.37774	-122.63707	5-Sep	11	0.5564	7.06	1.317	0.16	5.59	8.53
Flats											
Flats10	Nooksack Delta E.	48.76776	-122.55054	2-Jul	N/A	N/A	0	N/A	N/A	N/A	N/A
Flats11	Samish Bay N.	48.55837	-122.52759	24-Jul	9	0.8655	1,267.02	2,546.297	0.04	1,202.43	1,331.61
Flats18	Similk Bay	48.43667	-122.56061	17-Jul	21	0.5234	42.29	10.115	0.08	38.22	46.36
Flats20	Skagit Bay N.	48.38564	-122.57115	18-Jul	17	0.3360	227.94	836.046	0.13	190.93	264.96
Flats28	Snohomish Delta S.	47.98805	-122.23443	28,29-Sep	11	0.6688	100.23	116.956	0.11	86.39	114.08
Flats35	Nisqually Delta E.	47.11264	-122.69174	4-Sep	10	0.3583	15.72	6.926	0.17	12.35	19.08
Flats37	Wing Point	47.61775	-122.48772	27-Aug	11	0.3674	14.76	11.273	0.23	10.46	19.06
Flats43	Dabob Bay	47.83891	-122.81747	16-Aug	13	0.6797	14.21	2.471	0.11	12.20	16.22
Flats60	Hunter Bay	48.46520	-122.85394	3-Jul	15	0.2610	2.28	0.058	0.11	1.98	2.59
Flats62	Swifts Bay	48.55140	-122.86195	4-Jul	22	0.5308	11.68	2.291	0.13	9.74	13.61
Narrow Fringe											
cps0221	SE Harstene Island	47.18247	-122.84974	4-Sep	N/A	N/A	0	N/A	N/A	N/A	N/A
cps1046	Battle Point	47.66684	-122.58744	28-Aug	16	0.2706	0.09	0.001	0.35	0.05	0.13
cps1118	Neill Point (Vashon Island)	47.34018	-122.48922	29-Aug	15	0.4544	2.30	0.078	0.12	1.95	2.66
cps1128	Paradise Cove (Vashon Island)	47.38423	-122.52060	7-Sep	11	0.5615	2.59	0.022	0.06	2.40	2.77
cps1156	Klahanic Beach (Vashon Island)	47.43463	-122.43504	30-Aug	12	0.7025	6.02	0.214	0.08	5.43	6.61
cps1164	N. of Pt. Robinson (Maury Island)	47.39574	-122.38260	30-Aug	11	0.6799	5.57	0.119	0.06	5.13	6.01
cps1245	Gertrude Island (by McNeil)	47.21872	-122.65472	31-Aug	N/A	N/A	0	N/A	N/A	N/A	N/A
cps1282	NE. Anderson Island	47.15803	-122.73662	3-Sep	N/A	N/A	0	N/A	N/A	N/A	N/A
cps1295	NW Ketron Island	47.16711	-122.63191	31-Aug	15	0.5659	0.28	0.001	0.11	0.24	0.32
cps1296	NE Ketron Island	47.16328	-122.62795	31-Aug	N/A	N/A	0	N/A	N/A	N/A	N/A
cps1686	Fort Lawton	47.66715	-122.42635	28-Aug	10	0.6814	7.15	0.231	0.07	6.54	7.77
cps1804	Salmon Beach (S of Pt. Defiance)	47.28700	-122.52856	30-Aug	N/A	N/A	0.00	N/A	N/A	N/A	N/A
cps2003	Pitt Passage	47.21870	-122.71950	3-Sep	11	0.5524	1.79	0.083	0.16	1.43	2.16
cps2154	N. Bremerton	47.57681	-122.62183	29-Aug	N/A	N/A	0	N/A	N/A	N/A	N/A
cps2157	S. Bremerton	47.57126	-122.60386	29-Aug	N/A	N/A	0	N/A	N/A	N/A	N/A
cps2545	Olele Point	47.97090	-122.67849	26-Aug	13	0.5063	0.41	0.006	0.19	0.31	0.51
cps2573	Ft. Flagler	48.09745	-122.72160	21-Jun	11	0.3569	3.49	0.515	0.21	2.57	4.41
cps2584	Lower Hadlock	48.03606	-122.75153	21-Jun	11	0.4256	1.22	0.010	0.08	1.09	1.35

Appendix C. Summary of *Z. marina* Area Estimates at 2002 SVMP Sample Sites

Site	Location	Approximate Latitude (decimal degrees)	Approximate Longitude (decimal degrees)	Date Sampled	Number of Transects	Eelgrass Fraction Along Transects	Eelgrass Area at Site (hectares)	Variance	Coefficient of Variation	Estimated Eelgrass Coverage Confidence Interval (hectares)	
										80% Lower Limit	80% Upper Limit
hdc2310	Holly	47.55856	-122.98433	13-Aug	15	0.6105	2.49	0.026	0.07	2.29	2.70
hdc2338	Across from Union	47.37391	-123.07831	13-Aug	16	0.6124	1.52	0.009	0.06	1.40	1.64
hdc2359	Lynch Cove Fringe	47.40760	-122.89194	14-Aug	11	0.7857	10.68	0.192	0.04	10.12	11.24
hdc2433	Pleasant Harbor	47.67361	-122.89993	16-Aug	13	0.7892	1.93	0.003	0.03	1.86	1.99
hdc2529	S. of Tala Point	47.91407	-122.65129	12-Aug	12	0.5182	5.48	0.258	0.09	4.83	6.13
nps0059	Sinclair Island	48.60780	-122.67027	12-Jul	8	0.5654	0.55	0.005	0.13	0.46	0.65
nps0522	Eliza Island NE	48.65539	-122.57840	5-Aug	10	0.7148	3.72	0.064	0.07	3.39	4.04
nps0669	Guemes Island	48.55147	-122.58155	12-Jul	N/A	N/A	0	N/A	N/A	N/A	N/A
nps1363	Village Pt. (Lummi Island)	48.71571	-122.71381	11-Jul	11	0.4439	1.01	0.015	0.12	0.85	1.16
sjs0081	Broken Point (Shaw Island)	48.59528	-122.96486	9-Jul	11	0.8013	1.90	0.009	0.05	1.78	2.02
sjs0311	Clark Island	48.69796	-122.76405	11-Jul	11	0.6787	1.84	0.013	0.06	1.69	1.99
sjs0365	Thatcher Pass	48.53190	-122.80193	5-Jul	11	0.8374	1.83	0.005	0.04	1.75	1.92
sjs0617	Lopez Sound Road	48.50891	-122.86472	1-Jul	11	0.1783	1.42	0.110	0.23	1.00	1.85
sjs0637	Watmough Head (Lopez Island)	48.42688	-122.80167	2-Jul	11	0.6624	2.96	0.217	0.16	2.36	3.55
sjs0649	Canoe Island (Shaw Island)	48.55695	-122.92123	8-Jul	3	0.2957	0.02	0.000	0.40	0.01	0.03
sjs0695	Trump Island (near Decatur Island)	48.50396	-122.83958	1-Jul	N/A	N/A	0	N/A	N/A	N/A	N/A
sjs0736	Charles Island, south side	48.44040	-122.90471	2-Jul	N/A	N/A	0	N/A	N/A	N/A	N/A
sjs0819	N of Partridge Point	48.24140	-122.76352	12-Sep	8	0.3074	0.62	0.006	0.13	0.52	0.72
sjs2646	Discovery Bay	48.06700	-122.92414	13-Sep	11	0.7280	1.35	0.005	0.05	1.26	1.44
sjs2813	Rasmusson Creek	48.33870	-124.49399	10-Sep	11	0.5054	2.87	0.059	0.08	2.56	3.18
swh0718	Swinomish Channel	48.42820	-122.49960	16-Jul	9	0.1421	0.04	0.000	0.50	0.02	0.07
swh1556	NW Camano Island	48.21356	-122.53895	29-Jul	11	0.7584	5.70	0.095	0.05	5.31	6.10
swh1593	Camano Island, Cornell	48.12136	-122.41851	6-Aug	10	0.4378	4.09	0.226	0.12	3.48	4.69
swh1625	So of Tulalip Bay	48.04926	-122.28672	7-Aug	14	0.1305	0.22	0.006	0.35	0.12	0.32
swh1647	Mukilteo	47.93962	-122.31035	8-Aug	11	0.6247	6.07	0.133	0.06	5.60	6.53
Wide Fringe											
cps2215	Eglon, Kitsap	47.85787	-122.50452	26-Aug	11	0.4332	8.70	0.625	0.09	7.69	9.71
cps2218	Pilot Pt.	47.88290	-122.51054	17-Aug	10	0.1713	3.88	0.312	0.14	3.17	4.60
cps2221	Point no Point	47.90831	-122.52171	17-Aug	10	0.3520	9.52	0.432	0.07	8.67	10.36
hdc2239	Hood Canal NE	47.88957	-122.58418	12-Aug	11	0.5222	10.68	0.495	0.07	9.78	11.58
nps0654	Yellow Reef (Guemes Island)	48.53537	-122.65604	12-Jul	10	0.8014	8.25	0.155	0.05	7.74	8.75
sjs0005	Cypress Island S.	48.53615	-122.71677	15-Jul	N/A	N/A	0	N/A	N/A	N/A	N/A
sjs0351	NW Waldron Island	48.70554	-123.05815	9-Jul	11	0.9011	25.45	0.215	0.02	24.86	26.04
sjs2678	Dungeness Spit Lighthouse Res.	48.18048	-123.12492	11-Sep	11	0.6024	13.84	0.909	0.07	12.62	15.06
sjs2695	W. Green Point	48.11803	-123.31007	11-Sep	N/A	N/A	0	N/A	N/A	N/A	N/A
sjs2741	West of Crescent Bay	48.16444	-123.71955	9-Sep	11	0.3551	10.72	10.170	0.30	6.64	14.80
sjs2766	E of Deep Creek	48.17797	-124.00035	10-Sep	N/A	N/A	0	N/A	N/A	N/A	N/A
swh0848	Ala Spit	48.40135	-122.58722	16-Jul	11	0.7554	24.96	2.010	0.06	23.15	26.78
swh0943	Hackney Island (Whidbey)	48.10306	-122.53057	31-Jul	11	0.8991	17.80	0.380	0.03	17.01	18.59
swh1575	Camp Dianna, Camano Island	48.10025	-122.42591	30-Jul	11	0.7363	15.60	1.425	0.08	14.07	17.13

Sites that were visited but could not be sampled due to obstructions (i.e. rocks, kelp etc.) - nps1342, sjs2692, sjs2815

Appendix D. Year to Year Change in *Z. marina* Area at Sites, 2000-2002

		2000 to 2001			2001 to 2002			
Site code	**Location**	**Relative % change at 80% CI**	**Relative % change at 95% CI**	**Overall Assessment of Change***	**Relative % change at 80% CI**	**Relative % change at 95% CI**	**Overall Assessment of Change***	**Comments**
Core001	Padilla Bay	N/A	N/A	N/A	8.1 ± 7.9	8.1 ± 12.0	no	Entire site not sampled in 2000
Core002	Picnic Cove	-26.6 ± 10.6	-26.6 ± 16.2	yes	-7.4 ± 13.1	-7.4 ± 20.0	no	
Core003	Jamestown	18.2 ± 26.2	18.2 ± 40.1	no	-7.5 ± 19.0	-7.5 ± 29.0	no	
Core004	Lynch Cove	67.2 ± 33.1	67.2 ± 50.6	yes	-11.9 ± 13.4	-11.9 ± 20.5	no	
Core005	Dumas Bay	43.2 ± 64.9	43.2 ± 99.3	no	-65.4 ± 14.4	-65.4 ± 22.0	yes	
Core006	Burley Spit	12.0 ± 33.8	12.0 ± 51.7	no	34.3 ± 38.5	34.3 ± 58.8	no	
cps0221	SE Harstene Island	N/A	N/A	N/A	N/A	N/A	N/A	Sampled in 2003 only
cps1046	Battle Point	-76.0 ± 17.8	-76.0 ± 27.3	yes	-43.2 ± 40.8	-43.2 ± 62.4	no	
cps1118	Neill Point (Vashon Island)	48.9 ± 56.9	48.9 ± 87.0	no	-13.9 ± 25.8	-13.9 ± 39.4	no	
cps1128	Paradise Cove (Vashon Island)	N/A	N/A	N/A	N/A	N/A	N/A	Sampled in 2003 only
cps1156	Klahanic Beach (Vashon Island)	N/A	N/A	N/A	N/A	N/A	N/A	Sampled in 2003 only
cps1164	N. of Pt. Robinson (Maury Island)	N/A	N/A	N/A	N/A	N/A	N/A	Sampled in 2003 only
cps1203	Fox Island	1.0 ± 65.7	1.0 ± 100.4	no	N/A	N/A	N/A	Sampled in 2000 and 2001 only
cps1245	Gertrude Island (by McNeil Island)	0	0	no	0	0	no	No *Z. marina* in 2000, 2001 or 2002
cps1282	NE. Anderson Island	0	0	no	0	0	no	No *Z. marina* in 2000, 2001 or 2002
cps1285	NW Anderson Island	0	0	no	N/A	N/A	N/A	No *Z. marina* in 2000 and 2001, not sampled in 2002
cps1295	NW Ketron Island	61.7 ± 76.6	61.7 ± 117.1	no	-2.3 ± 24.6	-2.3 ± 37.7	no	
cps1296	NE Ketron Island	0	0	no	0	0	no	No *Z. marina* in 2000, 2001 or 2002
cps1686	Fort Lawton	11.1 ± 17.1	11.1 ± 26.1	no	-13.3 ± 10.5	-13.3 ± 16.1	no	
cps1804	Salmon Beach (S of Pt. Defiance)	0	0	no	0	0	no	No *Z. marina* in 2000, 2001 or 2002
cps1986	S. of Whitman Cove (Case Inlet)	0	0	no	N/A	N/A	N/A	No *Z. marina* in 2000 and 2001, not sampled in 2002
cps2003	Pitt Passage	5.9 ± 71.7	5.9 ± 109.6	no	-36.4 ± 41.5	-36.4 ± 63.4	no	
cps2154	N. Bremerton	0	0	no	0	0	no	No *Z. marina* in 2000, 2001 or 2002
cps2157	S. Bremerton	0	0	no	0	0	no	No *Z. marina* in 2000, 2001 or 2002
cps2215	Eglon, Kitsap	N/A	N/A	N/A	-20.6 ± 11.0	-20.6 ± 16.8	yes	Sampled in 2001 and 2002 only
cps2218	Pilot Pt.	N/A	N/A	N/A	N/A	N/A	N/A	Sampled in 2003 only
cps2221	Point no Point	N/A	N/A	N/A	N/A	N/A	N/A	Sampled in 2003 only
cps2545	Olele Point	-10.4 ± 43.0	-10.4 ± 65.7	no	-38.5 ± 24.2	-38.5 ± 36.9	no	
cps2573	Ft. Flagler	N/A	N/A	N/A	N/A	N/A	N/A	Sampled in 2003 only
cps2584	Lower Hadlock	39.8 ± 39.2	-39.8 ± 59.9	no	-26.5 ± 16.2	-26.5 ± 24.8	no	
Flats11	Samish Bay N.	N/A	N/A	N/A	10.1 ± 9.0	10.1 ± 13.8	no	Sampled in 2001 and 2002 only
Flats18	Similk Bay	-8.6 ± 18.9	-8.6 ± 28.9	no	5.5 ± 17.6	5.5 ± 26.8	no	
Flats20	Skagit Bay N.	-22.5 ± 23.8	-22.5 ± 36.4	no	50.0 ± 31.2	50.0 ± 47.8	yes	
Flats28	Snohomish Delta S.	15.3 ± 23.0	15.3 ± 35.1	no	-23.7 ± 12.8	-23.7 ± 19.6	yes	
Flats35	Nisqually Delta E.	78.9 ± 74.7	78.9 ± 114.2	no	-3.6 ± 35.7	-3.6 ± 54.6	no	
Flats37	Wing Point	N/A	N/A	N/A	N/A	N/A	N/A	Sampled in 2003 only
Flats43	Dabob Bay	2.9 ± 18.5	2.9 ± 28.2	no	3.2 ± 20.9	3.2 ± 32.0	no	
Flats47	Travis Spit	37.7 ± 30.9	37.7 ± 47.2	yes	N/A	N/A	N/A	Sampled in 2000 and 2001 only
Flats53	Westcott Bay	-23.8 ± 21.1	-23.8 ± 32.3	yes	N/A	N/A	N/A	Sampled in 2000 and 2001 only
Flats60	Hunter Bay	72.2 ± 54.2	72.2 ± 82.9	yes	-17.1 ± 19.1	-17.1 ± 29.2	no	
Flats62	Swifts Bay	26.4 ± 37.5	26.4 ± 57.4	no	-26.1 ± 16.9	-26.1 ± 25.8	no	
hdc2239	Hood Canal NE	N/A	N/A	N/A	N/A	N/A	N/A	Sampled in 2003 only
hdc2240	N of Port Gamble	N/A	N/A	N/A	N/A	N/A	N/A	Sampled in 2001 only
hdc2310	Holly	25.0 ± 43.2	25.0 ± 66.0	no	5.0 ± 28.8	5.0 ± 44.0	no	

Appendix D. Year to Year Change in *Z. marina* Area at Sites, 2000-2002

		2000 to 2001			2001 to 2002			
Site code	Location	Relative % change at 80% CI	Relative % change at 95% CI	Overall Assessment of Change*	Relative % change at 80% CI	Relative % change at 95% CI	Overall Assessment of Change*	Comments
hdc2338	Across from Union	-2.9 ± 29.2	-2.9 ± 44.6	no	-21.4 ± 17.9	-21.4 ± 27.3	no	
hdc2345	Sisters Point	-15.2 ± 36.8	-15.2 ± 56.3	no	N/A	N/A	N/A	Sampled in 2000 and 2001 only
hdc2359	Lynch Cove Fringe	11.5 ± 9.7	11.5 ± 14.8	no	-12.4 ± 6.3	-12.4 ± 9.7	yes	
hdc2433	Pleasant Harbor	27.3 ± 33.7	27.3 ± 51.5	no	-7.8 ± 17.9	-7.8 ± 27.4	no	
hdc2487	Oak Head	21.0 ± 37.8	21.0 ± 57.7	no	N/A	N/A	N/A	Sampled in 2000 and 2001 only
hdc2504	Thorndyke Bay	2.5 ± 22.8	2.5 ± 34.8	no	N/A	N/A	N/A	Sampled in 2000 and 2001 only
hdc2529	S. of Tala Point	20.3 ± 16.8	20.3 ± 25.7	no	-29.3 ± 10.7	-29.3 ± 16.4	yes	
sjs0005	Cypress Island, S.	N/A	N/A	N/A	0	0	no	No *Z. marina* in 2001 and 2002, not sampled in 2000
nps0059	Sinclair Island	-13.3 ± 20.2	-13.3 ± 30.9	no	-23.8 ± 16.5	-23.8 ± 25.2	no	
nps0522	Eliza Island NE	N/A	N/A	N/A	N/A	N/A	N/A	Sampled in 2003 only
nps0654	Yellow Reef (Guemes Island)	N/A	N/A	N/A	N/A	N/A	N/A	Sampled in 2003 only
nps0669	Guemes Island	0	0	no	0	0	no	No *Z. marina* in 2000, 2001 or 2002
nps1363	Village Pt. (Lummi Island)	-23.6 ± 34.5	-23.6 ± 52.8	no	-25.7 ± 27.0	-25.7 ± 41.3	no	
sjs0081	Broken Point (Shaw Island)	1.8 ± 20.1	1.8 ± 30.8	no	12.5 ± 15.5	12.5 ± 23.6	no	
sjs0311	Clark Island	2.0 ± 14.7	2.0 ± 22.5	no	-3.3 ± 10.5	-3.3 ± 16.1	no	
sjs0335	Sattelite Island (Stuart Island)	-21.6 ± 42.5	-21.6 ± 65.0	no	N/A	N/A	N/A	Sampled in 2000 and 2001 only
sjs0351	NW Waldron Island	N/A	N/A	N/A	-2.3 ± 2.7	-2.3 ± 4.1	no	Sampled in 2001 and 2002 only
sjs0365	Thatcher Pass	-5.7 ± 17.0	-5.7 ± 26.0	no	5.0 ± 11.0	5.0 ± 16.7	no	
sjs0480	SE Orcas Island	-6.8 ± 15.5	-6.8 ± 23.7	no	N/A	N/A	N/A	Sampled in 2000 and 2001 only
sjs0617	Lopez Sound Road	N/A	N/A	N/A	N/A	N/A	N/A	Sampled in 2003 only
sjs0622	Jasper Cove (Lopez Island)	96.8 ± 216.4	96.8 ± 330.9	no	N/A	N/A	N/A	Sampled in 2000 and 2001 only
sjs0637	Watmough Head (Lopez Island)	12.98 ± 28.9	12.98 ± 44.1	no	-18.2 ± 21.0	-18.2 ± 32.1	no	
sjs0649	Canoe Island (Shaw Island)	N/A	N/A	N/A	N/A	N/A	N/A	Sampled in 2003 only
sjs0695	Trump Island (near Decatur Island)	0	0	no	0	0	no	No *Z. marina* in 2000, 2001 or 2002
sjs0736	Charles Island, south side	0	0	no	0	0	no	No *Z. marina* in 2000, 2001 or 2002
sjs0819	N of Partridge Point	N/A	N/A	N/A	37.3 ± 65.2	37.3 ± 99.7	no	Site was unsamplable in 2000 (kelp)
sjs2646	Discovery Bay	41.3 ± 36.9	41.3 ± 56.4	no	-37.2 ± 13.6	-37.2 ± 20.8	yes	
sjs2678	Dungeness Spit Lighthouse Res.	N/A	N/A	N/A	-7.6 ± 18.4	-7.6 ± 28.8	no	Sampled in 2000 and 2001 only
sjs2695	W. Green Point	no	no	no	no	no	no	No *Z. marina* in 2000, 2001 or 2002
sjs2741	West of Crescent Bay	52.3 ± 58.6	52.3 ± 58.6	no	-44.9 ± 24.8	-44.9 ± 37.8	no	
sjs2766	E of Deep Creek	0	0	no	0	0	no	No *Z. marina* in 2000, 2001 or 2002
sjs2769	Deep Creek	N/A	N/A	N/A	N/A	N/A	N/A	Sampled in 2001 only
sjs2813	Rasmusson Creek	27.9 ± 28.2	27.9 ± 43.2	no	-24.3 ± 14.3	-24.3 ± 21.9	yes	
swh0718	Swinomish Channel	N/A	N/A	N/A	-24.9 ± 61.9	-24.9 ± 94.6	no	Trace in 2000, more *Z. marina* in 2001 and 2002
swh0848	Ala Spit	-1.6 ± 17.0	-1.6 ± 26.0	no	-0.4 ± 16.5	-0.4 ± 25.2	no	
swh0943	Hackney Island (Whidbey)	N/A	N/A	N/A	-0.4 ± 7.3	-0.4 ± 11.2	no	Sampled in 2001 and 2002 only
swh1556	NW Camano Island	1.6 ± 25.4	1.6 ± 38.8	no	-3.9 ± 21.0	-3.9 ± 32.1	no	
swh1575	Camp Dianna, Camano Island	N/A	N/A	N/A	-1.8 ± 5.6	-1.8 ± 8.6	no	Sampled in 2001 and 2002 only
swh1593	Camano Island, Cornell	40.2 ± 31.9	40.2 ± 48.7	yes	-6.6 ± 17.9	-6.6 ± 27.3	no	
swh1625	So of Tulalip Bay	2.3 ± 62.2	2.3 ± 95.1	no	-53.3 ± 26.9	-53.3 ± 41.1	no	
swh1647	Mukilteo	10.4 ± 12.4	10.4 ± 19.0	no	-17.2 ± 8.8	-17.2 ± 13.5	yes	

▨ = Statistically significant difference from previous year

* Overall assessment reflects statistical test results and evaulation of whether sampling effects (ie. Polygon size/shape, random transect placement, species discrimination) could have produced apparent change.

Appendix E. Summary of *Z. marina* Depth Estimates at 2000 SVMP Sample Sites (Garmin depth sounder).

		Minimum Eelgrass Depth						Maximum Eelgrass Depth					
Site	Location	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)
Core													
Core002	Picnic Cove	8	0.7	0.1	0.9	-0.5	0.7	37	-7.9	-6.5	0.5	-6.8	-6.2
Core003	Jamestown	11	0.4	-0.5	0.6	-0.8	-0.1	13	-3.7	-3.1	0.5	-3.4	-2.8
Core004	Lynch Cove	8	0.9	0.5	0.6	0.1	0.9	6	-1.4	-3.4	2.2	-5.1	-1.6
Core005	Dumas Bay	13	0.3	-0.5	0.4	-0.7	-0.2	13	-2.7	-2.3	0.2	-2.2	-2.4
Core006	Burley Spit												
Flats													
Flats18	Similk Bay	26	1.3	0.2	0.3	0.0	0.4	26	-4.0	-1.8	0.5	-2.1	-1.5
Flats20	Skagit Bay N.	7	0.0	-0.4	0.4	-0.7	-0.1	7	-4.2	-3.2	0.9	-3.9	-2.6
Flats28	Snohomish Delta S.	4	0.2	-0.1	0.4	-0.4	0.3	4	-3.4	-2.5	0.9	-3.4	-1.6
Flats35	Nisqually Delta E.	7	0.9	0.1	0.9	-0.6	0.7	7	-2.2	-1.3	0.5	-1.7	-0.9
Flats43	Dabob Bay	9	-0.1	-0.4	0.2	-0.5	-0.2	33	-6.5	-3.2	0.6	-3.5	-2.8
Flats47	Travis Spit	14	0.2	-0.3	0.6	-0.7	0.1	16	-5.8	-3.7	1.0	-4.4	-2.9
Flats53	Westcott Bay	15	0.1	-0.1	0.4	-0.4	0.2	15	-7.9	-4.1	2.4	-5.7	-2.5
Flats60	Hunter Bay	14	-0.3	-1.4	0.7	-1.9	-0.9	14	-4.5	-3.1	0.9	-3.7	-2.5
Flats62	Swifts Bay	10	0.2	-0.9	1.1	-1.9	-0.1	20	-6.7	-4.1	1.1	-4.8	-3.3
Narrow Fringe													
cps1046	Battle Point	7	-0.5	-0.9	0.4	-1.2	-0.7	7	-2.0	-1.7	0.4	-2.0	-1.3
cps1118	Neill Point (Vashon Island)	11	0.5	0.2	0.3	0.0	0.3	12	-2.8	-1.8	0.6	-2.2	-1.4
cps1203	Fox Island	8	-0.7	-0.9	0.3	-1.1	-0.7	7	-3.8	-2.4	1.4	-3.4	-1.3
cps1295	NW Ketron Island	14	0.2	-0.2	0.3	-0.3	0.0	14	-1.9	-1.2	0.3	-1.4	-0.9
cps1686	Fort Lawton	8	0.1	-0.2	0.2	-0.3	0.0	10	-5.9	-4.7	0.9	-5.2	-4.1
cps2003	Pitt Passage	9	0.5	0.0	0.5	-0.3	0.4	11	-2.4	-1.3	0.7	-1.8	-0.9
cps2545	Olele Point	8	0.1	-0.9	1.2	-1.7	0.0	9	-3.9	-3.1	1.1	-3.9	-2.3
cps2584	Lower Hadlock	12	1.1	0.0	0.5	-0.3	0.3	14	-3.6	-2.3	0.8	-2.8	-1.8
hdc2310	Holly	10	0.0	-1.1	0.7	-1.6	-0.7	10	-5.6	-4.3	0.8	-4.8	-3.8
hdc2338	Across from Union	12	0.0	-0.5	0.3	-0.7	-0.3	11	-4.1	-2.9	0.8	-3.4	-2.3
hdc2345	Sisters Point	8	-1.0	-1.4	0.5	-1.8	-1.0	8	-3.9	-3.0	0.6	-3.5	-2.6
hdc2359	Lynch Cove Fringe	6	0.1	-0.6	0.6	-1.1	-0.1	8	-4.8	-4.1	0.6	-4.6	-3.6
hdc2433	Pleasant Harbor	12	-0.5	-1.2	0.9	-1.8	-0.6	12	-4.9	-3.8	0.9	-4.4	-3.3
hdc2487	Oak Head	12	-0.3	-0.8	0.5	-1.2	-0.5	11	-5.6	-3.7	1.0	-4.4	-3.1

Appendix E. Summary of *Z. marina* Depth Estimates at 2000 SVMP Sample Sites (Garmin depth sounder).

		Minimum Eelgrass Depth						Maximum Eelgrass Depth					
Site	Location	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)
hdc2504	Thorndyke Bay	10	1.4	0.5	0.4	0.2	0.8	9	-4.2	-3.6	0.4	-3.9	-3.3
hdc2529	S. of Tala Point	12	1.5	1.1	0.3	0.9	1.2	12	-4.3	-3.0	0.7	-3.5	-2.6
nps0059	Sinclair Island S.	7	-0.8	-1.6	0.9	-2.2	-0.9	8	-7.6	-6.6	1.0	-7.3	-5.8
nps1363	Village Pt. (Lummi Island)	11	-0.6	-1.9	1.1	-2.6	-1.2	11	-7.0	-5.0	1.7	-6.2	-3.9
sjs0081	Broken Point (Shaw Island)	6	0.0	-0.2	0.2	-0.3	0.0	11	-6.8	-5.3	1.1	-6.1	-4.6
sjs0311	Clark Island	9	0.8	0.4	0.4	0.2	0.7	10	-4.1	-2.8	1.2	-3.6	-1.9
sjs0335	Sattelite Island (Stuart Island)	6	-1.5	-2.7	1.1	-3.6	-1.9	6	-7.7	-6.2	1.2	-7.2	-5.3
sjs0480	SE Orcas Island	7	-0.6	-2.2	1.6	-3.4	-1.0	10	-8.2	-7.0	0.9	-7.7	-6.4
sjs0622	Jasper Cove (Lopez Island)	3	0.1	-0.3	0.7	-1.1	0.6	3	-0.9	-0.8	0.3	-1.2	-0.4
sjs0637	Watmough Head (Lopez Island)	8	-0.2	-1.4	1.7	-2.7	-0.2	9	-7.7	-6.3	2.2	-7.9	-4.8
sjs2646	Discovery Bay	7	0.7	-0.5	1.7	-1.7	0.8	10	-4.9	-2.9	1.2	-3.7	-2.1
sjs2813	Rasmusson Creek	13	-3.1	-4.4	0.7	-4.8	-3.9	13	-7.8	-6.9	0.6	-7.3	-6.5
swh1556	NW Camano Island	10	0.5	0.0	0.3	-0.2	0.2	12	-3.4	-2.5	1.0	-3.1	-1.9
swh1593	Camano Island, Cornell	9	0.5	-0.1	0.5	-1.4	0.3	9	-1.8	-1.2	0.3	-1.5	-1.0
swh1625	So of Tulalip Bay	6	0.8	0.1	0.6	-0.4	0.6	6	-1.7	-0.8	0.6	-1.2	-0.2
swh1647	Mukilteo	12	-0.1	-0.5	0.3	-0.7	-0.3	12	-5.0	-4.1	0.7	-4.5	-3.5
Wide Fringe													
sjs2741	West of Crescent Bay	9	0.0	-3.3	2.5	-5.1	-1.5	9	-8.8	-7.5	0.9	-8.1	-6.8
swh0848	Ala Spit	9	0.2	0.0	0.2	-0.2	0.2	23	-3.4	-2.3	0.5	-2.7	-2.0

Appendix F. Summary of *Z. marina* Depth Estimates at 2001 SVMP Sample Sites (Garmin depth sounder).

		Minimum Eelgrass Depth						Maximum Eelgrass Depth					
Site	Location	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)
<u>Core</u>													
Core001	Padilla Bay	12	1.0	0.5	0.4	0.2	0.8	93	-3.4	-2.6	0.2	-2.7	-2.4
Core002	Picnic Cove	13	-0.2	-1.3	1.1	-2.0	-0.6	5	-5.7	-5.1	0.9	-5.8	-4.3
Core003	Jamestown	10	0.9	-0.2	1.3	-1.1	0.7	30	-8.1	-6.1	0.7	-6.5	-5.6
Core004	Lynch Cove	17	1.8	0.8	0.4	0.5	1.0	8	-3.3	-2.5	0.7	-3.1	-2.0
Core005	Dumas Bay	7	1.6	0.7	0.8	0.1	1.3	7	-1.4	-1.1	0.2	-1.2	-0.9
Core006	Burley Spit	17	0.9	-0.5	0.3	-0.8	-0.3	17	-3.7	-2.3	0.3	-2.6	-2.1
<u>Flats</u>													
Flats11	Samish Bay N.	5	1.1	0.6	0.6	0.2	1.1	23	-4.7	-2.7	0.4	-3.0	-2.5
Flats20	Skagit Bay N.	15	0.9	0.2	0.2	0.1	0.4	17	-2.7	-1.1	0.5	-1.4	-0.9
Flats28	Snohomish Delta S.	9	0.7	0.5	0.2	0.4	0.7	14	-3.2	-1.9	0.5	-2.2	-1.6
Flats35	Nisqually Delta E.	9	0.6	0.4	0.2	0.3	0.5	9	-1.0	-0.5	0.3	-0.7	-0.3
Flats43	Dabob Bay	19	0.6	-0.1	0.3	-0.3	0.1	15	-3.4	-2.3	0.6	-2.7	-2.0
Flats47	Travis Spit	26	0.8	-0.1	0.4	-0.4	0.2	34	-5.9	-3.0	1.0	-3.7	-2.5
Flats53	Westcott Bay	16	0.8	0.0	0.4	-0.2	0.2	16	-2.3	-1.7	0.3	-2.0	-1.6
Flats60	Hunter Bay	19	1.5	-0.4	0.8	-0.9	0.2	19	-3.7	-2.1	0.9	-2.7	-1.6
Flats62	Swifts Bay	10	0.8	-0.2	0.6	-0.7	0.2	23	-6.0	-3.9	1.4	-4.7	-3.0
<u>Narrow Fringe</u>													
cps1046	Battle Point	7	-0.2	-0.6	0.4	-0.9	-0.3	7	-4.8	-1.8	1.7	-3.1	-0.5
cps1118	Neill Point (Vashon Island)	13	0.9	0.3	0.2	0.1	0.5	13	-2.9	-1.1	0.7	-1.6	-0.7
cps1203	Fox Island	9	0.1	-0.4	0.7	-0.9	0.1	9	-3.1	-1.7	1.1	-2.5	-1.0
cps1295	NW Ketron Island	14	0.5	-0.1	0.3	-0.3	0.1	14	-2.5	-1.1	0.6	-1.5	-0.7
cps1686	Fort Lawton	9	0.2	-0.2	0.2	-0.4	0.0	9	-5.8	-4.8	0.8	-5.4	-4.3
cps2003	Pitt Passage	7	0.3	-0.1	0.4	-0.4	0.2	7	-2.5	-1.1	1.2	-2.0	-0.2
cps2545	Olele Point	7	-0.4	-0.9	0.6	-1.4	-0.5	7	-3.5	-2.7	0.8	-3.3	-2.2
cps2584	Lower Hadlock	16	0.8	0.1	0.3	-0.1	0.3	15	-4.0	-2.5	1.0	-3.2	-1.9
hdc2310	Holly	13	-0.2	-0.6	0.3	-0.9	-0.4	13	-4.3	-3.6	0.5	-3.9	-3.3
hdc2338	Across from Union	13	-0.4	-0.9	0.3	-1.1	-0.8	13	-3.6	-2.9	0.4	-3.1	-2.6
hdc2345	Sisters Point	12	0.5	-0.7	0.5	-1.1	-0.4	12	-3.1	-2.3	0.5	-2.6	-2.0
hdc2359	Lynch Cove Fringe	9	0.6	0.1	0.3	-0.2	0.3	9	-4.9	-3.9	0.5	-4.3	-3.5

Appendix F. Summary of *Z. marina* Depth Estimates at 2001 SVMP Sample Sites (Garmin depth sounder).

		Minimum Eelgrass Depth						Maximum Eelgrass Depth					
Site	Location	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)
hdc2433	Pleasant Harbor	12	-0.8	-1.4	1.2	-2.1	-0.6	12	-5.4	-3.9	1.0	-4.5	-3.2
hdc2487	Oak Head	11	-0.1	-0.6	0.5	-0.9	-0.3	11	-4.6	-3.7	0.7	-4.1	-3.2
hdc2504	Thorndyke Bay	11	1.2	0.5	0.3	0.3	0.8	11	-3.7	-2.9	0.4	-3.2	-2.6
hdc2529	S. of Tala Point	11	1.2	0.6	0.4	0.4	0.9	11	-4.5	-3.2	0.8	-3.7	-2.7
nps0059	Sinclair Island S.	13	0.7	-1.3	0.8	-1.9	-0.8	14	-6.1	-5.2	0.5	-5.5	-4.8
nps1363	Village Pt. (Lummi Island)	10	-0.9	-1.7	0.8	-2.3	-1.2	10	-5.4	-4.1	1.2	-4.9	-3.3
sjs0081	Broken Point (Shaw Island)	11	0.7	0.1	0.4	-0.2	0.3	10	-5.7	-4.4	1.2	-5.3	-3.6
sjs0311	Clark Island	8	0.8	0.1	1.0	-0.7	0.8	10	-5.1	-3.4	1.4	-4.5	-2.5
sjs0335	Sattelite Island (Stuart Island)	10	-1.5	-3.4	1.4	-4.4	-2.5	10	-7.1	-5.5	1.3	-6.4	-4.6
sjs0365	Thatcher Pass	8	-0.2	-0.7	0.8	-1.2	-0.1	14	-5.1	-3.8	1.4	-4.7	-2.8
sjs0480	SE Orcas Island	11	-0.8	-2.2	0.9	-2.8	-1.6	11	-7.6	-6.6	0.7	-7.0	-6.1
sjs0637	Watmough Head (Lopez Island)	11	-1.1	-2.8	1.6	-3.9	-1.8	11	-8.0	-6.7	1.4	-7.6	-5.7
sjs0819	N of Partridge Point	4	-4.1	-4.7	1.1	-5.8	-3.7	4	-6.2	-5.9	0.5	-6.4	-5.5
sjs2646	Discovery Bay	10	0.9	0.4	0.4	0.2	0.7	9	-4.8	-2.7	1.5	-3.8	-1.6
swh0718	Swinomish Channel	5	0.0	-0.4	0.4	-0.8	-0.1	5	-1.3	-1.0	0.4	-1.3	-0.6
swh1556	NW Camano Island	9	0.4	0.1	0.2	-0.1	0.3	8	-3.2	-2.7	0.5	-3.0	-2.3
swh1593	Camano Island, Cornell	12	0.5	0.3	0.2	0.2	0.5	12	-1.4	-1.1	0.3	-1.2	-0.9
swh1625	So of Tulalip Bay	11	1.0	0.2	0.4	-0.1	0.4	11	-0.6	-0.3	0.2	-0.5	-0.1
swh1647	Mukilteo	12	0.0	-0.7	0.4	-1.0	-0.4	12	-5.5	-4.3	0.9	-4.9	-3.7
Wide Fringe													
cps2215	Eglon, Kitsap	8	1.4	0.9	0.5	0.5	1.2	10	-5.6	-3.4	1.3	-4.3	-2.6
hdc2240	N of Port Gamble	9	1.5	0.8	0.5	0.5	1.2	9	-5.2	-4.3	0.6	-4.8	-3.9
sjs0351	NW Waldron Island	10	0.6	0.3	0.1	0.2	0.4	10	-7.9	-7.1	0.4	-7.4	-6.9
sjs2678	Dungeness Spit Lighthouse Res.	10	-1.6	-3.7	0.9	-4.3	-3.0	10	-7.3	-6.7	0.6	-7.1	-6.3
sjs2741	West of Crescent Bay	10	1.0	-2.8	2.3	-4.3	-1.3	12	-8.7	-7.7	0.7	-8.2	-7.3
sjs2769	Deep Creek	3	-0.9	-0.9	0.1	-1.1	-0.8	3	-5.1	-3.8	2.8	-7.4	-0.1
swh0848	Ala Spit	10	0.4	-0.2	0.3	-0.5	0.0	25	-2.7	-2.2	0.3	-2.4	-2.0
swh0943	Hackney Island (Whidbey Island)	8	0.9	0.2	0.6	-0.2	0.5	17	-4.6	-3.5	0.5	-3.8	-3.3
swh1575	Camp Dianna, Camano Island	10	0.2	0.0	0.2	-0.1	0.1	10	-3.2	-2.7	0.3	-2.9	-2.5

Appendix G. Summary of *Z. marina* Depth Estimates at 2002 SVMP Sample Sites (Garmin depth sounder).

		Minimum Eelgrass Depth						Maximum Eelgrass Depth					
Site	Location	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)
Core													
Core001	Padilla Bay	N/A	N/A	N/A	N/A	N/A	N/A	11	-4.2	-3.0	0.6	-3.4	-2.6
Core002	Picnic Cove	14	0.8	-0.2	0.9	-0.8	0.4	15	-6.0	-4.2	0.6	-4.6	-3.8
Core003	Jamestown	10	0.3	-0.1	0.7	-0.6	0.4	10	-6.9	-4.9	1.4	-5.9	-3.9
Core004	Lynch Cove	12	0.4	-0.2	0.5	-0.6	0.1	12	-3.5	-2.8	0.4	-3.1	-2.6
Core005	Dumas Bay	9	0.2	-0.2	0.3	-0.5	-0.1	9	-1.3	-1.2	0.3	-1.5	-1.0
Core006	Burley Spit	11	0.2	-0.9	0.2	-1.0	-0.7	11	-1.6	-2.5	0.2	-2.6	-2.3
Flats													
Flats11	Samish Bay N.	6	1.4	0.5	0.7	-0.1	1.1	8	-4.0	-3.0	0.5	-3.4	-2.7
Flats18	Similk Bay	17	0.9	-0.2	0.5	-0.5	0.1	15	-2.9	-1.9	0.6	-2.3	-1.5
Flats20	Skagit Bay N.	16	0.4	-0.2	0.4	-0.5	0.0	16	-3.5	-1.6	0.6	-1.9	-1.2
Flats28	Snohomish Delta S.	11	0.1	-0.3	0.2	-0.4	-0.2	11	-2.3	-2.0	0.3	-2.1	-1.8
Flats35	Nisqually Delta E.	7	0.3	0.2	0.1	0.1	0.3	7	-1.0	-0.7	0.3	-0.9	-0.5
Flats37	Wing Point	5	-0.4	-1.3	1.7	-2.7	0.2	11	-7.3	-4.8	1.6	-5.9	-3.6
Flats43	Dabob Bay	12	0.6	0.0	0.3	-0.2	0.2	12	-5.0	-3.1	1.2	-3.9	-2.3
Flats60	Hunter Bay	9	-0.2	-0.8	0.9	-1.5	-0.2	14	-3.7	-2.0	1.0	-2.6	-1.4
Flats62	Swifts Bay	13	0.6	-0.4	0.6	-0.9	0.0	15	-5.7	-3.3	1.5	-4.3	-2.4
Narrow Fringe													
cps1046	Battle Point	6	-0.4	-0.5	0.2	-0.7	-0.4	6	-1.6	-1.2	0.4	-1.5	-0.9
cps1118	Neill Point (Vashon Island)	12	0.7	0.0	0.3	-0.2	0.2	14	-2.8	-1.8	0.6	-2.2	-1.5
cps1128	Paradise Cove (Vashon Island)	9	0.3	-0.6	0.7	-1.1	-0.1	11	-5.3	-3.7	1.3	-4.5	-2.8
cps1156	Klahanic Beach (Vashon Island)	10	0.7	-0.2	0.5	-0.5	0.2	12	-3.9	-2.0	1.1	-2.7	-1.3
cps1164	N. of Pt. Robinson (Maury Island)	10	-0.4	-0.9	0.4	-1.1	-0.6	11	-2.3	-1.9	0.3	-2.1	-1.7
cps1295	NW Ketron Island	13	0.3	-0.2	0.4	-0.5	0.0	13	-3.6	-1.6	0.9	-2.2	-1.0
cps1686	Fort Lawton	9	0.1	-0.3	0.3	-0.5	-0.1	10	-5.9	-4.7	1.2	-5.5	-3.9
cps2545	Olele Point	6	-0.6	-1.1	0.5	-1.5	-0.7	8	-5.9	-3.5	1.3	-4.4	-2.6
cps2573	Ft. Flagler	7	-0.4	-0.7	0.3	-0.9	-0.5	10	-6.1	-3.8	2.1	-5.2	-2.3
cps2584	Lower Hadlock	10	-0.3	-0.7	0.2	-0.7	-0.5	10	-4.3	-2.0	1.0	-2.7	-1.3
hdc2310	Holly	15	0.2	-0.7	0.6	-1.1	-0.3	15	-4.8	-3.5	0.8	-4.1	-3.0
hdc2338	Across from Union	14	-0.6	-1.1	0.3	-1.3	-0.9	14	-5.7	-3.2	0.8	-3.7	-2.6

Appendix G. Summary of *Z. marina* Depth Estimates at 2002 SVMP Sample Sites (Garmin depth sounder).

		Minimum Eelgrass Depth						Maximum Eelgrass Depth					
Site	Location	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)
hdc2359	Lynch Cove Fringe	9	0.5	-0.1	0.5	-0.4	0.2	11	-3.9	-3.4	0.3	-3.6	-3.2
hdc2433	Pleasant Harbor	11	-0.6	-0.8	0.1	-0.9	-0.8	11	-4.5	-3.2	1.0	-3.9	-2.4
hdc2529	S. of Tala Point	9	0.9	0.3	0.6	-0.1	0.8	12	-3.7	-3.0	0.4	-3.3	-2.7
nps0059	Sinclair Island	6	-1.0	-1.9	0.8	-2.6	-1.2	7	-6.2	-5.2	1.1	-6.1	-4.4
nps0522	Eliza Island NE	10	-1.5	-2.2	0.4	-2.5	-2.0	10	-4.0	-3.5	0.4	-3.8	-3.2
nps1363	Village Pt. (Lummi Island)	11	-1.4	-2.0	0.5	-2.3	-1.6	11	-5.6	-3.8	1.0	-4.5	-3.1
sjs0081	Broken Point (Shaw Island)	10	-0.2	-0.8	0.4	-1.0	-0.5	11	-7.5	-4.8	1.8	-6.1	-3.6
sjs0311	Clark Island	11	-0.3	-0.5	0.1	-0.6	-0.4	5	-5.7	-4.4	1.5	-5.7	-3.2
sjs0365	Thatcher Pass	8	-0.1	-0.9	0.8	-1.5	-0.4	9	-6.0	-4.2	1.2	-5.1	-3.4
sjs0617	Lopez Sound Road	9	0.2	-0.4	0.4	-0.6	-0.1	9	-8.2	-5.1	2.5	-6.9	-3.3
sjs0637	Watmough Head (Lopez Island)	7	-0.7	-1.6	1.0	-2.4	-0.9	7	-7.9	-6.6	1.9	-8.1	-5.2
sjs0649	Canoe Island (Shaw Island)	3	-3.0	-3.4	1.0	-4.7	-2.2	3	-6.3	-5.1	1.9	-7.7	-2.6
sjs0819	N of Partridge Point	8	-4.5	-4.9	0.4	-5.3	-4.6	8	-6.6	-6.2	0.3	-6.4	-5.9
sjs2646	Discovery Bay	11	0.9	-0.2	0.5	-0.5	0.2	10	-3.7	-2.1	1.0	-2.7	-1.4
sjs2813	Rasmusson Creek	10	-3.4	-4.2	0.6	-4.6	-3.8	11	-7.8	-6.7	0.7	-7.2	-6.2
swh0718	Swinomish Channel	4	0.2	-0.4	0.8	-1.2	0.4	3	-1.3	-1.0	0.5	-1.7	-0.3
swh1556	NW Camano Island	11	0.1	-0.2	0.2	-0.3	0.0	11	-3.3	-2.7	0.5	-3.1	-2.4
swh1593	Camano Island, Cornell	9	0.5	0.1	0.4	-0.2	0.3	9	-1.6	-1.3	0.2	-1.5	-1.2
swh1625	So of Tulalip Bay	7	0.1	-0.4	0.4	-0.6	-0.1	6	-0.7	-0.4	0.4	-0.7	-0.1
swh1647	Mukilteo	11	-0.7	-0.9	0.2	-1.0	-0.8	11	-5.1	-4.4	0.4	-4.7	-4.1
Wide Fringe													
cps2215	Eglon, Kitsap	9	1.6	1.1	0.5	0.8	1.4	11	-5.1	-3.5	0.9	-4.2	-2.9
cps2218	Pilot Pt.	7	1.1	0.5	0.5	0.1	0.9	7	-4.8	-2.3	2.2	-4.0	-0.7
cps2221	Point no Point	9	0.8	0.4	0.6	0.0	0.8	10	-5.3	-4.0	1.4	-5.0	-3.0
hdc2239	Hood Canal NE	N/A	N/A	N/A	N/A	N/A	N/A	11	-5.7	-3.6	1.1	-4.3	-2.9
nps0654	Yellow Reef (Guemes Island)	10	-0.5	-0.7	0.2	-0.9	-0.6	10	-5.6	-3.0	1.6	-4.1	-2.0
sjs0351	NW Waldron Island	11	0.2	0.0	0.1	0.0	0.1	11	-7.9	-7.3	0.9	-7.9	-6.6
sjs2678	Dungeness Spit Lighthouse Res.	11	-3.7	-4.3	0.5	-4.6	-3.9	11	-7.2	-6.8	0.4	-7.1	-6.5
sjs2741	West of Crescent Bay	8	0.0	-4.3	2.7	-6.2	-2.3	9	-8.7	-7.8	0.6	-8.3	-7.4
swh0848	Ala Spit	11	0.4	-0.1	0.3	-0.3	0.1	11	-3.0	-1.9	0.7	-2.4	-1.4
swh0943	Hackney Island (Whidbey)	11	0.4	-0.9	0.5	-1.2	-0.5	10	-4.7	-4.1	0.6	-4.5	-3.7

Appendix G. Summary of *Z. marina* Depth Estimates at 2002 SVMP Sample Sites (Garmin depth sounder).

		Minimum Eelgrass Depth						Maximum Eelgrass Depth					
Site	Location	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)
swh1575	Camp Dianna, Camano Island	10	0.4	-0.1	0.2	-0.2	0.0	10	-3.6	-2.5	1.2	-3.3	-1.7

Appendix H. Summary of *Z. marina* Depth Estimates at 2002 SVMP Sample Sites (BioSonics echosounder).

		Minimum Eelgrass Depth						Maximum Eelgrass Depth					
Site	Location	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)
<u>Core</u>													
Core001	Padilla Bay	11	1.6	0.4	2.1	0.0	0.8	11	-4.2	-3.3	0.6	-3.7	-2.9
Core002	Picnic Cove	14	-0.2	-1.0	0.9	-1.6	-0.4	15	-5.4	-4.9	0.3	-5.1	-4.7
Core003	Jamestown	10	0.3	-0.2	1.0	-0.9	0.5	10	-7.5	-5.2	1.5	-6.2	-4.2
Core004	Lynch Cove	12	0.3	-0.4	0.5	-0.8	-0.1	12	-3.6	-3.1	0.3	-3.3	-2.9
Core005	Dumas Bay	4	0.2	-0.1	0.3	-0.5	0.2	4	-1.7	-1.0	0.6	-1.6	-0.5
Core006	Burley Spit	11	-0.6	-0.9	0.2	-1.0	-0.8	11	-3.1	-2.6	0.3	-2.8	-2.5
<u>Flats</u>													
Flats11	Samish Bay N.	6	0.6	0.0	0.5	-0.4	0.4	8	-3.9	-3.2	0.5	-3.6	-2.8
Flats18	Similk Bay	15	0.9	-0.4	0.7	-0.9	0.0	20	-3.6	-2.1	0.5	-2.4	-1.7
Flats20	Skagit Bay N.	16	-0.1	-0.5	0.4	-0.8	-0.3	16	-3.4	-1.7	0.6	-2.0	-1.3
Flats28	Snohomish Delta S.	11	0.0	-0.4	0.2	-0.5	-0.2	11	-2.5	-2.2	0.2	-2.3	-2.0
Flats35	Nisqually Delta E.	7	0.3	0.2	0.2	0.0	0.3	7	-1.2	-0.9	0.3	-1.1	-0.6
Flats37	Wing Point	4	-0.6	-1.2	0.9	-2.1	-0.4	11	-7.3	-5.0	1.5	-6.0	-3.9
Flats43	Dabob Bay	12	0.2	-0.2	0.2	-0.3	0.0	12	-5.1	-3.5	0.8	-4.1	-3.0
Flats60	Hunter Bay	9	-0.3	-0.9	0.9	-1.5	-0.3	15	-4.1	-2.2	0.9	-2.8	-1.6
Flats62	Swifts Bay	10	-0.1	-0.6	0.7	-1.1	-0.2	19	-6.0	-2.9	1.3	-3.7	-2.0
<u>Narrow Fringe</u>													
cps1046	Battle Point	6	-0.4	-0.7	0.2	-0.9	-0.5	6	-2.2	-1.5	0.6	-1.9	-1.1
cps1118	Neill Point (Vashon Island)	11	0.3	-0.2	0.3	-0.4	0.0	15	-3.9	-2.4	0.8	-2.9	-1.9
cps1128	Paradise Cove (Vashon Island)	10	0.3	-0.8	0.7	-1.2	-0.3	11	-5.7	-3.9	1.5	-4.9	-2.9
cps1156	Klahanic Beach (Vashon Island)	11	0.8	-0.1	0.6	-0.5	0.3	12	-4.9	-2.6	1.2	-3.4	-1.8
cps1164	N. of Pt. Robinson (Maury Island)	11	-0.5	-1.0	0.4	-1.2	-0.7	11	-3.2	-2.4	0.4	-2.7	-2.2
cps1295	NW Ketron Island	13	0.2	-0.5	0.5	-0.8	-0.2	13	-4.8	-2.6	1.2	-3.4	-1.8
cps1686	Fort Lawton	9	0.0	-0.5	0.4	-0.8	-0.2	10	-6.7	-5.3	1.3	-6.2	-4.5
cps2003	Pitt Passage	10	0.5	-0.2	0.5	-0.5	0.1	9	-5.2	-2.7	1.1	-3.5	-1.9
cps2545	Olele Point	7	-0.9	-1.4	0.5	-1.8	-1.1	8	-6.3	-4.1	1.3	-5.0	-3.2
cps2573	Ft. Flagler	7	-0.4	-0.9	0.3	-1.1	-0.6	10	-6.1	-4.0	1.9	-5.4	-2.7
cps2584	Lower Hadlock	8	-0.4	-0.8	0.3	-1.0	-0.5	11	-4.5	-2.3	0.9	-2.9	-1.7
hdc2310	Holly	15	0.2	-1.2	0.8	-1.7	-0.6	15	-6.2	-4.3	0.9	-4.8	-3.7

Appendix H. Summary of *Z. marina* Depth Estimates at 2002 SVMP Sample Sites (BioSonics echosounder).

		Minimum Eelgrass Depth						Maximum Eelgrass Depth					
Site	Location	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)
hdc2338	Across from Union	14	-0.7	-1.5	0.5	-1.8	-1.1	14	-4.5	-3.7	0.6	-4.1	-3.3
hdc2359	Lynch Cove Fringe	9	0.4	-0.2	0.3	-0.5	0.0	11	-4.3	-3.8	0.2	-4.0	-3.7
hdc2433	Pleasant Harbor	13	-1.2	-1.4	0.1	-1.5	-1.3	13	-5.4	-4.2	0.9	-4.8	-3.6
hdc2529	S. of Tala Point	10	0.7	0.1	0.6	-0.3	0.5	12	-4.8	-3.6	0.5	-4.0	-3.2
nps0059	Sinclair Island	6	-1.7	-2.9	1.5	-4.1	-1.7	7	-7.3	-6.2	1.2	-7.1	-5.3
nps0522	Eliza Island NE	10	-1.7	-2.3	0.4	-2.5	-2.0	10	-4.2	-3.9	0.2	-4.0	-3.7
nps1363	Village Pt. (Lummi Island)	11	-1.7	-2.5	0.6	-2.9	-2.0	11	-7.2	-3.7	3.2	-5.9	-1.5
sjs0081	Broken Point (Shaw Island)	10	-0.4	-1.1	0.4	-1.4	-0.8	11	-8.1	-6.0	1.7	-7.1	-4.8
sjs0311	Clark Island	11	-0.5	-0.8	0.2	-0.9	-0.6	11	-7.3	-4.1	1.7	-5.2	-3.0
sjs0365	Thatcher Pass	9	-0.1	-1.1	0.9	-1.7	-0.4	11	-7.3	-5.2	1.8	-6.3	-4.0
sjs0617	Lopez Sound Road	8	-0.2	-0.6	0.4	-0.9	-0.4	9	-8.6	-4.8	3.2	-7.1	-2.6
sjs0637	Watmough Head (Lopez Island)	7	-1.5	-2.4	1.2	-3.3	-1.5	7	-8.4	-7.3	1.6	-8.5	-6.1
sjs0649	Canoe Island (Shaw Island)	3	-4.4	-4.8	0.8	-5.9	-3.8	3	-7.7	-6.6	2.1	-9.3	-3.8
sjs0819	N of Partridge Point	8	-4.7	-5.2	0.6	-5.6	-4.8	8	-6.7	-6.4	0.3	-6.7	-6.2
sjs2646	Discovery Bay	10	0.1	-0.5	0.4	-0.8	-0.2	11	-4.3	-2.8	0.8	-3.4	-2.3
sjs2813	Rasmusson Creek	10	-3.5	-4.4	0.6	-4.8	-4.0	11	-8.0	-6.9	0.7	-7.4	-6.5
swh0718	Swinomish Channel	4	-0.6	-1.4	0.8	-2.2	-0.5	3	-2.2	-2.0	0.4	-2.5	-1.4
swh1556	NW Camano Island	10	0.0	-0.5	0.3	-0.7	-0.3	11	-3.6	-3.1	0.4	-3.4	-2.8
swh1593	Camano Island, Cornell	9	0.3	-0.1	0.4	-0.4	0.1	9	-2.1	-1.9	0.2	-2.0	-1.8
swh1625	So of Tulalip Bay	7	-0.1	-0.5	0.4	-0.8	-0.2	7	-0.9	-0.6	0.5	-1.0	-0.3
swh1647	Mukilteo	11	-1.0	-1.3	0.2	-1.4	-1.1	11	-6.1	-5.1	0.6	-5.5	-4.7
Wide Fringe													
cps2215	Eglon, Kitsap	9	1.5	0.9	0.4	0.6	1.2	11	-6.3	-4.7	1.0	-5.3	-4.0
cps2218	Pilot Pt.	6	0.8	0.2	0.5	-0.2	0.6	7	-6.1	-3.2	3.0	-5.4	-1.0
cps2221	Point no Point	10	0.7	0.3	0.6	-0.1	0.7	10	-5.9	-4.6	1.4	-5.6	-3.7
hdc2239	Hood Canal NE	N/A	N/A	N/A	N/A	N/A	N/A	11	-5.7	-4.5	1.0	-5.2	-3.8
nps0654	Yellow Reef (Guemes Island)	9	-0.5	-1.0	0.4	-1.3	-0.7	9	-5.9	-3.8	1.5	-4.8	-2.8
sjs0351	NW Waldron Island	11	0.1	-0.1	0.1	-0.2	0.0	11	-8.5	-8.0	0.8	-8.5	-7.4
sjs2678	Dungeness Spit Lighthouse Res.	10	-4.1	-4.5	0.4	-4.8	-4.2	11	-7.7	-7.3	0.4	-7.6	-7.1
sjs2741	West of Crescent Bay	8	-0.1	-4.4	2.8	-6.4	-2.4	9	-9.0	-8.1	0.7	-8.6	-7.6
swh0848	Ala Spit	11	0.2	-0.4	0.4	-0.7	-0.1	11	-3.4	-2.5	0.7	-3.0	-2.0

Appendix H. Summary of *Z. marina* Depth Estimates at 2002 SVMP Sample Sites (BioSonics echosounder).

		Minimum Eelgrass Depth						Maximum Eelgrass Depth					
Site	Location	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)	n	Absolute Depth (m)	Mean Depth (m)	Standard Error	80% Lower Limit (m)	80% Upper Limit (m)
swh0943	Hackney Island (Whidbey)	11	-0.8	-1.2	0.3	-1.5	-1.0	10	-5.5	-4.6	0.5	-5.0	-4.2
swh1575	Camp Dianna, Camano Island	9	0.3	-0.2	0.2	-0.3	0.0	11	-3.8	-2.9	1.1	-3.7	-2.2

Appendix I. Plant characteristics results by site for the 2000 field season.

Site code	Site name	Region	Date	Mean Density (m^{-2})	St.Dev. Density (m^{-2})	Max Density (m^{-2})	Mean Leaf Width (mm)	Min Leaf Width (mm)	Max Leaf Width (mm)	Mean Leaf Length (cm)	St.Dev. Leaf Length (cm)
	flats										
core001	Padilla Bay	nps	24-Aug	174.5	137.4	590	6	2	11	71.6	41.0
core002	Picnic Cove	sjs	14-Jul	101.0	59.0	180	10	7	14	83.0	24.9
core003	Jamestown	sjs	20-Sep	24.0	32.4	110	8	3	12	98.5	52.4
core004	Lynch Cove	hdc	17-Aug	161.1	149.8	470	6	3	9	35.6	36.2
flats18	Similk Bay	swh	26-Jul	40.0	26.2	80	7	4	11	51.3	28.7
flats20	Skagit Bay N.	swh	25-Jul	33.0	44.0	110	6	4	10	50.0	30.6
flats28	Snohomish Delta S.	swh	7-Jul	27.0	42.4	140	10	5	13	111.3	61.3
flats35	Nisqually Delta E.	cps	20-Jul	74.0	126.9	300	6	4	7	45.5	8.8
flats43	Dabob Bay	hdc	17-Sep	775.5	297.1	1220	4	2	6	27.1	12.4
flats47	Travis Spit	sjs	27-Jun	231.0	389.2	1150	7	2	11	46.6	20.1
flats53	Westcott Bay	sjs	13-Jul	22.0	23.9	60	10	6	13	67.1	27.6
flats62	Swifts Bay	sjs	12-Jul	15.0	21.2	100	8	5	11	80.4	52.6
	narrow fringe										
core005	Dumas Bay	cps	18-Jul	113.0	153.1	460	3	2	5	17.4	8.0
core006	Burley Spit	cps	19-Jul	307.0	489.2	1430	4	3	6	17.0	5.2
cps1046	Battle Point	cps	6-Sep	182.0	194.9	550	4	3	6	19.5	17.2
cps1118	Neill Pt (Vashon	cps	12-Sep	200.0	312.5	940	5	2	10	27.9	11.0
cps1686	Fort Lawton	cps	6-Sep	120.0	108.5	290	6	3	10	46.7	30.4
cps2545	Olele Point	cps	15-Aug	154.0	156.4	530	6	3	10	50.9	33.0
hdc2338	Across from Union	hdc	18-Aug	480.0	314.1	1000	4	2	6	42.7	17.7
hdc2504	Thorndyke Bay	hdc	16-Aug	1193.0	880.5	3050	3	1	7	21.6	9.8
sjs2646	Discovery Bay	sjs	19-Sep	155.0	33.3	1090	4	2	8	24.9	19.5
sjs2813	Rasmusson Creek	sjs	27-Sep	36.0	59.3	180	8	4	12	57.7	34.6
swh1556	NW Camano Island	swh	29-Aug	123.0	103.6	300	5	2	7	64.3	44.5
swh1593	Cornell, Camano	swh	10-Oct	50.0	57.3	150	7	3	11	60.5	38.6
swh1647	Mukilteo	swh	23-Aug	189.0	124.7	370	5	4	7	60.7	25.3
	wide fringe										
sjs2741	West of Crescent Bay	sjs	26-Sep	74.0	97.8	280	8.0	4	11	62.3	32.7

*After the first two weeks of sampling the protocol was adjusted to choose random stations for sampling along the transects were eelgrass was found during the survey. This ensured that we sampled within the eelgrass bed and not outside the border or in a large gap. For sites Core002, Flats53, Flats 62, Flats 28 which were sampled prior to this change, repeated sampling occured at the station until eelgrass was collected with the benthic grab. The density reported here reflects the last grab taken at the site.

Appendix J. Plant characteristics results by site for the 2001 field season.

Site code	Site name	Region	Date	Mean Density (m^{-2})	St.Dev. (m^{-2})	Max Density (m^{-2})	Mean Leaf Width (mm)	Min Leaf Width (mm)	Max Leaf Width (mm)	Mean Leaf Length (cm)	St.Dev. Leaf Length (cm)
	flat										
core001	Padilla Bay	nps	18-Aug	194.4	227.5	980	5	2	12	52.2	28.8
core002	Picnic Cove	sjs	4-Aug	65.6	84.4	300	9	4	13	90.2	46.8
core003	Jamestown	sjs	20-Oct	41.6	50.1	210	7	4	10	78.0	46.2
core004	Lynch Cove	hdc	21-Sep	74.4	57.2	220	6	4	10	77.6	38.8
flats11	Samish Bay N	nps	18-Aug	92.4	83.0	290	8	5	12	118.8	37.6
flats18	Similk Bay	swh	11-Aug	38.0	41.7	140	8	5	13	90.1	49.3
flats20	Skagit Bay N.	swh	12-Aug	30.4	39.1	140	7	5	9	54.6	23.5
flats28	Snohomish Delta S.	swh	30-Sep	20.8	23.6	90	9	5	12	133.5	50.9
flats35	Nisqually Delta E.	cps	13-Oct	88.8	132.7	450	6	4	10	31.1	14.4
flats43	Dabob Bay	hdc	25-Sep	573.2	378.9	1240	4	2	5	24.4	9.9
flats47	Travis Spit	sjs	19-Oct	187.2	228.3	920	6	2	11	54.3	35.0
flats53	Westcott Bay	sjs	26-Aug	52.8	65.6	270	10	5	4	80.8	41.5
flats60	Hunter Bay	sjs	2-Aug	20.8	41.9	150	9	4	11	65.5	40.3
flats62	Swifts Bay	sjs	3-Aug	28.8	27.9	80	8	5	11	88.6	49.9
	narrow fringe										
core005	Dumas Bay	cps	5-Oct	371.6	390.1	1070	3	2	4	27.7	11.0
core006	Burley Spit	cps	11-Oct	422.4	502.7	1880	4	3	5	27.8	9.5
cps1046	Battle Point	cps	18-Oct	177.6	187.4	690	4	2	5	27.2	10.7
cps1118	Neill Point	cps	9-Oct	296.8	291.5	930	4	2	6	33.9	19.8
cps1686	Fort Lawton	cps	2-Oct	139.2	176.6	640	5	3	9	44.2	29.0
cps2545	Olele Point	cps	26-Sep	36.0	59.2	230	5	3	12	46.8	30.2
hdc2338	Across from Union	hdc	19-Sep	366.0	271.1	880	4	2	6	38.7	19.5
hdc2504	Thorndyke Bay	hdc	18-Sep	715.6	678.5	2790	3	1	4	22.1	7.8
sjs2646	Discovery Bay	sjs	28-Jul	104.8	147.3	640	6	2	10	42.8	35.4
sjs2813	Rasmusson Creek	sjs	14-Sep	27.2	52.3	160	7	5	10	66.3	31.4
swh1556	NW Camano Island	swh	1-Sep	149.6	98.3	380	5	3	8	43.1	25.7
swh1593	Camano I, Cornell	swh	5-Sep	50.0	75.3	260	7	3	12	43.6	28.3
swh1625	So of Tulalip Bay	swh	29-Sep	77.2	109.2	450	5	2	8	55.4	37.1
swh1647	Mukilteo	swh	28-Sep	192.8	149.5	570	5	2	9	43.6	22.5
	wide fringe										
sjs2678	Dungeness Spit Lighthouse Res.	sjs	11-Sep	23.6	45.5	170	7	4	10	56.2	22.7
sjs2741	West of Crescent Bay	sjs	12-Sep	58.4	90.2	430	6	2	10	41.1	23.7
swh0943	Hackney I (Whidbey)	swh	4-Sep	336.4	210.6	770	4	2	7	48.1	28.1

Appendix K. Plant characteristics results by site for the 2002 field season.

Site code	Site name	Region	Date	Mean Density (m^{-2})	St.Dev. (m^{-2})	Max Density (m^{-2})	Mean Leaf Width (mm)	Min Leaf Width (mm)	Max Leaf Width (mm)	Mean Leaf Length (cm)	St.Dev. Leaf Length (cm)
	flat										
core001	Padilla Bay	nps	25-Jul	149.2	136.8	460	7	3	12	79.6	31.7
core002	Picnic Cove	sjs	8-Jul	66.0	86.6	300	10	5	14	74.0	29.3
core003	Jamestown	sjs	17-Sep	87.6	118.8	520	8	3	10	73.4	32.5
core004	Lynch Cove	hdc	14-Aug	82.4	112.1	480	7	3	10	66.2	29.6
flats11	Samish Bay N	nps	24-Jul	98.8	84.0	320	7	4	13	81.2	37.7
flats18	Similk Bay	swh	17-Jul	49.2	59.9	180	9	4	14	79.9	32.4
flats20	Skagit Bay N.	swh	18-Jul	38.8	55.6	230	8	3	12	82.2	38.1
flats28	Snohomish Delta S.	swh	8-Aug	53.6	48.1	160	9	6	12	136.7	58.8
flats35	Nisqually Delta E.	cps	4-Sep	129.6	137.2	650	4	3	6	37.6	14.0
flats37	Wing Point	cps	27-Aug	47.6	51.5	150	5	3	9	51.5	25.1
flats43	Dabob Bay	hdc	16-Aug	206.0	208.5	590	3	3	4	21.1	5.4
flats60	Hunter Bay	sjs	3-Jul	6.4	14.4	50	10	5	14	73.0	73.0
flats62	Swifts Bay	sjs	4-Jul	36.0	67.2	240	8	3	10	70.3	52.4
	narrow fringe										
core005	Dumas Bay	cps	6-Sep	95.2	174.5	550	3	3	5	24.7	9.1
cps1118	Neill Point (Vashon I)	cps	29-Aug	124.8	143.1	360	3	3	6	30.2	14.3
cps1686	Fort Lawton	cps	28-Aug	106.0	109.9	370	6	3	10	61.9	29.5
hdc2338	Across from Union	hdc	13-Aug	252.0	178.8	550	5	3	6	46.9	16.0
nps0522	Eliza Island NE	nps	5-Aug	33.2	42.5	140	7	5	10	78.8	27.7
sjs0365	Thatcher Pass	sjs	5-Jul	75.8	89.3	300	10	5	14	97.2	32.4
swh1556	NW Camano Island	swh	29-Jul	45.9	52.1	160	6	3	8	80.8	30.3
swh1593	Camano Island, Cornell	swh	6-Aug	43.5	73.3	320	6	3	10	39.0	18.7
swh1625	So of Tulalip Bay	swh	7-Aug	73.5	107.7	350	5	2	9	37.5	23.0
swh1647	Mukilteo	swh	8-Aug	126.8	121.4	380	7	3	10	60.4	21.3
	wide fringe										
sjs2741	W of Crescent Bay	sjs	9-Sep	63.3	72.8	240	6	3	9	60.4	29.9
swh0943	Hackney Island	swh	31-Jul	173.6	121.9	620	5	3	7	47.2	33.6

APPENDIX L

Statistical Framework for Monitoring Zostera marina (Eelgrass) Area in Puget Sound

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1.0 Introduction

The purpose of this report is to describe the statistical methods used to estimate eelgrass area within sites and across Puget Sound based on survey sampling data. This report describes the calculation of variance estimates for within-site sampling error as well as Puget Sound-wide sampling error. Rotational sampling designs will be used to estimate eelgrass area and updated annual estimates in year i using data collected in year $i+1$. Annual change in eelgrass area will be calculated and methods for determining a five-year trend described.

The sampling in Puget Sound for a particular year can be conceptualized as a stratified sampling program. The four strata correspond to four mutually exclusive and exhaustive categories as follows:

Stratum 1: Core areas selected nonprobabilistically.
Stratum 2: Embayment areas encompassing an eelgrass meadow on two or more sides of the shoreline (i.e., flats).
Stratum 3: Shoreline strips with moderate eelgrass abundance (i.e., narrow fringe).
Stratum 4: Shoreline strips with high eelgrass abundance (i.e., wide fringe).

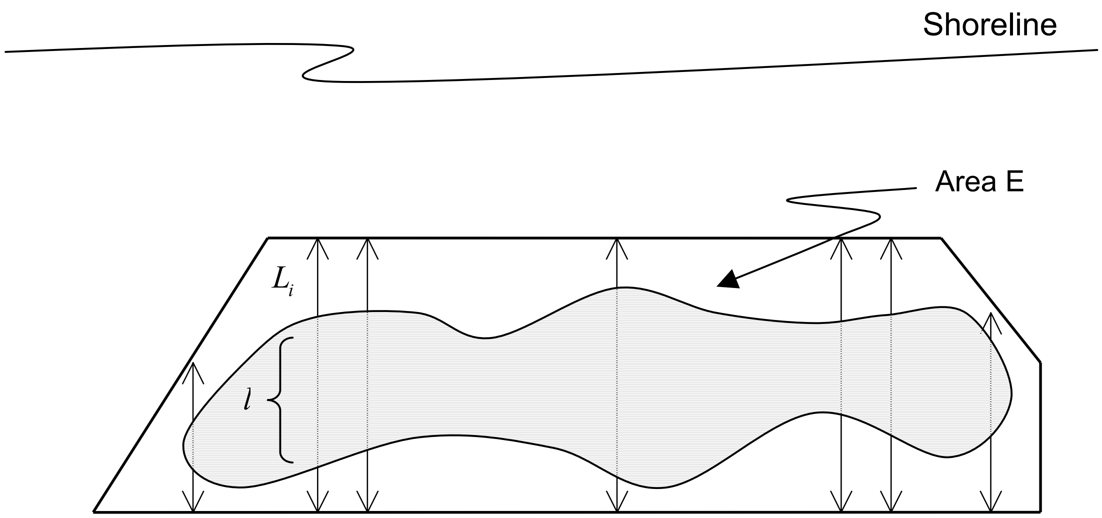
Within embayment and fringe strata, site selection will be conducted using simple random sampling (SRS).

Over years, rotational sampling will be conducted independently within the three probabilistically sampled strata. The fractional rotation of sampling units in and out of strata will be approximately 20%.

2.0 Within-Site Estimation of Eelgrass Area

Within a sampling unit, eelgrass abundance (i.e., area) will be estimated in a two-step process of (1) delineating the area of the bed, (2) conducting line-intercept transect sampling to estimate the percent cover. Figure 1 illustrates conceptually the sampling process. The estimator of eelgrass eelgrass area can then be expressed as

Figure 1. Schematic of sampling an eelgrass bed for eelgrass area. Perimeter of bed based on minimum convex polygon and percent cover estimated from replicate line-intercept transects.



$$\hat{X} = E \cdot \hat{\bar{p}} \tag{1}$$

where

E = maximum outward size of the eelgrass bed based on a minimum convex polygon,

$\hat{\bar{p}}$ = estimated average percent cover along a transect through the eelgrass bed.

The estimate of average percent cover $\left(\hat{\bar{p}}\right)$ will be based on a ratio estimator of the form

$$\hat{\bar{p}} = \frac{\sum_{i=1}^{m} l_i}{\sum_{i=1}^{m} L_i}$$

where

l_i = length of the ith transect $(i = 1, \ldots, m)$ that contains eelgrass,

L_i = actual total length of the ith transect $(i = 1, \ldots, m)$.

This ratio estimator has an approximate variance of

$$V\hat{a}r\left(\hat{\bar{p}}\right) = \frac{\sum_{i=1}^{m} \left(l_i - \hat{\bar{p}} L_i\right)^2}{(m-1)m\bar{L}^2}$$

where

$$\bar{L} = \frac{\sum_{i=1}^{m} L_i}{m}.$$

Should all the transects be of equal length (i.e., $L_i = L \ \forall_i$), then the variance estimate for $\hat{\bar{p}}$ simplifies to

$$\widehat{Var}\left(\hat{\bar{p}}\right)=\frac{\sum_{i=1}^{m}\left(p_i-\hat{\bar{p}}\right)^2}{(m-1)m}$$

where

$$p_i=\frac{l_i}{L_i}.$$

The variance of the estimate of eelgrass area for the site is then

$$\widehat{Var}\left(\hat{X}\right)=E^2 Var\left(\hat{\bar{p}}\right). \tag{2}$$

Estimator (1) and its variance are based on the following assumptions:

1. Area E is known without error.
2. The transect lines are randomly distributed within the area E.
3. The transect lines are infinitely narrow.
4. The fraction of the lines intercepting eelgrass is measured accurately.

3.0 Estimating Regional Abundance in Year i

Within any year i, the monitoring program is a stratified random sampling scheme within Puget Sound. Define

X_{ij} = eelgrass area in the *j*th sample location $\left(j=1,\ldots,m_i\right)$ for the *i*th strata $(i=1,\ldots,4)$;

$\hat{X}_{ij}$ = estimated eelgrass area in the *j*th sample location $\left(j=1,\ldots,m_i\right)$ in the *i*th stratum $(i=1,\ldots,4)$;

N_i = number of sample locations in the *i*th stratum;

n_i = actual number of sample locations drawn in the *i*th stratum;

$Var\left(\hat{X}_{ij} \middle| X_{ij}\right)$ = sampling variance associated with estimating eelgrass area X_{ij} by $\hat{X}_{ij}$ at the *j*th sample location $\left(j = 1,\ldots,n_i\right)$ for the *i*th stratum $(i = 1,\ldots,4)$.

It is worth noting that the within-site eelgrass abundance X_{ij} will be actually estimated by $\hat{X}_{ij}$ which will be assumed to be an unbiased estimator , i.e.,

$$E\left(\hat{X}_{ij}\right) = X_{ij}$$

with an unbiased variance estimator

$$E\left[V\hat{a}r\left(\hat{X}_{ij} \middle| X_{ij}\right)\right] = Var\left(\hat{X}_{ij} \middle| X_{ij}\right).$$

The total eelgrass area (B_T) of eelgrass in Puget Sound will be expressed as

$$B_T = B_1 + B_2 + B_3 + B_4$$

where B_i is the eelgrass area in stratum i $(i = 1,\ldots,4)$ and estimated by

$$\hat{B}_T = \sum_{i=1}^{4} \hat{B}_i \tag{3}$$

with associated variance

$$Var\left(\hat{B}_T\right) = \sum_{i=1}^{4} Var\left(\hat{B}_i \middle| B_i\right).$$

and estimated variance

$$\widehat{Var}\left(\hat{B}_T\right) = \sum_{i=1}^{4} \widehat{Var}\left(\hat{B}_i \middle| B_i\right). \tag{4}$$

3.1 Estimation Within Core Stratum

In this stratum, all N_1 of N_1 sites will be sampled, in which case

$$\hat{B}_1 = \sum_{j=1}^{N_1} \hat{X}_{ij} \tag{5}$$

with associated variance estimator

$$\widehat{Var}\left(\hat{B}_1 \middle| B_1\right) = \sum_{j=1}^{N_1} \widehat{Var}\left(\hat{X}_{ij} \middle| X_{ij}\right) \tag{6}$$

the sum of the within-site measurement errors.

3.2 Estimation Within Fringe Strata

The shoreline strata (i.e., regular fringe and wide fringe) were subdivided into N_i segments of equal length (i.e., 1000 m). A simple random sample of n_i of the shoreline segments were was selected for measurement. However, the shoreline could not be subdivided evenly into 1000-m segments in all cases. There were instances where smaller segments of beach were left over because the beaches were not exact multiples of 1000 m. In order to correctly extrapolate the sample observations to the entire stratum, the sample observations have to be expanded by the multiplier

$$\frac{L_T}{L_N}$$

where

L_T = total linear length of a fringe stratum,

$L_N = N_i \cdot 1000 \text{ m}$ = total linear length of the sampling frame for a fringe stratum.

The estimate of total eelgrass area for a fringe stratum is then calculated as follows:

$$\hat{B}_3 = \left(\frac{L_T}{L_N}\right)\left[\frac{N_3}{n_3}\sum_{j=1}^{n_3}\hat{X}_{ij}\right] \tag{7}$$

with associated estimated sampling variance

$$\widehat{Var}\left(\hat{A}_3 \middle| A_3\right) = \left(\frac{L_T}{L_N}\right)^2 \left[\frac{N_3^2\left(1-\frac{n_3}{N_3}\right)s^2_{\hat{X}_{ij}}}{n_3} + \frac{N_3}{n_3}\sum_{j=1}^{n_3}\widehat{Var}\left(\hat{X}_{ij}\middle| X_{ij}\right)\right] \tag{8}$$

and where

N_3 = number of regular fringe sites in Puget Sound,
n_3 = number of sites actually surveyed,
$$s^2_{\hat{X}_{ij}} = \frac{\sum_{j=1}^{n_3}\left(\hat{X}_{ij} - \hat{\bar{X}}_{ij}\right)^2}{\left(n_3 - 1\right)},$$
$$\hat{\bar{X}}_{ij} = \frac{\sum_{j=1}^{n_3}\hat{X}_{ij}}{n_3}.$$

The estimates of $\hat{B}_4$ and $\widehat{Var}\left(\hat{B}_4 \middle| B_4\right)$ are analogous to Equations (7) and (8), respectively.

3.3 Estimation Within Embayment Stratum

In this stratum, the sampling units are of dramatically different sizes. A simple random sample of embayments/flats will be performed and eelgrass area estimated using a ratio estimator (Cochran 1977: p. 151) of the form

$$\hat{B}_2 = \left[\frac{\sum_{j=1}^{n_2} \hat{X}_{2j}}{\sum_{j=1}^{n_2} a_{2j}}\right] \cdot \sum_{j=1}^{N_2} a_{2j} = \left[\frac{\sum_{j=1}^{n_2} \hat{X}_{2j}}{\sum_{j=1}^{n_2} a_{2j}}\right] \cdot A_2 \tag{9}$$

where

a_{2j} = area of the *j*th embayment $(j = 1, \ldots, n_2)$ in the second stratum,

$A_2 = \sum_{j=1}^{N_2} a_{2j}$ = the total areal extent of embayment sites within stratum 2.

The estimator and associated variance assume the areas a_{2j} $(j = 1, \ldots, L_2)$ are measured without error. The variance for $\hat{B}_2$ can be expressed (Appendix B) as

$$Var\left(\hat{B}_2\right) = N_2^2 \left(1 - \frac{n_2}{N_2}\right) \frac{\sum_{j=1}^{N_2} \left(X_{2j} - a_{2j} R\right)^2}{n_2 \left(N_2 - 1\right)} + \frac{N_2}{n_2} \sum_{j=1}^{N_2} Var\left(\hat{X}_{2j} \middle| X_{2j}\right) \tag{10}$$

and where

$$R = \frac{\sum_{j=1}^{N_2} X_{2j}}{\sum_{j=1}^{N_2} a_{2j}}.$$

In turn, this variance can be estimated by

$$\widehat{Var}\left(\hat{B}_2\right) = N_2^2 \left(1 - \frac{n_2}{N_2}\right) \frac{\sum_{j=1}^{n_2} \left(\hat{X}_{2j} - a_{2j} \hat{R}\right)^2}{n_2 \left(n_2 - 1\right)} + \frac{N_2 \sum_{j=1}^{n_2} \widehat{Var}\left(\hat{X}_{2j} \middle| X_{2j}\right)}{n_2} \tag{11}$$

where

$$\hat{R} = \frac{\sum_{j=1}^{n_2} \hat{X}_{2j}}{\sum_{j=1}^{n_2} a_{2j}}.$$

4.0 Retrospective Adjustment of Eelgrass Area in Year i Using Year $i+1$ Data

During the monitoring program, rotational sampling will be conducted at strata 2-4 where probabilistic sampling occurs. At those strata, some fraction f_i of the sampling sites in the previous year will be replaced with new locations selected at random. In the core area stratum, the same reference sites will be sampled each year. The current year's estimate of eelgrass area will be based on the same estimators presented in Section 3.0.

However, because of the positive correlation between eelgrass measurements in consecutive years, the estimate of abundance in the past year can be updated with an anticipated improvement in precision. The estimate of the updated total eelgrass area will be computed as

$$\tilde{B}_T = \hat{B}_1 + \tilde{B}_2 + \tilde{B}_3 + \tilde{B}_4 \tag{12}$$

for a previous year where $\tilde{B}_2$, $\tilde{B}_3$, and $\tilde{B}_4$ are updated estimates of eelgrass area in strata 2-4 using information from both years i and $i+1$. The retrospective adjustment for total eelgrass area will be done on a stratum-by-stratum basis. The goal of the rotational design is to improve upon the initial estimate taking into account data collected in year $i+1$. The variance for the updated estimate of total eelgrass area for Puget Sound will be calculated as follows:

$$Var\left(\tilde{B}_T\right) = \widehat{Var}\left(\hat{B}_1\right) + \widehat{Var}\left(\tilde{B}_2\right) + \widehat{Var}\left(\tilde{B}_3\right) + \widehat{Var}\left(\tilde{B}_4\right) \tag{13}$$

based on the stratified sampling scheme.

4.1 Core Area Stratum

Rotational sampling is not conducted within the core stratum. Hence, no further update is possible using the $(i+1)$ th year data. As such, for the core stratum $\tilde{B}_1 = \hat{B}_1$, and the estimate remains unchanged with regard to the $(i+1)$ data update.

4.2 Fringe Strata

For the fringe strata under rotational sampling, the initial estimator $\hat{B}_i$ is composed of an estimate based on matched sites (sampled both years i and $i+1$) and nonmatched sites (sampled year i but not in year $i+1$).

An updated estimator for $\hat{B}_i$ [Equation (13)] using the sample data in year $(i+1)$ is

$$\tilde{B}_i = \left(\frac{L_T}{L_N}\right) N \left[W\hat{\bar{X}}'_{U1} + \left(1-W\right)\hat{\bar{X}}'_{M1} \right] \tag{14}$$

where

$\hat{\bar{X}}'_{U1} = \frac{1}{u}\sum_{j=1}^{u}\hat{X}_{j1}$ estimate of the mean based on unmatched (u) sites surveyed in year i;

$\hat{\bar{X}}'_{M1}$ = revised estimate of the mean in year i based on regression of matched values in year i and $i+1$, where

$$\begin{aligned}\hat{\bar{X}}'_{M1} &= \hat{\bar{X}}_{M1} + \hat{\beta}\left(\hat{\bar{X}}_2 - \hat{\bar{X}}_{2M}\right)\\ &= \alpha + \beta\left(\hat{\bar{X}}_2\right);\end{aligned}$$

and where

$\hat{\hat{X}}_{M1}$ = estimated mean based on matched sites measured in year i;

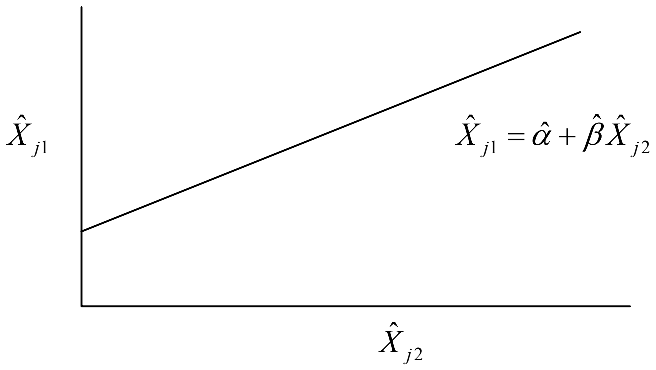
$\hat{\hat{X}}_{2M}$ = estimated mean based on matched sites measured in year $i+1$;

$\hat{\hat{X}}_{2}$ = estimated mean based on all sites measured in year $i+1$.

To estimate $\hat{\hat{X}}'_{M1}$, calculate the regression relationship

$$\hat{X}_{j1} = \hat{\alpha} + \hat{\beta}\hat{X}_{j2}$$

of the form



using the m matched samples collected in year i $(\hat{X}_{j1};\ j = 1,\ldots,m)$ and your $i+1$ $(\hat{X}_{j2};\ j = 1,\ldots,m)$.

The weights used in Equation (14) are of the form

$$W = \frac{\dfrac{1}{\widehat{Var}\left(\hat{\hat{X}}'_{U1}\right)}}{\dfrac{1}{\widehat{Var}\left(\hat{\hat{X}}'_{U1}\right)} + \dfrac{1}{\widehat{Var}\left(\hat{\hat{X}}'_{M1}\right)}} = \frac{\widehat{Var}\left(\hat{\hat{X}}'_{M1}\right)}{\widehat{Var}\left(\hat{\hat{X}}'_{U1}\right) + \widehat{Var}\left(\hat{\hat{X}}'_{M1}\right)}. \qquad (15)$$

In turn,

$$\widehat{Var}\left(\hat{\bar{X}}'_{U1}\right)=\frac{s^2_{\hat{X}_{j1}}\left(1-\frac{u}{N}\right)}{u} \tag{16}$$

where

$$s^2_{\hat{X}_{j1}}=\frac{\sum_{j=1}^{u}\left(\hat{X}_{1j}-\hat{\bar{X}}_{U1}\right)^2}{\left(u-1\right)}.$$

The variance of $\hat{\bar{X}}'_{M1}$ is based on double sampling (Cochran 1977: p. 339), in which case

$$\widehat{Var}\left(\hat{\bar{X}}'_{M1}\right)=\frac{s^2_{\hat{X}_{j1}\cdot\hat{X}_{j2}}}{m}+\frac{s^2_{\hat{X}_{j1}}-s^2_{\hat{X}_{j1}\cdot\hat{X}_{j2}}}{n}-\frac{s^2_{\hat{X}_{j1}}}{N} \tag{17}$$

and where

$$s^2_{\hat{X}_{j1}}=\frac{\sum_{j=1}^{m}\left(\hat{X}_{j1}-\hat{\bar{X}}_{m1}\right)^2}{m-1}, \tag{18}$$

$$\begin{aligned} s^2_{\hat{X}_{j1}\cdot\hat{X}_{j2}} &= \frac{1}{m-2}\left[\sum_{j=1}^{m}\left(\hat{X}_{j1}-\hat{\bar{X}}_{m1}\right)^2-\hat{B}^2\sum_{j=1}^{m}\left(\hat{X}_{j2}-\hat{\bar{X}}_{m2}\right)^2\right] \\ &= \frac{\text{SSE}}{m-2}=\text{ MSE from the ANOVA for the regression analysis.}\end{aligned} \tag{19}$$

The weighted estimator [Equation (13)] is composed of two independent estimators, in which case

$$Var\left(\tilde{B}_i\right)=\left(\frac{L_T}{L_N}\right)^2 N^2\left[W^2 Var\left(\hat{\bar{X}}'_{U1}\right)+\left(1-W\right)^2 Var\left(\hat{\bar{X}}'_{M1}\right)\right]$$

which simplifies to

$$Var\left(\tilde{B}_i\right)=\left(\frac{L_T}{L_N}\right)^2 N^2\left[\frac{1}{\dfrac{1}{\widehat{Var}\left(\hat{\bar{X}}'_{U1}\right)}+\dfrac{1}{\widehat{Var}\left(\hat{\bar{X}}'_{M1}\right)}}\right]$$

$$=\left(\frac{L_T}{L_N}\right)^2 N^2\left[\frac{\widehat{Var}\left(\hat{\bar{X}}'_{U1}\right)\cdot\widehat{Var}\left(\hat{\bar{X}}'_{M1}\right)}{\widehat{Var}\left(\hat{\bar{X}}'_{U1}\right)+\widehat{Var}\left(\hat{\bar{X}}'_{M1}\right)}\right]. \qquad (20)$$

Cochran (1977: pp. 346-347) shows the variance estimator has the expected value of

$$Var\left(\tilde{B}_i\right)=\left(\frac{L_T}{L_N}\right)^2\frac{N^2\left(1-\dfrac{n}{N}\right)S_1^2\left(n-u\rho^2\right)}{\left(n^2-u^2\rho^2\right)}. \qquad (21)$$

Optimal fraction (P_{OPT}) of n that should be matched one year to the next is

$$P_{OPT}=\frac{\sqrt{1-\rho^2}}{1+\sqrt{1-\rho^2}}$$

where ρ is the correlation coefficient from year i to year $i+1$.

4.2.1 Simple Illustration for Calculating an Adjusted Fringe Stratum Total

Consider the following dataset collected in years i and $i+1$ for a population of size $N = 40$, and where $L_N = L_T$,

	Year 1	Year 2	
$u_1 = 4$ $\hat{\bar{X}}'_{u1} = 9.75$	7		
	10		
	8		
	14		
$m = 7$ $\hat{\bar{X}}'_{m1} = 10.571428$	9	12	$m = 7$ $\hat{\bar{X}}_{m2} = 14.428571$
	15	21	
	14	17	
	10	14	
	7	10	
	8	13	
	11	14	
		15	$u_2 = 4$ $\hat{\bar{X}}_{u2} = 16.25$
		17	
		14	
		19	
	$\hat{\bar{X}}_{n_1} = 10.27\overline{27}$	$\hat{\bar{X}}_{n_2} = 15.09\overline{09}$	

The stratum total for year 1 is estimated to be

$$\hat{B}_1 = 40(10.2727) = 410.9091.$$

For year 2, the stratum of total is estimated to be

$$\hat{B}_2 = 40\left(15.09\overline{09}\right) = 603.6364.$$

Using the $n = 7$ matched samples, the following regression model is constructed

$$\hat{X}_{j1} = -0.806985 + 0.788603\,\hat{X}_{j2}\ .$$

Then the updated estimate of the sample mean at time 1 is computed as

$$\hat{\bar{X}}'_{M1} = -0.806985 + 0.788603(15.0909)$$
$$= 11.09375.$$

There are now two estimates of $\hat{\bar{X}}_1$, $\hat{\bar{X}}'_{U1}$ = 9.750 based on the unmatched samples in year 1, and $\hat{\bar{X}}'_{M1}$ = 11.094 based on the regression model. The best adjusted estimate is their weighted average

$$\tilde{B} = W(9.750) + (1-W)(11.094).$$

The variance of $\hat{\bar{X}}'_{U1}$ is computed to be

$$\widehat{Var}\left(\hat{\bar{X}}'_{U1}\right) = \frac{\left(1-\frac{4}{40}\right)(9.5833)}{4} = 2.15625$$

where

$$s^2_{\hat{X}_1} = 9.5833.$$

The variance of $\hat{\bar{X}}'_{M1}$ is computed to be

$$\widehat{Var}\left(\hat{\bar{X}}'_{M1}\right) = \frac{1.0768}{7} + \frac{8.9524-1.0768}{11} - \frac{8.9524}{40}$$
$$= 0.64598$$

where

$$s^2_{\hat{X}_{j1}} = \frac{\sum_{j=1}^{7}\left(\hat{X}_{j1} - 10.5714\right)^2}{(7-1)} = 8.9524$$
$$s^2_{\hat{X}_{j1}\cdot\hat{X}_{j2}} = \frac{1}{(7-2)}\left[\sum_{j=1}^{7}\left(\hat{X}_{j1} - 10.5714\right)^2 - 0.7886^2\sum_{j=1}^{7}\left(\hat{X}_{j2} - 14.4286\right)^2\right]$$
$$= \frac{5.3842}{5} = 1.0768.$$

The subsequent weight W is computed as

$$W = \frac{0.64598}{2.15625 + 0.64598} = 0.23052.$$

The adjusted average $\tilde{X}_1$ is then estimated to be

$$\begin{aligned} \tilde{X}_1 &= 0.23052(9.750) + 0.76948(11.094) \\ &= 10.7840 \end{aligned}$$

and the adjusted total $\tilde{B}_1$ = 40 (10.7840) = 431.36. The estimated variance $\tilde{X}_1$ is then

$$\widehat{Var}\left(\tilde{X}_1\right) = \frac{1}{\dfrac{1}{2.15625} + \dfrac{1}{0.64598}} = 0.49707$$

and the variance of $\tilde{B}$ is

$$\widehat{Var}\left(\tilde{B}_1\right) = 40^2\left(0.49707\right) = 795.309$$

or

$$\widehat{SE}\left(\tilde{B}_1\right) = 28.201.$$

Note in year 1, the original sample had a mean of $\hat{\bar{X}}'_{M1} = 10.\overline{27}$ with a variance estimate of

$$\widehat{Var}\left(\hat{\bar{X}}_{M1}\right) = \frac{\left(1 - \dfrac{11}{40}\right)\left(8.41\overline{81}\right)}{11} = 0.5548.$$

This translates to a total of $\hat{B}_1$ = 410.9091 and a standard error of $\widehat{SE}(\hat{B}_1)$ = 29.7949. In this artificial example, with r =0.9486, the variance decreased by 10.4% and the standard error by 5.3% using the rotational adjustment.

4.3 Flats Stratum

The estimate of total eelgrass area in the flats stratum is calculated as follows:

$$\hat{B}_2 = \left[\frac{\sum_{j=1}^{n_2} \hat{X}_{2j}}{\sum_{j=1}^{n_2} a_{2j}} \right] \cdot A_2 \qquad (22)$$

where

$\hat{X}_{2j}$ = estimate of eelgrass area in the *j*th embayment ($j = 1,\ldots,N_2$) in the flats stratum;

a_{2j} = area of the *j*th embayment ($j = 1,\ldots,N_2$) in the flats stratum;

$A_2 = \sum_{j=1}^{N_2} a_{2j}$ = total area in flats stratum.

It is assumed the a_{2j} are measured without error and represents the geographic area of an embayment that does not change over time.

An adjusted estimator of eelgrass area in year 1, $\hat{B}_i$, using the data collected in both years i and $i+1$, can be written as

$$\tilde{B} = W \cdot \hat{B}'_{U1} + \left(1 - W\right) \hat{B}'_{M1} \qquad (23)$$

where

$$\hat{B}'_{U1} = \frac{\sum_{j=1}^{u_1} \hat{X}_{2jU_1}}{\sum_{j=1}^{u_1} a_{2jU_1}} \cdot A_2 \qquad (24)$$

= estimate of BAC using only the unmatched sites sampled in year 1.

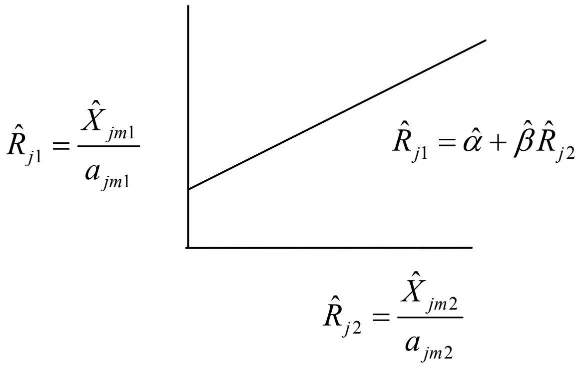
The variance of $\hat{B}'_{U1}$ is estimated using Equation (11) based on the u_1 unmatched sites only in year i; in other words

$$\widehat{Var}\left(\hat{B}'_{U1}\right) = N^2\left(1-\frac{u_1}{N}\right)\frac{\sum_{j=1}^{u_1}\left(\hat{X}_{j1}-a_{j1}\hat{R}_{U1}\right)^2}{u_1\left(u_1-1\right)} + \frac{N\sum_{j=1}^{u_1}\left(\hat{X}_{j1}\middle|X_{j1}\right)}{u_1} \tag{25}$$

where

$$\hat{R}_{U1} = \frac{\sum_{j=1}^{u_1}\hat{X}_{j1}}{\sum_{j=1}^{u_1}a_{j1}}.$$

The estimator $\hat{B}'_{M1}$ is calculated from a regression relationship of the form



which is a straight-line relationship between the site ratios (i.e., density $\hat{X}_{jm1}/a_{jm1}$) measured in year 1 against site ratios measured in year 2 for the m matched sites. The estimate of $\hat{B}'_{M1}$ is then calculated as

$$\hat{B}'_{M1} = \hat{\alpha} + \hat{\beta}\left(\frac{\sum_{j=1}^{n}\hat{X}_{j2}}{\sum_{j=1}^{n}a_{j2}}\right). \tag{26}$$

The quotient $\sum_{j=1}^{n}\hat{X}_{j2}\Big/\sum_{j=1}^{n}a_{j2}$ is the ratio estimator using all n sites measured in year 2.

The variance of $\hat{B}'_{M1}$ is estimated by the expression

$$\widehat{Var}\left(\hat{B}'_{M1}\right)=A_2^2\left[\frac{s^2_{\hat{R}_{j1}\hat{R}_{j2}}}{m}+\frac{s^2_{\hat{R}_{j1}}-s^2_{\hat{R}_{j1}\hat{R}_{j2}}}{n}-\frac{s^2_{\hat{R}_{j1}}}{N}\right] \tag{27}$$

where

$$s^2_{\hat{R}_{j1}}=\frac{\sum_{j=1}^{m}\left(\hat{R}_{j1}-\hat{\bar{R}}_1\right)^2}{m-1}$$

where

$$\hat{\bar{R}}_1=\frac{\sum_{j=1}^{m}\hat{R}_{j1}}{m}$$

$$\hat{R}_{j1}=\frac{\hat{X}_{j1}}{a_{j1}}\ \text{for}\ j=1,\ldots,m$$

and where

$s^2_{\hat{R}_{j1}\hat{R}_{j2}}$ = MSE from the ANOVA for the regression analysis.

The weight (W) used in Equation (23) is calculated as follows

$$W=\frac{\widehat{Var}\left(\hat{B}'_{M1}\right)}{\widehat{Var}\left(\hat{B}'_{U1}\right)+\widehat{Var}\left(\hat{B}'_{M1}\right)}. \tag{28}$$

The adjusted estimator [Equation (23)] is composed of two independent estimators, in which case

$$\widehat{Var}\left(\tilde{B}\right) = W^2 \widehat{Var}\left(\hat{B}'_{U1}\right) + \left(1 - W\right)^2 \widehat{Var}\left(\hat{B}'_{M1}\right) \tag{29}$$

which simplifies to

$$\widehat{Var}\left(\tilde{B}\right) = \frac{\widehat{Var}\left(\hat{B}'_{U1}\right) \cdot \widehat{Var}\left(\hat{B}'_{M1}\right)}{\widehat{Var}\left(\hat{B}'_{U1}\right) + \widehat{Var}\left(\hat{B}'_{M1}\right)} \tag{30}$$

analogous to Equation (20) for fringe sites.

4.3.1 Simple Illustration for Calculating an Adjusted Flats Stratum Total

Consider the following dataset collected in years i and $i+1$ for a population of size N = 20, with total area A_2 = 1705, and where

	Year 1		Year 2		
	X	a	X	a	
$u_1 = 5$	12	53			
	6	37			
	19	101			
	5	21			
	13	72			
$m = 5$	27	133	31	133	$m = 5$
	18	97	20	97	
	31	165	35	165	
	8	36	10	36	
	14	74	16	74	
			15	81	$u_2 = 5$
			24	111	
			6	37	
			11	60	
			26	151	
Totals	153	789	194	945	
	$\hat{R}_1 = 0.19392$		$\hat{R}_2 = 0.20529$		

For this simple example, measure error will be ignored.

In year 1, the estimate of eelgrass area would be computed to be

$$\hat{B} = \frac{153}{789} \cdot 1705 = 330.6274$$

with associated variance estimator

$$\widehat{Var}\left(\hat{B}\right) = 20^2 \left(1 - \frac{10}{20}\right) \frac{\sum_{j=1}^{10} \left(X_j - a_j \left(\frac{153}{789} \right) \right)^2}{10(10-1)} = 23.8828.$$

An updated estimator using the data in year 2 is computed in two steps. First, using the unmatched data in year 1

$$\hat{B}'_{U1} = \frac{55}{284} \cdot 1705 = 330.1937$$

with an associated variance estimate of

$$\widehat{Var}\left(\hat{B}'_{U1}\right) = 20^2 \left(1 - \frac{5}{20}\right) \frac{\sum_{j=1}^{5} \left(X_{j1} - a_j \left(\frac{55}{284} \right) \right)^2}{5(5-1)} = 96.6958.$$

Next, fitting a linear regression model for the site ratios (i.e., $\hat{X}_j / a_j$) in year 1 against year 2 for the matched sites yields

$$R_{1j} = 0.07712 + 0.5258\, R_{2j}$$

with r = 0.98389 and MSE = 0.000005077.

The estimate of $\hat{B}'_{M1}$ is then calculated to be

$$\begin{aligned}\hat{B}'_{M1} &= \left[0.07712 + 0.5258\left(\frac{194}{945}\right)\right]1705 \\ &= 0.18506(1705) \\ &= 315.5375\end{aligned}$$

with associated variance estimator

$$\begin{aligned}\widehat{Var}\left(\hat{B}'_{M1}\right) &= (1705)^2\left[\frac{0.000005077}{5} + \frac{0.00023638 - 0.000005077}{10} - \frac{0.00023638}{20}\right] \\ &= (1705)^2(0.000012327) \\ &= 35.8344\end{aligned}$$

where

$$s^2_{\hat{R}_{j1}} = 0.00023638$$

$$s^2_{\hat{R}_{j1}\hat{R}_{j2}} = \text{MSE} = 0.000005077.$$

The weight is computed from the variance estimates to be

$$W = \frac{35.8344}{96.6958 + 35.8344} = 0.27039.$$

The adjusted eelgrass area estimate for year 1 is then computed to be

$$\begin{aligned}\tilde{B} &= 330.1937(0.27039) + 315.5307(1 - 0.27039) \\ &= 319.5003.\end{aligned}$$

The variance of $\tilde{B}$, in turn, is calculated to be

$$\begin{aligned}\widehat{Var}\left(\tilde{B}\right) &= \frac{96.6958(35.8344)}{96.6958 + 35.8344} \\ &= 26.1453.\end{aligned}$$

In this example, the variance of the adjusted eelgrass area actually increased over the original estimate.

5.0 Estimating the Change in Eelgrass Area Between Years i and $i+1$

5.1 Relative Change Within a Stratum

The best and easiest way of estimating the fractional change (RC) in eelgrass area defined as

$$RC = \frac{B_{i+1} - B_i}{B_i} = \frac{B_{i+1}}{B_i} - 1 \qquad (31)$$

is to perform a regression analysis. Fit a straight-line regression through the origin of the form

$$\hat{X}_{i+1,j} = \hat{X}_{i+1,j}\beta + \varepsilon_j \qquad (32)$$

where

$\hat{X}_{ij}$ = estimated eelgrass area at the *j*th location in year i,

$\hat{X}_{i+1,j}$ = estimated eelgrass area at the *j*th location in year $i+1$,

β = regression coefficient;

ε_i = random error term $\sim N(0, \sigma^2)$.

Equation (32) describes a straight-line regression through the origin. Then it is easy to see

$$\frac{\hat{X}_{i+1,j}}{\hat{X}_{ij}} = \beta + \varepsilon_j \; .$$

Hence, we can estimate the fractional change by

$$\widehat{RC} = \hat{\beta} - 1 \qquad (33)$$

and where

$$\begin{aligned}\widehat{Var}\left(\widehat{RC}\right) &= \widehat{Var}\left(\hat{\beta}-1\right) \\ &= \widehat{Var}\left(\hat{\beta}\right).\end{aligned} \tag{34}$$

The analysis should be conducted on the *m*-matched sites surveyed during both years i and $i+1$ in a stratum. Separate analyses should be performed for each stratum.

5.2 Relative Change in Puget Sound

The estimate of relative change between years i and $i+1$ across Puget Sound is then estimated by the quantity

$$\widehat{RC}_T = \frac{\sum_{j=1}^{4} \hat{B}_{ij}\widehat{RC}_j}{\sum_{j=1}^{4} \hat{B}_{ij}} \tag{35}$$

where

$\hat{B}_{ij}$ = estimated eelgrass area in the *j*th stratum in year i,

$\widehat{RC}_j$ = estimated relative change in the eelgrass area in the *j*th stratum between years i and $i+1$.

The variance of $\widehat{RC_T}$ for Puget Sound can be approximated using the delta method (Seber 1982: p. 7) where

$$Var\left(\widehat{RC}_T\right) = \sum_{j=1}^{4}\left[\widehat{Var}\left(\widehat{RC}_j\right)\left(\frac{\hat{B}_{ij}}{\sum_{j=1}^{4}\hat{B}_{ij}}\right)^2\right] + \sum_{j=1}^{4}\left[\widehat{Var}\left(\hat{B}_{ij}\right)\left(\frac{\widehat{RC}_j\sum_{j=1}^{4}\hat{B}_{ij} - \sum_{j=1}^{4}\hat{B}_{ij}\widehat{RC}_j}{\left(\sum_{j=1}^{4}\hat{B}_{ij}\right)^2}\right)^2\right]. \tag{36}$$

5.3 Areal Change Within a Stratum

For the *j*th stratum $(j = 1, \ldots, 4)$, the areal change (AC_j) in eelgrass area between years i and $i+1$ can be estimated by the quantity

$$\widehat{AC}_j = \hat{B}_{ij} \cdot \widehat{RC}_j \tag{37}$$

with estimated variance

$$\widehat{Var}\left(\widehat{AC}_i\right) = \widehat{Var}\left(\hat{B}_{ij}\right) \cdot \widehat{RC}_j^{\,2} + \widehat{Var}\left(\widehat{RC}_j\right) \cdot \hat{B}_{ij}^2 - \widehat{Var}\left(\hat{B}_{ij}\right) \cdot \widehat{Var}\left(\widehat{RC}_j\right). \tag{38}$$

5.4 Areal Change in Puget Sound

For the entire Puget Sound, areal change would be estimated by the quantity

$$\widehat{AC}_T = \sum_{j=1}^{4} \widehat{AC}_j \tag{39}$$

with associated variance estimator

$$\widehat{Var}\left(\widehat{AC}_T\right) = \sum_{j=1}^{4} \widehat{Var}\left(\widehat{AC}_j\right). \tag{40}$$

5.5 Relative Change Within a Site

The percent relative change (RC) in eelgrass area (B) from one year (i.e., B_i) to the next year (B_{i+1}) at a site can be estimated by the quantity

$$\begin{aligned} \widehat{RC} &= \left(\frac{\hat{B}_{i+1} - \hat{B}_i}{\hat{B}_i} \right) \cdot 100\% \\ &= \left(\frac{\hat{B}_{i+1}}{\hat{B}_i} - 1 \right) \cdot 100\%. \end{aligned} \tag{41}$$

The $\widehat{RC}$ estimates the percent increase or decrease in eelgrass area from year i to year $i+1$. The variance of $\widehat{RC}$ is expressed as

$$\widehat{Var}\left(\widehat{RC}\right)=\left(\frac{\hat{B}_{i+1}}{\hat{B}_i}\right)^2\left[\frac{\widehat{Var}\left(\hat{B}_i\right)}{\hat{B}_i^2}+\frac{\widehat{Var}\left(\hat{B}_{i+1}\right)}{\hat{B}_{i+1}^2}\right]\cdot\left(100\%\right)^2. \tag{42}$$

The standard error is expressed as

$$\widehat{SE}\left(\widehat{RC}\right)=\left(\frac{\hat{B}_{i+1}}{\hat{B}_i}\right)\cdot 100\%\sqrt{\frac{\widehat{Var}\left(\hat{B}_i\right)}{\hat{B}_i^2}+\frac{\widehat{Var}\left(\hat{B}_{i+1}\right)}{\hat{B}_{i+1}^2}}\,. \tag{43}$$

Finally, an asymptotic normal confidence interval is then calculated as

$$\widehat{RC}\pm Z_{1-\frac{\alpha}{2}}\cdot\widehat{SE}\left(\widehat{RC}\right) \tag{44}$$

where for a 95% CI, $Z_{1-\frac{\alpha}{2}}$ = 1.96 or for a 90% CI, $Z_{1-\frac{\alpha}{2}}$ = 1.645.

6.0 Test for a Five-Year Regional Trend

6.1 Test of Slope

Using a straight-line regression of annual response versus year (i.e., t = 0, 1, 2, 3, 4), the null hypothesis of no decline can be written as

$$\mathrm{H_o}:\quad \beta\geq 0 \tag{45}$$

vs.

$$\mathrm{H_a}:\quad \beta<0$$

where β is the slope of the regression model $\hat{B}_t=\alpha+\beta t$. The null hypothesis can be tested using the t-statistic

$$t_{m-2} = \frac{\left|\hat{\beta} - 0\right|}{\sqrt{\dfrac{\text{MSE}}{\sum_{i=1}^{m}\left(t_i - \overline{t}\right)^2}}}. \tag{46}$$

6.2 Power Calculations

In the special case of a five-year test of trend

a. $\sum_{i=1}^{m}\left(t_i - \overline{t}\right)^2 = 10$ for $t_i = \left(0,1,2,3,4\right)$

b. $E\left(\text{MSE}\right) = \sigma_N^2 + \overline{\text{Var}\left(\hat{B}_T \middle| B_T\right)}$

where

σ_N^2 = natural variation in response,

$\text{Var}\left(\hat{B}_T \middle| B_T\right)$ = variance in the annual estimate of Puget-Sound-wide eelgrass area.

c. $\beta = B_0\Delta$ for a linear change in response $B_i = B_0\left(1 - i\Delta\right)$

and where

Δ = annual fractional reduction in response,

B_0 = regional eelgrass area in the first year.

Taking into account factors a-c, the noncentrality parameter associated with the noncentral F-distribution under H_a can be written as

$$\Phi_{1,3} = \frac{1}{\sqrt{2}} \cdot \frac{\left|B_0\Delta\right|}{\sqrt{\dfrac{\sigma_N^2 + \overline{\text{Var}\left(\hat{B} \middle| B\right)}}{10}}}. \tag{47}$$

Currently, based on observations for 2000-2002, we would estimate $\sigma_N^2 = 0$. Therefore, if we assume the magnitude of the natural variation is near zero (i.e., $\sigma_N^2 = 0$), then the noncentrality parameter can be rewritten as

$$\Phi_{1,3} = \sqrt{5} \cdot \frac{|\Delta|}{\sqrt{\text{CV}^2}} \tag{48}$$

where

$$\text{CV}^2 = \frac{\overline{Var\left(\hat{B} \middle| B\right)}}{B_0^2}.$$

6.2.1 Example: Power Calculations for Detecting a Five-Year Decline

For the sound-wide estimates of eelgrass area, the average CV for the years 2000-2002 was 0.256 based on unadjusted annual estimates. However, for the one year (i.e., 2001) for which we have a rotational-design, adjusted estimate, the CV = 0.070. Consider, first, the case where CV = 0.256 and Δ = -0.0625 [i.e., -0.25 = (-0.0625) 4 changes in five years], then

$$\Phi_{1,3} = \sqrt{5} \cdot \frac{|-0.0625|}{\sqrt{(0.256)^2}} = 0.5459.$$

Reading for the noncentral table, statistical power is $1 - \beta \approx 0.30$ (Skalski and Robson 1992) at α = 0.10, one-tailed. In the second case where future CVs are anticipated to be approximately 0.070, the power to detect a 25% decline in five years is

$$\Phi_{1,3} = \sqrt{5} \cdot \frac{|-0.0625|}{\sqrt{(0.07)^2}} = 1.9965 \ ,$$

corresponding to a statistical power of $1 - \beta \approx 0.8666$ at α = 0.10, one-tailed.

6.3 Detecting a 10-Year Decline

The noncentrality parameter for a 10-year test of a linear trend is

$$\Phi_{1,8} = \frac{1}{\sqrt{2}} \cdot \frac{\left|B_0 \Delta\right|}{\sqrt{\frac{\text{Var}\left(\hat{B}\middle|B\right)}{82.5}}}$$

or

$$\Phi_{1,8} = \sqrt{41.25} \cdot \frac{|\Delta|}{\sqrt{\text{CV}^2}}. \tag{49}$$

Using Equation (49), the power to detect a 25% reduction in regional eelgrass within 10 years can be calculated where Δ = 0.02778 [i.e., -0.02778 (9) = -0.25].

$$\Phi_{1,8} = \sqrt{41.25} \cdot \frac{|-0.02778|}{\sqrt{(0.07)^2}} = 2.5489.$$

Reading for the noncentral F-table, $1 - \beta \approx 0.9460$ at α = 0.10, one-tailed. This power calculation is based on the assumption that the average CV for the future rotational adjusted estimates of sound-wide eelgrass area will be 0.070.

7.0 Literature Cited

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Appendix B1: Derivation of Variance for SRS with Measurement Error

The variance of $\hat{B}_3$ can be found in stages as follows:

$$Var\left(\hat{B}_3\right) = Var\left(\frac{N_3}{n_3}\sum_{j=1}^{n_3}\hat{X}_{ij}\right) = Var_2\left[E_1\left(\frac{N_3}{n_3}\sum_{j=1}^{n_3}\left(\hat{X}_{ij}\middle|2\right)\right)\right] + E_2\left[Var_1\left(\frac{N_3}{n_3}\sum_{j=1}^{n_3}\left(\hat{X}_{ij}\middle|2\right)\right)\right]$$

where

1 denotes selection of sampling units within a stratum,

2 denotes sampling of eelgrass abundance within a sampling unit.

Then

$$Var\left(\hat{B}_3\middle|B_3\right) = Var_2\left[\left(\frac{N_3}{n_3}\sum_{j=1}^{n_3}X_{ij}\right)\right] + E_2\left[\frac{N_3^2}{n_3^2}\sum_{j=1}^{n_3}Var\left(\hat{X}_{ij}\middle|X_{ij}\right)\right]$$

$$= \frac{N_3^2\left(1-\frac{n_3}{N_3}\right)S_{x_i}^2}{n_3} + \frac{N_3}{n_3}\sum_{j=1}^{n_3}Var\left(\hat{X}_{ij}\middle|X_{ij}\right). \tag{A1}$$

The second term of Equation (A1) can be unbiasedly estimated by

$$\left(\frac{N_3}{n_3}\right)^2\sum_{j=1}^{n_3}V\hat{a}r\left(\hat{X}_{ij}\middle|X_{ij}\right). \tag{A2}$$

However, substituting $s_{\hat{X}_i}^2$ into the first term of Equation (A1) results in an expected value of

$$E\left[\frac{N_3^2\left(1-\frac{n_3}{N_3}\right)s_{\hat{X}_{ij}}^2}{n_3}\right] = \frac{N_3^2\left(1-\frac{n_3}{N_3}\right)S_{X_i}^2}{n_3} + \frac{N_3^2\left(1-\frac{n_3}{N_3}\right)}{n_3}\cdot\frac{1}{N_3}\sum_{j=1}^{N_3}Var\left(\hat{X}_{ij}\middle|X_{ij}\right). \tag{A3}$$

Hence, there is a positive bias of

$$\frac{N_3\left(1-\frac{n_3}{N_3}\right)}{n_3}\sum_{j=1}^{N_3} Var\left(\hat{X}_{ij}\middle|X_{ij}\right). \tag{A4}$$

Combing the results of Equations (A1- A4), the estimated variance of $\hat{B}_3$ can be written as

$$\widehat{Var}\left(\hat{B}_3\middle|B_3\right)=\frac{N_3^2\left(1-\frac{n_3}{N_3}\right)s_{\hat{X}_i}^2}{n_3}-\frac{N_3\left(1-\frac{n_3}{N_3}\right)}{n_3}\frac{N_3}{n_3}\sum_{j=1}^{n_3}\widehat{Var}\left(\hat{X}_{ij}\middle|X_{ij}\right)+\left(\frac{N_3}{n_3}\right)^2\sum_{j=1}^{n_3}\widehat{Var}\left(\hat{X}_{ij}\middle|X_{ij}\right)$$

which simplifies to

$$\widehat{Var}\left(\hat{B}_3\middle|B_3\right)=\frac{N_3^2\left(1-\frac{n_3}{N_3}\right)s_{\hat{X}_i}^2}{n_3}+\frac{N_3}{n_3}\sum_{j=1}^{n_3}V\hat{a}r\left(\hat{X}_{ij}\middle|X_{ij}\right). \tag{A5}$$

Appendix B2: Variance for Ratio Estimator with Sampling Error

$$Var\left(\hat{B}_2\right) = Var\left(A_2 \frac{\sum_{j=1}^{n_2} \hat{X}_{2j}}{\sum_{j=1}^{n_2} a_{2j}}\right) = Var_1\left[E_2\left(A_2 \frac{\sum_{j=1}^{n_2} \hat{X}_{2j}}{\sum_{j=1}^{n_2} a_{2j}} \middle| 1\right)\right] + E_1\left[Var_2\left(A_2 \frac{\sum_{j=1}^{n_2} \hat{X}_{2j}}{\sum_{j=1}^{n_2} a_{2j}} \middle| 1\right)\right]$$

where

1 denotes stage one sampling of n_2 of N_2 sites,

2 denotes stage two sampling within a site.

Then

$$Var\left(\hat{B}_2\right) = Var_1\left[A_2 \frac{\sum_{j=1}^{n_2} X_{2j}}{\sum_{j=1}^{n_2} a_{2j}}\right] + E_1\left[\left(\frac{A_2}{\sum_{j=1}^{n_2} a_{2j}}\right)^2 \sum_{j=1}^{n_2} Var\left(\hat{X}_{2j} \middle| X_{2j}\right)\right]$$

$$= A_2^2\left(1 - \frac{n_2}{N_2}\right) \frac{\sum_{j=1}^{N_2}\left(x_{2j} - a_{2j}R\right)^2}{\bar{A}^2 n_2\left(N_2 - 1\right)} + \left(\frac{A_2}{\frac{n_2}{N_2}\sum_{j=1}^{N_2} a_{2j}}\right)^2 \frac{n_2}{N_2} \sum_{j=1}^{N_2} Var\left(\hat{X}_{2j} \middle| X_{2j}\right)$$

$$= N_2^2\left(1 - \frac{n_2}{N_2}\right) \frac{\sum_{j=1}^{N_2}\left(X_{2j} - a_{2j}R\right)^2}{n_2\left(N_2 - 1\right)} + \frac{N_2}{n_2} \sum_{j=1}^{N_2} Var\left(\hat{X}_{2j} \middle| X_{2j}\right) \qquad \text{(B1)}$$

$$Var\left(\hat{B}_2\right) = \frac{N_2^2\left[\left(1 - \frac{n_2}{N_2}\right) \frac{\sum_{j=1}^{N_2}\left(\hat{X}_{2j} - a_{2j}R\right)^2}{\left(N_2 - 1\right)} + \overline{Var\left(\hat{X}_{2j} \middle| X_{2j}\right)}\right]}{n_2} \qquad \text{(B2)}$$

Deriving an Estimated Variance for $\hat{B}_2$

The second term in Equation (B2) can be unbiasedly estimated by

$$\overline{Var\left(\hat{X}_{2j}\middle|X_{2j}\right)} = \frac{1}{n_2}\sum_{j=1}^{n_2}\widehat{Var}\left(\hat{X}_{2j}\middle|X_{2j}\right).$$

The term $\frac{\sum_{j=1}^{N_2}\left(X_{2j}-a_{2j}R\right)^2}{\left(N_2-1\right)}$ can be estimated by the expression

$$\frac{\sum_{j=1}^{n_2}\left(\hat{X}_{2j}-a_{2j}\hat{R}\right)^2}{\left(n_2-1\right)}$$

but its expected value is approximately

$$\begin{aligned}
&E\left[\frac{\sum_{j=1}^{n_2}\left(\hat{X}_{2j}-a_{2j}\hat{R}\right)^2}{n_2-1}\right] \\
&\qquad = E\left[\frac{\sum_{j=1}^{n_2}\left(\left(\hat{X}_{2j}-X_{2j}\right)+\left(X_{2j}-a_{2j}\hat{R}\right)\right)^2}{\left(n_2-1\right)}\right] \\
&\qquad = E\left[\frac{\sum_{j=1}^{n_2}\left(\hat{X}_{2j}-X_{2j}\right)^2}{\left(n_2-1\right)}+\frac{\sum_{j=1}^{n_2}\left(X_{2j}-a_{2j}\hat{R}\right)^2}{\left(n_2-1\right)}+\frac{2\sum_{j=1}^{n}\left(X_{2j}-a_{2j}\hat{R}\right)\left(\hat{X}_{2j}-X_{2j}\right)}{\left(n_2-1\right)}\right] \\
&\qquad = \frac{\frac{n_2}{N_2}\sum_{j=1}^{N_2}Var\left(\hat{X}_{2j}\middle|X_{2j}\right)}{\left(n_2-1\right)}+\frac{\sum_{j=1}^{N_2}\left(X_{2j}-a_{2j}R\right)^2}{\left(N_2-1\right)}. \qquad \text{(B4)}
\end{aligned}$$

Hence, (B4) has a positive bias of

$$\frac{\frac{n_2}{N_2}\sum_{j=1}^{N_2} Var\left(\hat{X}_{2j} \middle| X_{2j}\right)}{\left(n_2 - 1\right)}. \tag{B5}$$

This bias can be estimated by

$$\frac{\sum_{j=1}^{n_2} \widehat{Var}\left(\hat{X}_{2j} \middle| X_{2j}\right)}{\left(n_2 - 1\right)}. \tag{B6}$$

Combining terms (B2, B3, B4, and B6), a variance estimator for $\hat{B}_2$ can be expressed as

$$\widehat{Var}\left(\hat{B}_2\right) = \frac{N_2^2\left[\left(1 - \frac{n_2}{N_2}\right)\left[\frac{\sum_{j=1}^{n_2}\left(\hat{X}_{2j} - a_{2j}\hat{R}\right)^2}{\left(n_2 - 1\right)} - \frac{\sum_{j=1}^{n_2}\widehat{Var}\left(\hat{X}_{2j} \middle| X_{2j}\right)}{\left(n_2 - 1\right)}\right] + \frac{\sum_{j=1}^{n_2} Var\left(\hat{X}_{2j} \middle| X_{2j}\right)}{n_2}\right]}{n_2}$$

which simplifies to

$$\widehat{Var}\left(\hat{B}_2\right) = N_2^2\left(1 - \frac{n_2}{N_2}\right)\frac{\sum_{j=1}^{n_2}\left(\hat{X}_{2j} - a_{2j}\hat{R}\right)^2}{n_2\left(n_2 - 1\right)} + \frac{N_2\sum_{j=1}^{n_2}\widehat{Var}\left(\hat{X}_{2j} \middle| X_{2j}\right)}{n_2}. \tag{B7}$$

APPENDIX M

FINAL REPORT

A Bio-Physical Model Evaluation of Eelgrass Distribution and Habitat Potential in Dumas Bay, WA

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1 Executive Summary

This study reports the results of a simplified regression approach that incorporated eelgrass performance features predicted by a biophysical model of photosynthesis and whole plant carbon balance into a GIS visualization tool to map eelgrass distribution (density and depth range) as a function of submarine light availability. The purpose of this study was to evaluate the utility of model predictions for the management and monitoring of submerged aquatic vegetation resources in Puget Sound, WA.

Measured bathymetry and water column optical properties at Dumas Bay were used to drive the biophysical model of seagrass productivity. Maps of potential seagrass distributions at Dumas Bay were generated from model predictions for comparison with distributions obtained from field surveys conducted by The Washington State Department of Natural Resources(DNR) using GIS software. Sensitivity of predicted eelgrass distributions to uncertainty in the ratio of shoot:root biomass and water column turbidity were tested using a range of values obtained by field surveys conducted by ***DNR.***

The irradiance at any point in the seagrass canopy was modeled using a two-flow approximation to the radiative transfer equation. The horizontally projected leaf area at h was calculated as a function of the leaf area index (L) and the bending angle of the canopy (β). Instantaneous spectral photosynthesis was calculated using an exponential function based on target theory commonly used to model the photosynthesis-irradiance relationship. Spectral sensitivity was incorporated into the model by defining the photosynthetic efficiency of each layer of the canopy [$\alpha(\lambda,h)$] as a weighted function of the spectral leaf absorptance [$A(\lambda)$]. Aerobic respiratory demand of leaves, roots and rhizomes was scaled to P_{m}. Estimates of water column irradiance at the top of the eelgrass canopy were obtained from model calculations produced by the radiative transfer program *HydroLight.* Modeled water column chlorophyll (Chl) concentrations ranged from 20 to 50 mg m^{-3}. Total suspended solids (TSS) concentrations ranged from 0 to 25 mg L^{-1}.

Eelgrass distributions predicted by the biophysical model were qualitatively consistent with eelgrass distributions reported by ***DNR*** and previous surveys of Dumas Bay. Water column turbidity was identified as a major factor determining eelgrass distributions at Dumas Bay. Model predictions of eelgrass distributions were more sensitive to variations in [TSS] than in [Chl]. Consequently, the measurement of these factors, particularly with regard to accurate resolution of their spatial and temporal variations, should be given high priority in future efforts to monitor and manage SAV resources in Puget Sound. Uncertainty in seagrass morphology parameters, and shoot:root ratios in particular, represent a second-order problem with regard to accurately modeling eelgrass distributions at Dumas Bay.

2. Introduction

Recent advances in understanding the dynamics of seagrass physiology (Zimmerman et al. 1987, Zimmerman et al. 1989, Zimmerman et al. 1994, Zimmerman et al. 1995a, Zimmerman & Alberte 1996, Zimmerman et al. 1997) and seagrass canopy optics (Zimmerman & Mobley 1997) have permitted the construction of a physically accurate model of light driven photosynthesis that can be used to predict carbon balance of submerged aquatic vegetation, such as seagrasses (Zimmerman in prep). The biophysical model incorporates the spectral light environment (a function of water column turbidity), light absorption and photosynthetic properties of seagrass leaves and canopy architecture (shoot density, leaf size-frequency distribution, shoot:root ratios) to predict physiological carbon balance and light limited seagrass distributions (shoot density, depth range).

Detailed mechanistic simulation models of complex processes are often difficult to test or incorporate into resource management efforts because (i) they require extensive parameterization with data that are difficult or impossible to obtain, (ii) they cannot be inverted to predict the relevant parameters of interest and (iii) they can require prohibitively large amounts of computational resources. This study reports the results of a simplified approach that incorporated seagrass performance features predicted by a biophysical model of seagrass photosynthesis and whole plant carbon balance into a GIS visualization tool to map seagrass distribution (density and depth range) as a function of submarine light availability. The integrated biophysical/GIS models, when populated with site-specific data, will predict potential seagrass distributions as a function of water column light transparency for a specific coastal environment.

The purpose of this study was to evaluate the utility of model predictions for the management and monitoring of submerged aquatic vegetation resources in Puget Sound, WA. In this study, measured bathymetry and water column optical properties at Dumas Bay were used to drive the biophysical model of seagrass productivity. Maps of potential seagrass distributions at Dumas Bay were generated from model predictions for comparison with distributions obtained from field surveys conducted by Marine Resources Consultants, under contract to the Washington State Department of Natural Resources (***DNR***). Sensitivity of predicted eelgrass distributions to uncertainty in water column turbidity and the ratio of shoot:root biomass were tested using a range of values obtained by field surveys conducted by ***DNR.***

3. The Model

3.1 Theory

3.1.1. Radiative Transfer. The irradiance at any point in the seagrass canopy was modeled using a two-flow approximation to the radiative transfer equation. The downwelling spectral irradiance at any height (h) within the canopy was calculated as:

$$E_d(\lambda,h)=E_d(\lambda,0)\cdot\left\{\exp\left[-K_{d-w}(\lambda)\cdot h\cdot\frac{a_L(\lambda)\cdot L_p(h)}{\cos\theta_z}\right]-\rho_c(\lambda,h)\right\} \quad (1)$$

where $E_d(\lambda,0)$ was the spectral irradiance at the top of a submerged seagrass canopy, $\rho_c(\lambda,h)$ was the irradiance reflected from the canopy by layer h, $K_{d\text{-}w}(\lambda)$ was the spectral diffuse attenuation coefficient for downwelling irradiance resulting from the water column including its dissolved and suspended components, $a_L(\lambda)$ was the spectral absorption coefficient of the seagrass leaf, $L_p(h)$ was the horizontally projected leaf area at h, and θ_z was the average zenith angle of $E_d(\lambda,0)$. Canopy reflectance was calculated as:

$$\rho_C(\lambda,h) = \rho_L(\lambda) \cdot L_p(h) \tag{2}$$

where $\rho_L(\lambda)$ was the spectrophotometrically determined reflectance of seagrass leaves.

The seabed beneath the seagrass canopy was assumed to be a Lambertian boundary of reflectance $\rho_b(\lambda)$. Consequently the upwelling irradiance at the seabed was calculated as the product of seabed reflectance $[\rho_b(\lambda)]$ and the downwelling irradiance reaching the seabed $[E_d(\lambda,b)]$:

$$E_u(\lambda,b) = E_d(\lambda,b) \cdot \rho_b(\lambda) \tag{3}$$

The upwelling irradiance at any height h within the canopy was calculated by adding the downwelling irradiance reflected from layer $(h + 1)$ below to the upwelling irradiance originating at the seabed as it was attenuated by the water column and the plant canopy:

$$E_u(\lambda,h) = E_u(\lambda,b) \cdot \left\{ \exp\left[-K_{u-w}(\lambda) \cdot h \cdot \frac{a_L(\lambda) \cdot L_p(h)}{\cos\theta_n} \right] - \rho_c(\lambda,h) \right\} \tag{4}$$
$$+Ed(\lambda,h) \cdot \rho_c(\lambda,h+1)$$

where θ_n was the average nadir angle of E_u.

3.1.2. Biomass Distribution. The horizontally projected leaf area at h was calculated as a function of the leaf area index (L) and the bending angle of the canopy (β):

$$L_p(h) = L(h) \cdot \sin(\beta) \tag{5}$$

Leaf area index for the entire canopy was calculated as the product of the shoot density and the mean one-sided leaf area per shoot. L was distributed through the canopy as a function of the relative amount of biomass $[B(h)]$ at h. The vertical biomass distribution was defined as a logistic function of the asymptotic fraction of biomass present at the base of the canopy (ψ), a shape factor (s) and the inflection point of the curve (I) above the seabed:

$$B(h) = \frac{\psi}{\left(1 + \frac{h}{l}\right)^s} \tag{6}$$

.3.1.3. Canopy Photosynthesis. Instantaneous spectral photosynthesis was calculated using an exponential function based on target theory commonly used to model the photosynthesis-irradiance relationship (Webb et al. 1974). Spectral sensitivity was incorporated into the model by defining the photosynthetic efficiency of each layer of the canopy [$\alpha(\lambda,h)$] as a weighted function of the spectral leaf absorptance [$A(\lambda)$]:

$$\alpha(\lambda,h) = \phi_m \cdot A(\lambda) \cdot L_p(h) \tag{7}$$

where ϕ_{m} was the photosynthetic quantum efficiency. The photosynthetic absorptance [$A(\lambda)$] was calculated from the absorption coefficient after correction for reflectance [$\rho_{\mathrm{L}}(\lambda)$] and non-specific absorption [a(750)]:

$$A(\lambda) = \{1 - \rho_L(\lambda) - \exp[a(\lambda) - a(750)]\} \tag{8}$$

The photosynthetically utilized irradiance [$\Pi(h)$] was then calculated as:

$$\Pi(h) = \sum_{\lambda} \alpha(\lambda,h) \cdot E(\lambda,h) \tag{9}$$

where $E(\lambda,h)$ was in units of mol quanta m^{-2} s^{-1}. The instantaneous spectral photosynthesis at any height (h) within the canopy was expressed as:

$$P_i(h) = B(h) \cdot P_m \left[1 - \exp\left(-\frac{\Pi(h)}{P_m}\right)\right] \tag{10}$$

Instantaneous whole canopy photosynthesis (P_{c}) was then determined by numerical integration of $P_i(h)$ over h:

$$P_c = \sum_h P_i(h) \tag{11}$$

Daily-integrated photosynthesis was calculated as:

$$P_d = \sum_h B(h) \cdot P_m \left[1 - \left(-\frac{0.67\Pi(h)}{P_m}\right)\right] \cdot D \tag{12}$$

In this case, $\Pi(h)$ was calculated from the value of $E(\lambda,h)$ at noon and D was the length of the daily photoperiod. The value 0.67 was an empirically determined integration constant that assumes the daily variation in $E(\lambda,h)$ to be sinusoidal.

3.1.4. Whole Plant Respiration and Daily Carbon Balance. Aerobic respiratory demand of leaves, roots and rhizomes was scaled to P_m according to (Zimmerman et al. 1989):

$$R_{leaf} = 0.2P_m \tag{13}$$

$$R_{root} = 0.5R_{leaf} \tag{14}$$

$$R_{rhiz} = 0.5R_{root} \tag{15}$$

Nighttime respiratory demand of roots and rhizomes was reduced to 65% of the aerobic (daytime) rate to account for the reverse Pastéur effect observed when these tissues become anoxic ((Smith et al. 1988, Smith 1989). Consequently daily whole plant respiratory demand (R_d) was calculated as the sum of daily respiratory rates for each of the different tissue components scaled to σ (Zimmerman et al. 1996, Alcoverro et al. 1999):

$$R_d = 24 \cdot R_{leaf} + \left\{ \frac{\left[D \cdot (R_{root} + R_{rhiz}) + 0.65 \cdot (24 - D) \cdot (R_{root} + R_{rhiz}) \right]}{\sigma} \right\} \tag{16}$$

Finally, daily carbon balance was determined as the ratio of $P_d{:}R_d$. Values of $P_d{:}R_d \geq 1$ indicated light environments capable of sustaining the given shoot density and accumulating internal carbon reserves. Values of $P_d{:}R_d < 1$ indicated light environments that could not sustain the given shoot density without the use of carbon reserves stored in the plants.

4. Model Parameterization

4.1. The submarine light environment. Estimates of the submarine irradiance field above the eelgrass canopy were obtained from model calculations produced by the radiative transfer program *HydroLight* (Mobley 1989) for local solar noon on the spring equinox at the latitude of Dumas Bay. Modeled water column chlorophyll (Chl) concentrations ranged from 20 to 50 mg m^{-3}. Total suspended solids (TSS) concentrations from 0 to 25 mg L^{-1}. Dumas Bay water quality data collected by ***DNR*** were not completely analyzed at the time this model analysis was performed, but Chl concentrations determined from bulk water samples averaged 37 mg m^{-3} and ranged from 24 to 54 mg m^{-3}. Estimates of TSS have not yet been fully analyzed for this site but TSS loads appear to be relatively high in Dumas Bay (J. Norris, ***Marine Resource Consultants***). Downwelling irradiance spectra at any depth in the water column were calculated from the surface irradiance spectrum [$E_d(\lambda,sfc)$] provided by *HydroLight* (Fig. 1.A) and the corresponding spectrum of $K_{d\text{-}w}$ (Fig. 1.B and 1.C) for the appropriate Chl and TSS treatment, using radiative transfer theory (Kirk 1994).

No measurements were available for modeling the specific seabed reflectance at Dumas Bay, so seabed reflectance [$\rho_b(\lambda)$] was parameterized from spectral reflectances measured over carbonate sand (R. Zimmerman, unpubl.). Although the carbonate reflectance spectrum used here may be more than twice as bright as the reflectance of siliciclastic marine sediments with a high clay/mud content more typical of Dumas Bay, the irradiance reaching the seabed through the dense eelgrass canopies used in these simulations was so small that $\rho_b(\lambda)$ would not materially affect the irradiance profiles even if it were modeled as a perfect reflector [i.e., $\rho_b(\lambda)=1$].

4.2 Absorption and reflectance spectra of intact leaves. No measurements of leaf absorbance and reflectance from Dumas Bay eelgrass were available for modeling canopy optical properties, so a spectral library of leaf optical properties created from twenty *Zostera marina* (L.) plants collected at Del Monte Beach, Monterey Bay, California was used in these model calculations (R. Zimmerman, unpubl.). Leaf absorption and reflectance spectra were measured at 1 nm resolution (2 nm slit width) using a Shimadzu 2101UV-PC scanning spectrophotometer fitted with an integrating sphere and referenced against $BaSO_4$ plaques. Since leaf optical properties exhibited no significant effect of leaf age, all spectra were pooled to create mean absorption, absorptance and reflectance spectra for use by the model (Fig. 2).

4.3. Canopy architecture for the Dumas Bay eelgrass population was modeled from leaf length-frequency data provided by ***DNR***. Although many size classes in the data set contained only one leaf, a very good logistic fit was obtained to the vertical biomass distribution calculated from the leaf length-frequency data (Fig. 3). Model calculations were performed assuming zero current speed. Consequently the bending angle (β) of the canopy was set to 0 degrees from the vertical, which is typical for seagrass leaves in calm water (R. Zimmerman, pers. obs.).

4.4. Photosynthesis and respiration rates for eelgrass were scaled relative to P_m, enabling the model formulation to be independent of dimensional constraints imposed by specific units. For these calculations, P_m was arbitrarily set to a value of 1 hour^{-1}. Aerobic respiration rates of leaves, roots and rhizomes were scaled to P_m as described in Eqs. 13 to 15.

4.5. Computational Algorithm. The biophysical model computed the maximum sustainable eelgrass density for a given set of environmental parameters (Fig. 4). Input data provided boundary conditions and initial parameterizations, including downwelling spectral irradiance incident at the top of the eelgrass canopy [$E_d(\lambda,0)$], the spectral downwelling and upwelling diffuse attenuation coefficients [$K_{d\text{-}w}(\lambda)$ and $K_{u\text{-}w}(\lambda)$,], eelgrass leaf absorption coefficients and reflectances [$a_L(\lambda)$, $\rho_L(\lambda)$], and leaf canopy architecture, including leaf length-frequency distribution, shoot leaf area and shoot:root ratio (σ). The model then computed the vertical biomass distribution and leaf area projected toward the incoming irradiance, vertical profiles of spectral irradiance and photosynthetic absorptance, whole plant photosynthesis, respiration and carbon balance. The maximum sustainable shoot density for any particular parameterization was obtained when daily whole plant P:R = 1. Simple equations describing the maximum sustainable eelgrass density as a function of depth were generated for different parameterizations of σ and water quality ([Chl] + [TSS]) conditions using polynomial regression techniques.

5. Eelgrass Density Distribution Maps

Tracks of tidally corrected depth soundings provided by ***DNR*** were contoured using a cubic spline interpolation and visualized using ArcView GIS software (Fig. 5). Maximum potential seagrass densities were calculated as a function of water depth from polynomial regressions developed using the biophysical model. Predicted eelgrass densities were then mapped over the bathymetry contours using an inverse distance weighting interpolation. The model arbitrarily assumed the shallow limit of eelgrass distribution to coincide with the tidally corrected 0 m (MLLW) isobath.

6. Results

6.1. Sensitivity to shoot:root. Shoot:root ratios (σ) were measured in the field using two methods (see text of ***DNR*** report for details). Method 1 returned a mean σ of 3.91, while Method 2 returned a mean σ of 1.68. The impact of uncertainty in this parameter, which determined the amount of below-ground biomass (and therefore respiratory carbon demand) on model predictions was evaluated using the light environment generated for a water column consisting of 30 mg m^{-3} Chl + 10 mg L^{-1} TSS and 30 mg m^{-3} Chl + 25 mg L^{-1} TSS. The model predicted a relatively modest difference in daily carbon demand resulting from differences in the value of σ (Fig. 6). A σ value of 4 produced a daily carbon demand of 5.1 P_m equivalents. Reducing σ to 1, however, increased the daily respiratory demand only to 5.53 P_m equivalents. The small difference in daily respiratory demand produced by uncertainty in σ values determined by ***DNR*** led a 5% difference in predicted eelgrass density and 1 m depth and 15% at 3 m depth (Fig. 7).

6.2. Impact of water column constituents on eelgrass density profiles. Model calculations produced well-behaved second order relationships between maximum sustainable eelgrass densities and depth (Fig. 8, Table 3). Predicted eelgrass densities declined more rapidly with depth as water column [Chl] and [TSS] increased. In the absence of TSS, the model predicted eelgrass to extend as deep as 6 m. [Chl] had less impact on predicted seagrass distributions than did [TSS].

6.3. Visualization of potential eelgrass distributions at Dumas Bay. Model regressions of density vs. depth (Table 3) were used to populate distribution maps of potential eelgrass density at Dumas Bay, and to evaluate the relative impacts of [Chl] and [TSS] on those distributions. Maximum densities exceeding 7000 shoots m^{-2} ($L > 10$ m^2 leaf m^{-2} seabed) were predicted for a continuous band running along the 0 to –1 m depth contours for a TSS load of 25 mg L^{-1} (Fig. 9). The maximum depth of eelgrass survival was predicted to be about 2 m under this scenario. The distribution of grab samples collected by DNR with (red dots) and without (white dots) eelgrass generally supports the habitable eelgrass zone predicted by the model for the western part of Dumas Bay. Preliminary analysis of video transects obtained by ***DNR*** revealed eelgrass to be absent from the eastern reach of Dumas Bay (J. Norris, ***MRC***, pers. comm.). Norman et al. (1995), however reported the existence of a dense eelgrass meadow extending across the entire east-west reach of Dumas Bay, as predicted by the bio-physical model (c.f. their Fig. 2). Preliminary analysis of the field data indicates that the eastern reach of the bay was more turbid than the western part where eelgrass were found (J. Norris, ***MRC***, pers. comm). Consistently higher turbidity in the eastern half of Dumas Bay may represent a significant change in local hydrography and/or patterns of coastal runoff since 1995. If true, accurate mapping of potential eelgrass habitat may will require the application of different regression functions to different regions of Dumas Bay. If water column optical properties are found to be relatively homogeneous across Dumas Bay, the absence of eelgrass from the eastern reach in the 2000 ***DNR*** survey may reflect changes in other bio-mechanical processes, including physical disturbance since 1995.

[Chl] between 30 and 50 mg m^{-3} had very little effect on predicted seagrass density or distribution at a TSS load of 25 mg L^{-1}. At this high TSS loading, $K_d(\lambda)$ was consistently above 1.5 m^{-1} across the photosynthetically available spectrum (400 to 700 nm, Fig. 1), regardless of the Chl concentration. Reduction of [TSS] from 25 to 10 mg L^{-1} increased the potential eelgrass habitation zone to at least 3 m depth and greatly increased potential eelgrass density in the shallower reaches of the area, even in the presence of a relatively high concentration of water column chlorophyll (Fig. 10). Elimination of all suspended solids extended the potential eelgrass habitation zone to at least 6 m, even in the presence of Chl concentrations as high as 50 mg m^{-3} (Fig. 11).

7. Conclusions and Recommendations

Eelgrass distributions predicted by the biophysical modeling approach employed here were qualitatively consistent with eelgrass distributions reported by *DNR* and previous surveys of Dumas Bay. The model predictions of supportable shoot density (or leaf area index) must be viewed as the upper bounds for light-limited populations, assuming water column conditions used to create the submarine light environment were representative of the annual mean condition at the site. This biophysical model used here did not evaluate other factors that might limit eelgrass density, including nutrient availability, physical disturbances such as dredging operations, burial events or erosive currents. Nor does it include the effects of space competition with macroalgae (e.g. *Ulva* spp., *Enteromorpha* spp., *Gracilaria* spp.) or other seagrasses (e.g. *Zostera japonica*). Thus, disagreement between observed and predicted eelgrass distributions/densities may require investigation into controlling factors other than water column light availability.

The biophysical model used here has provided three important findings for the development of a long-term program monitoring SAV resources in Puget Sound:

1. Water column turbidity was identified as a major factor determining eelgrass distributions at Dumas Bay. Model predictions of eelgrass distributions were more sensitive to variations in [TSS] than in [Chl]. This indicates that suspended sediments, either from terrestrial runoff or resuspension of tidal mudflats, and not phytoplankton, probably controls the submarine light environment, and therefore

eelgrass distributions at Dumas Bay. This is very similar to the situation in San Francisco Bay were light limitation caused by high water column sediment loads can prevent phytoplankton growth and eelgrass distribution in this otherwise eutrophic estuary (Alpine & Cloern 1988, Zimmerman et al. 1991, Zimmerman et al. 1995b).

2. The reliability of any numerical model is always limited by the data used to parameterize the important driving variables. This study clearly identified the importance of water column optical properties as modeled by [Chl], and particularly [TSS], to predict eelgrass densities and depth distributions. Consequently, the measurement of these factors, especially with regard to accurate resolution of their spatial and temporal variations, should be given high priority in future efforts to monitor and manage SAV resources in Puget Sound.

3. Uncertainty in seagrass morphological parameters, and shoot:root ratios in particular, represent a second-order problem with regard to accurately modeling eelgrass distributions at Dumas Bay. Although field estimates of σ varied by more than a factor of 2, this uncertainty translated into a 5% variation in predicted eelgrass density and depth distribution. Insensitivity of the model to rather large uncertainties in σ makes it difficult to justify extensive field efforts to further refine measurements of plant morphology if the goal is to predict the potential distribution of submerged aquatic vegetation in Puget Sound.

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Table 1. List of model parameters, their definitions and dimensions.

Parameter	Definition	Dimensions
$\alpha(\lambda)$	Photosynthetic efficiency of the canopy	(mol quanta m^{-2} $nm^{-1})^{-1}$
$a_L(\lambda)$	Leaf-specific absorption coefficient	Unit leaf $area^{-1}$
$A_L(\lambda)$	Leaf specific photosynthetic absorptance	Unit leaf $area^{-1}$
$B(h)$	Biomass fraction at height h	Dimensionless
β	Bending angle of the seagrass canopy	Degrees
D	Daily photoperiod	hours day^{-1}
$E_d(\lambda,h)$	Downwelling spectral irradiance at height h	W (or mol quanta) m^{-2} nm^{-1}
$E_u(\lambda,h)$	Upwelling spectral irradiance at height h	W (or mol quanta) m^{-2} nm^{-1}
θ_z	Zenith angle of downwelling irradiance	Degrees
θ_n	Nadir angle of downwelling irradiance	Degrees
h	Height above the sea floor	mm
$K_d(\lambda)$	Coefficient of diffuse attenuation, downwelling	m^{-1}
$K_u(\lambda)$	Coefficient of diffuse attenuation, upwelling	m^{-1}
I	Inflection height of logistic biomass distribution	mm
L	Leaf area index	m^2 leaf m^{-2} seabed
$L_p(h)$	Horizontally projected leaf area	m^2 leaf m^{-2} seabed
$\Pi(h)$	Photosynthetically Utilized Irradiance at height h	Dimensionless
$P_i(h)$	Instantaneous photosynthesis rate at height h	$hour^{-1}$
P_c	Instantaneous whole canopy photosynthesis	$hour^{-1}$
P_d	Daily whole canopy photosynthesis	Day^{-1}
P_m	Maximum light saturated photosynthesis rate	$hour^{-1}$
R_{leaf}	Leaf respiration rate	$hour^{-1}$
R_{root}	Root respiration rate (aerobic)	$hour^{-1}$
R_{rhiz}	Rhizome respiration rate (aerobic)	$hour^{-1}$
R_d	Whole plant daily respiration rate	Day^{-1}
$\rho_L(\lambda)$	Leaf reflectance	Unit leaf $area^{-1}$
$\rho_b(\lambda)$	Seafloor reflectance	Dimensionless
$\rho_c(\lambda)$	Canopy reflectance at height h	Dimensionless
σ	Shoot:root ratio	Dimensionless
s	Shape factor for logistic biomass distribution	Dimensionless
ϕ_m	Photosynthetic quantum efficiency	(mol quanta m^{-2} $nm^{-1})^{-1}$
ψ	Asymptotic canopy biomass fraction at the seabed	Dimensionless

Table 2. Values (or value ranges) of parameters used for the Dumas Bay calculations.

Parameter	Value	Units
β	0	Degrees
D	12	hours day^{-1}
I	115	mm
P_m	1	hour^{-1}
θ_z	25	Degrees
θ_n	0	Degrees
s	4	Dimensionless
σ	1.67	Dimensionless
ϕ_{m}	0.1	(mol quanta m^{-2} s^{-1})$^{-1}$
ψ	0.083	Dimensionless

Table 3. Polynomial regression coefficients relating maximum sustainable seagrass density and depth for different levels of water column Chl and TSS. General form of the regression equations:

$$Density(or\ LAI) = C_2 \cdot z^2 - C_1 \cdot z + Intercept$$

where *z* was the depth of the water in meters. The resulting curves relating shoot density to depth were plotted in Fig. 8.

TSS	Chl	Shoot Density (shoots m^{-2})			Leaf Area Index		
(mg L^{-1})	mg m^{-3}	C_2	C_1	Intercept	C_2	C_1	Intercept
0	50	101	-2533	9324	0.16	-4.05	14.92
	40	75	-2250	9400	0.12	-3.6	15.04
	30	43	-1877	9350	0.069	-3.003	14.96
	20	14	-1456	9245	0.023	-2.329	14.79
10	50	325	-4323	9049	0.52	-6.92	14.48
	40	225	-3793	8871	0.36	-6.07	14.19
	30	136	-3078	8850	0.217	-4.92	14.16
	20	129	-3004	8990	0.206	-4.81	14.38
25	50	795	-6340	8999	1.272	-10.144	14.4
	40	696	-5986	9041	1.114	-9.58	14.46
	30	747	-6118	9124	1.195	-9.79	14.6
	20	377	-4434	9064	0.603	-7.09	14.5

Figure 1. A. In water irradiance at the sea surface [$E_d(sfc)$] computed by the radiative transfer program *HydroLight* (Mobley 1989) for local solar noon on the spring equinox at the latitude of Dumas Bay, Washington. B. Spectral K_d for Chl *a* ranging from 20 to 50 mg m^{-3}, 25 mg L^{-1} TSS. C. Spectral K_d for Chl *a* ranging from 20 to 50 mg m^{-3}, 10 mg L^{-1} TSS. Plots colored as in 1.B

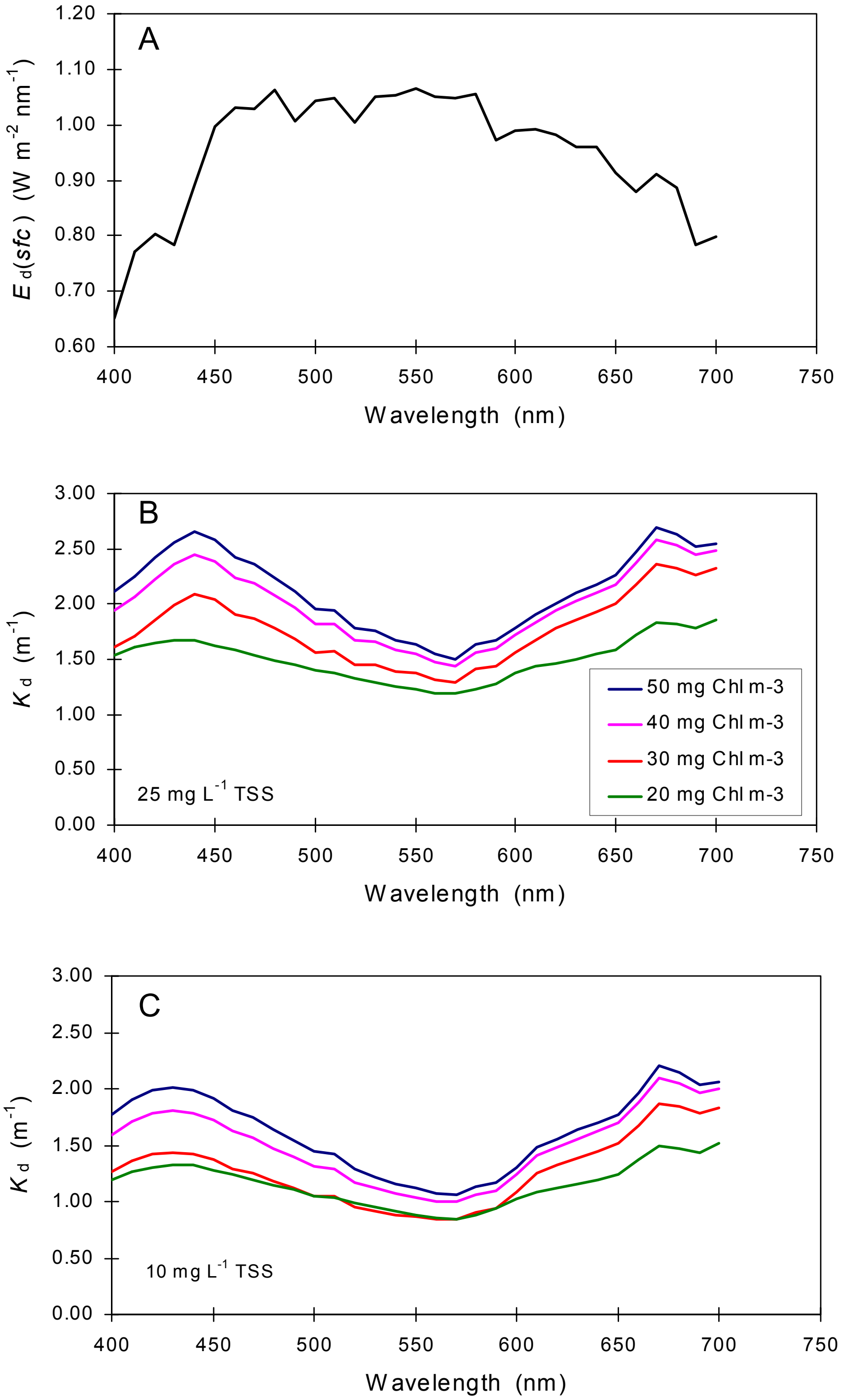


Figure 2. Average leaf optical properties used to parameterize the biophysical model from *Zostera marina* L. growing at Del Monte Beach, Monterey Bay, California. A. Leaf absorption coefficient. B. Leaf absorptance. C. Leaf reflectance.

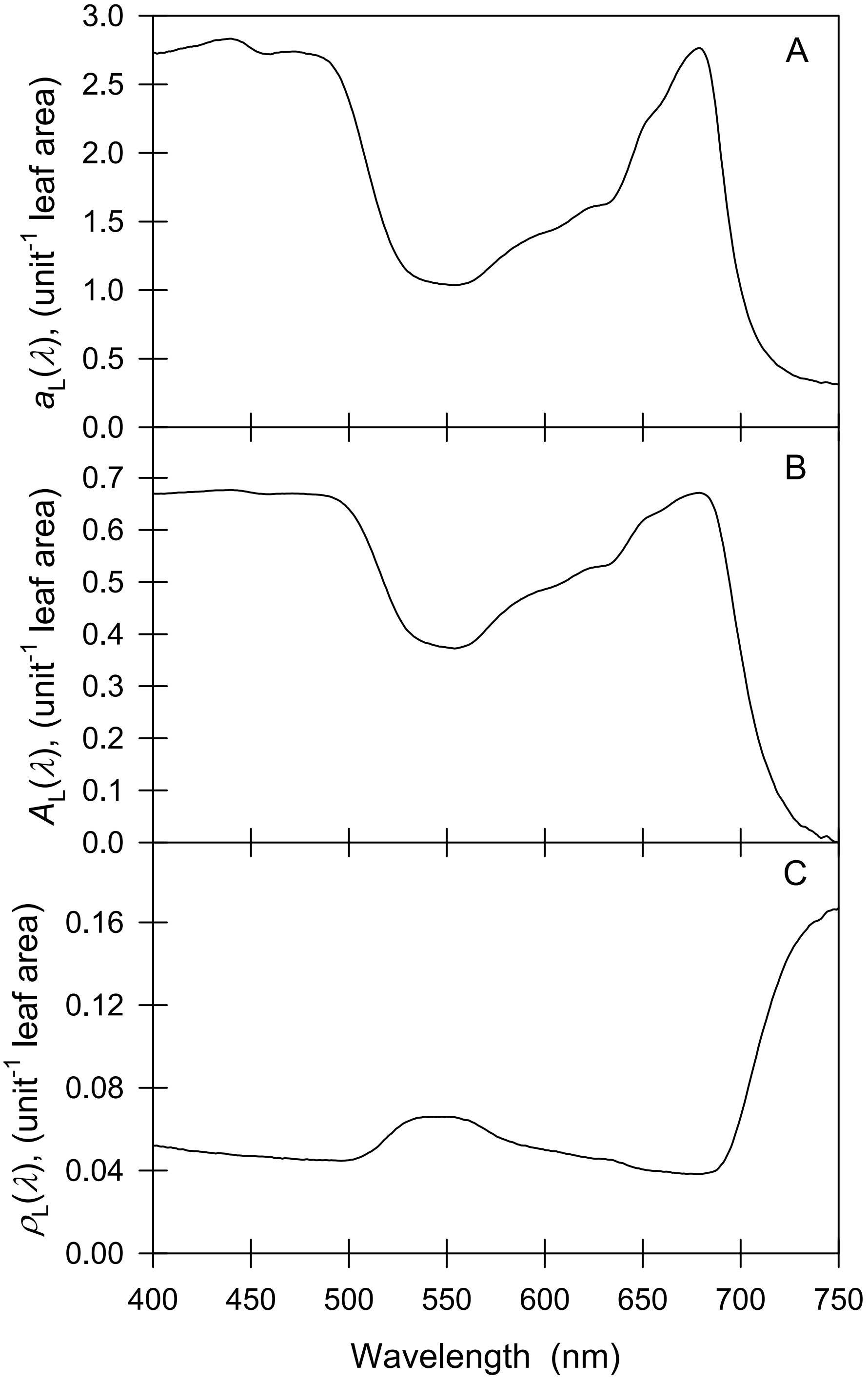


Figure 3. A. Leaf length-frequency distribution for the Dumas Bay eelgrass population from data provided by *DNR*. B. Vertical biomass distribution of the eelgrass canopy based on the leaf length-frequency data. The curve is a least-squares logistic fit to the observed data points. Parameter values derived for the logistic curve are listed in Table 2.

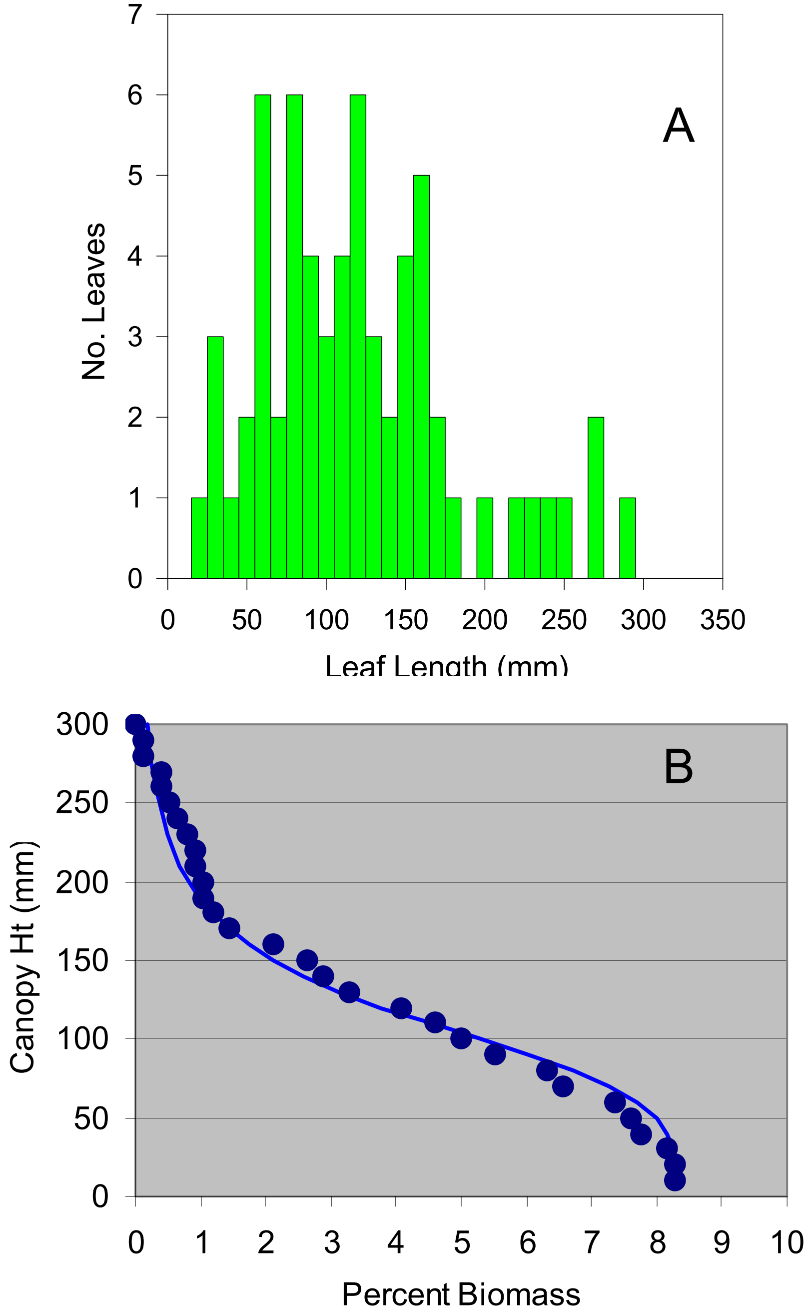


Figure 4. Flow diagram illustrating the basic inputs and computational algorithm of the seagrass biophysical model.

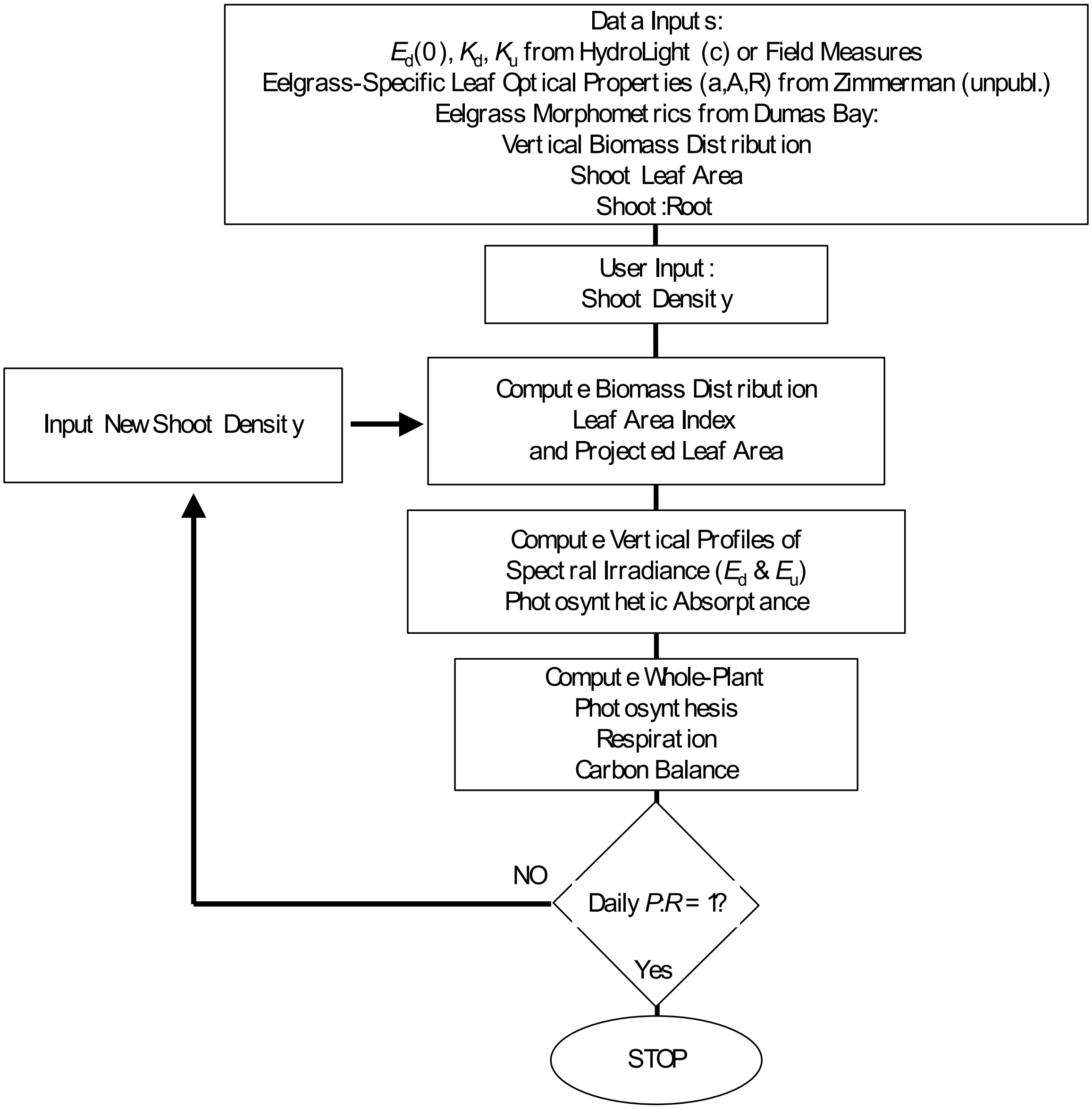


Figure 5. A. Tracks of depth soundings recorded by *DNR* at Dumas Bay. B. Resulting contour map of bathymetry at Dumas Bay derived from the depth sounding tracks. Red dots represent grab samples where eelgrasses were found, white dots represent grab samples without eelgrass. The area mapped in brown represents tidal mudflats (z < 0 m MLLW)

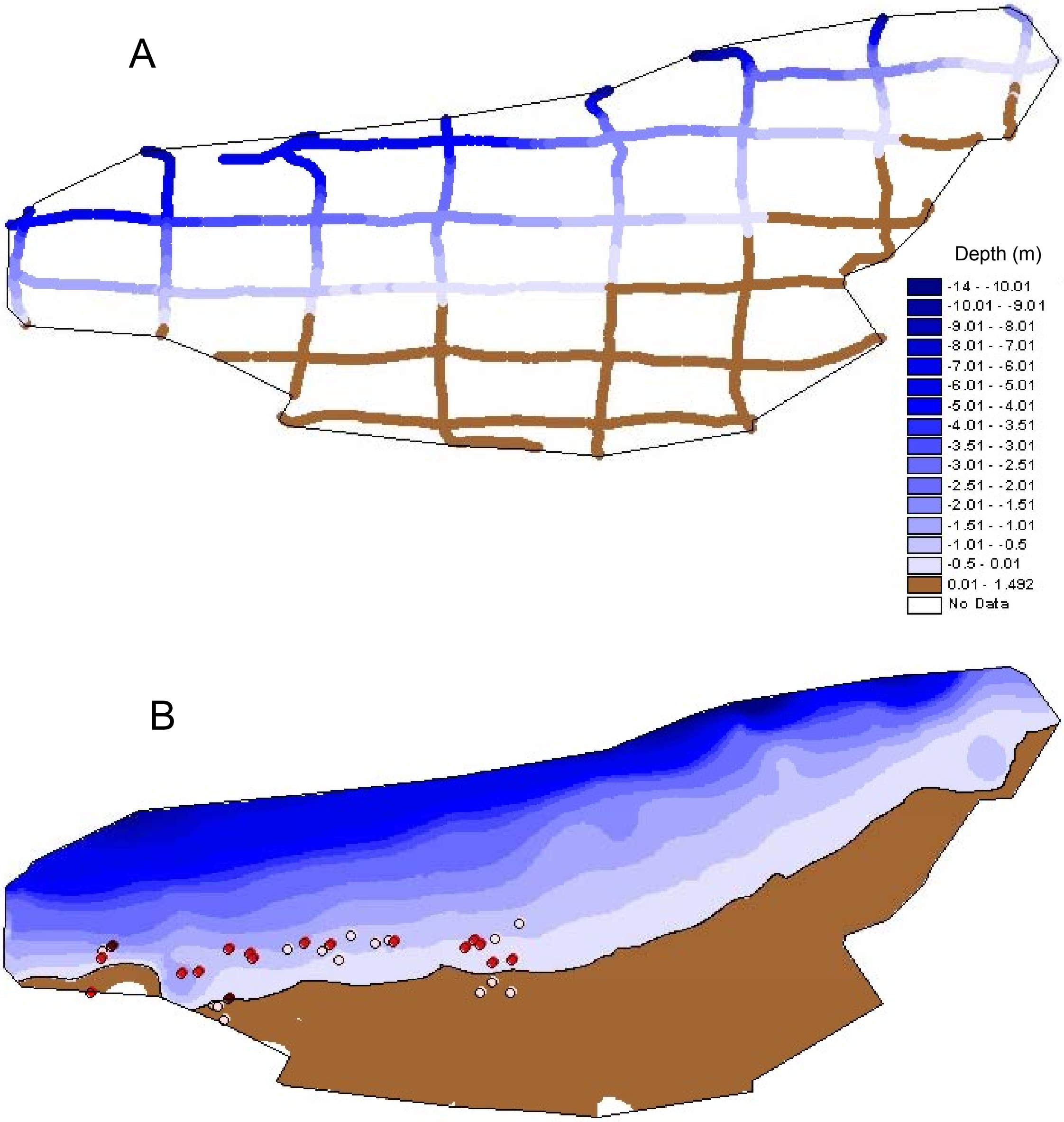


Figure 6. Effect of shoot:root ratio (σ) on daily respiratory demand for whole eelgrass plants. Shoot:root ratios determined by *DNR* Methods 1 and 2, respectively are indicated on the plot.

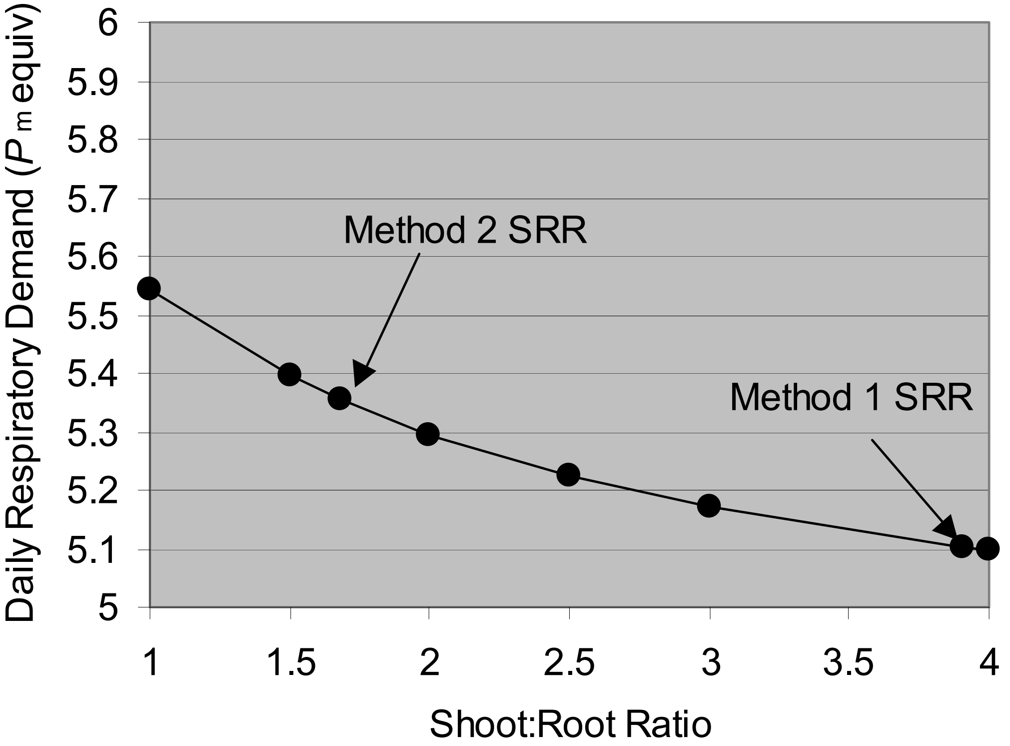


Figure 7. A. Effect of shoot:root ratio on depth distribution of sustainable eelgrass densities for water column conditions indicated in the legend. B. Percent difference in sustainable eelgrass density resulting from uncertainty in shoot:root ratio observed by *DNR* with Methods 1 and 2.

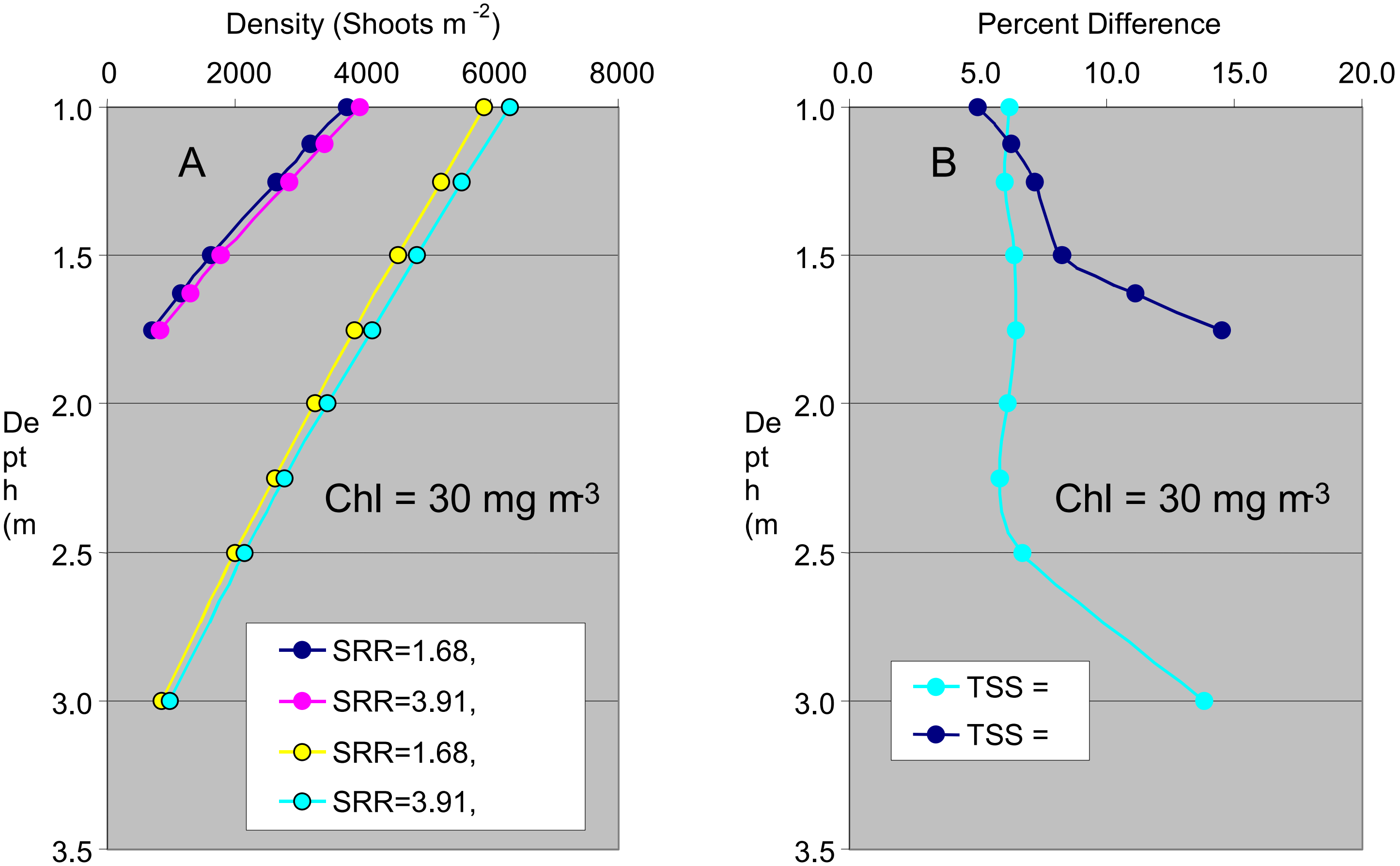


Figure 8. Maximum sustainable density of eelgrass shoots predicted by the biophysical model for different levels of water column [Chl] and TSS].

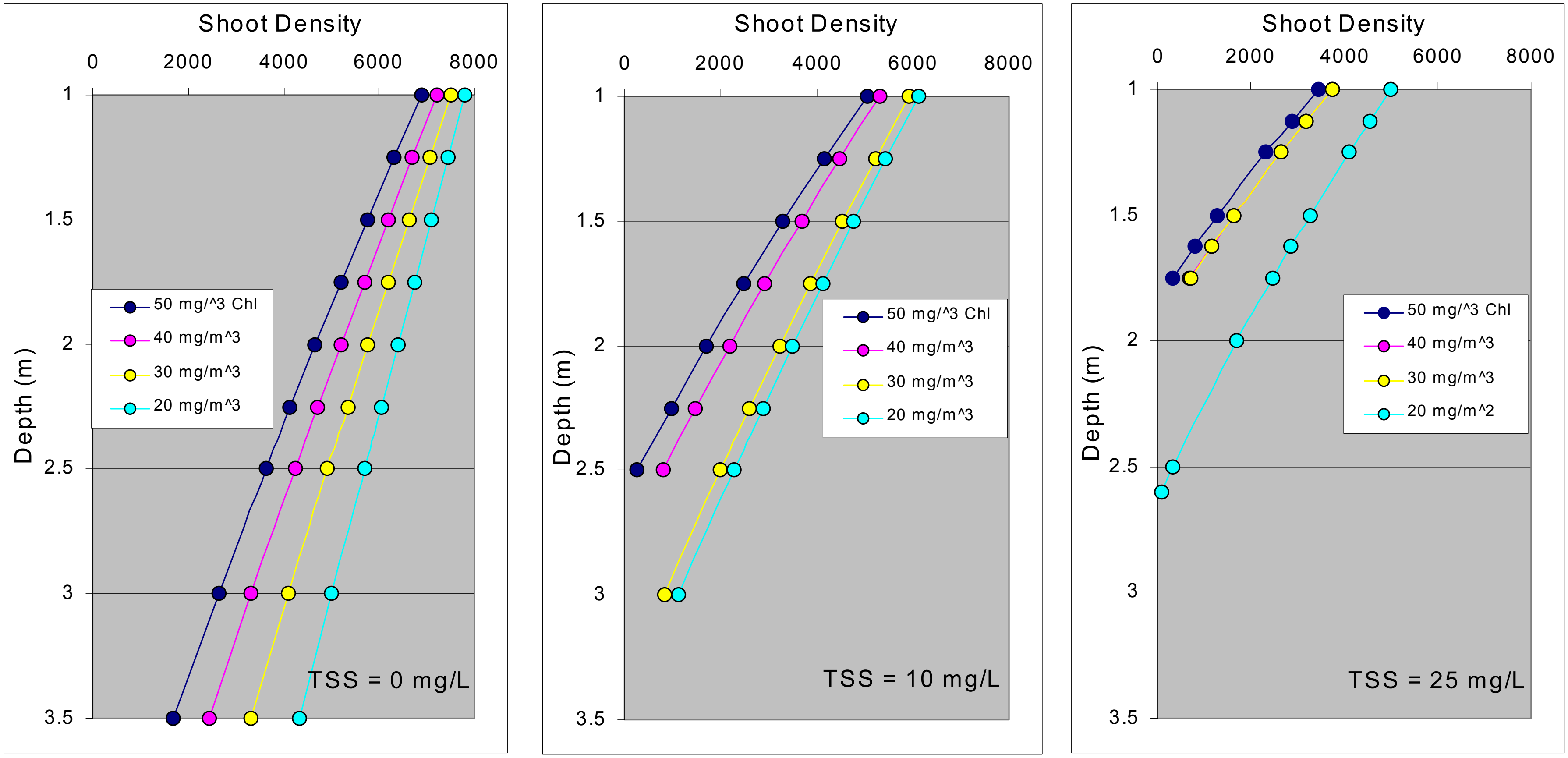


Figure 9. Maps of potential eelgrass distribution at Dumas Bay for A. 50 mg m^{-3} Chl and 25 mg L^{-1} TSS and B. 30 mg m^{-3} Chl and 25 mg L^{-1} TSS. Red dots indicate locations of grab samples with eelgrass, white dots indicate grab samples without eelgrass. Depth contours (blue isopleths) are from Fig. 5.

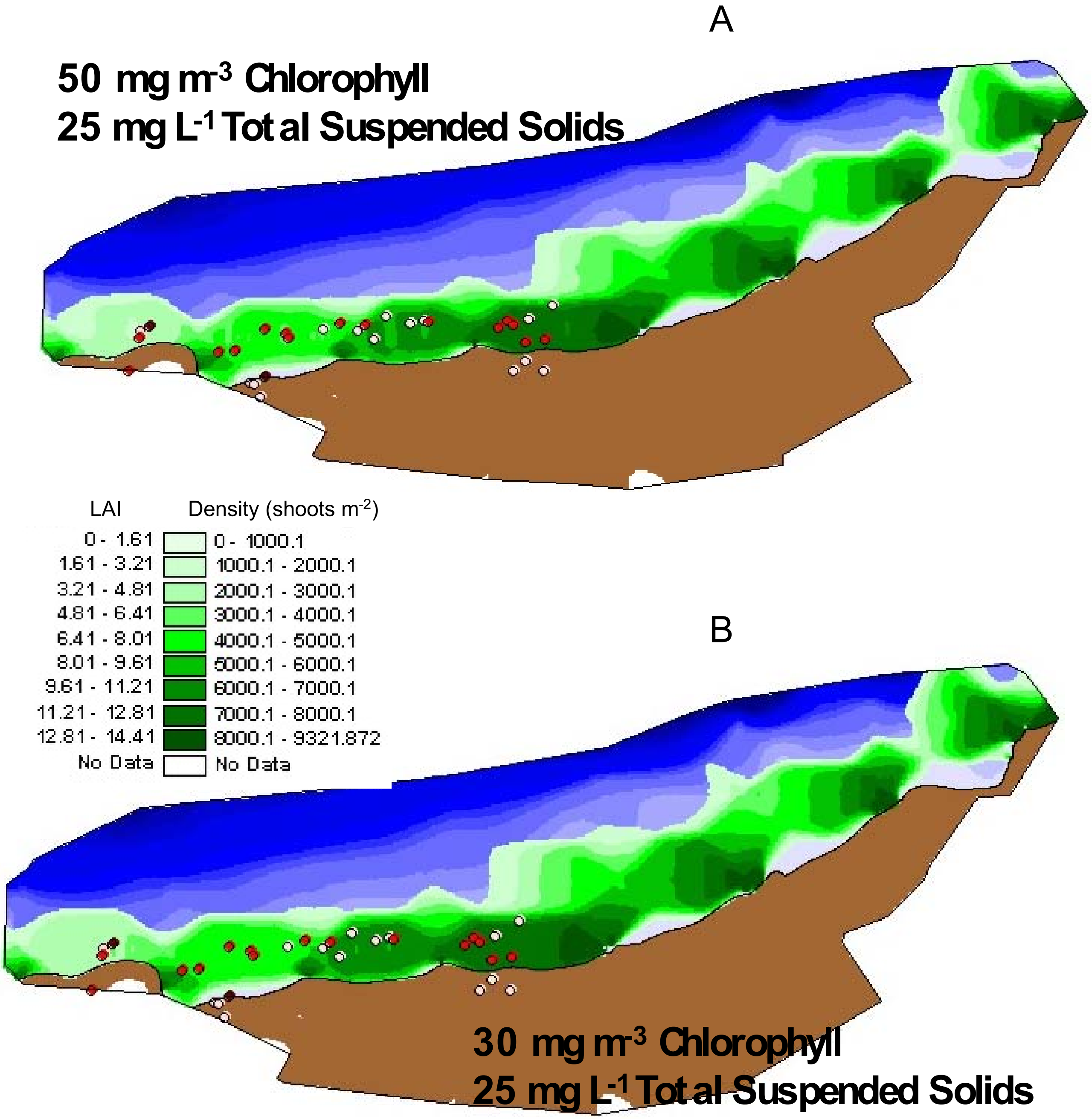


Figure 10. Impact of TSS on potential eelgrass distribution at 30 mg m^{-3} Chl. Red dots indicate locations of grab samples with eelgrass, white dots indicate grab samples without eelgrass. Depth contours (blue isopleths) are from Fig. 5.

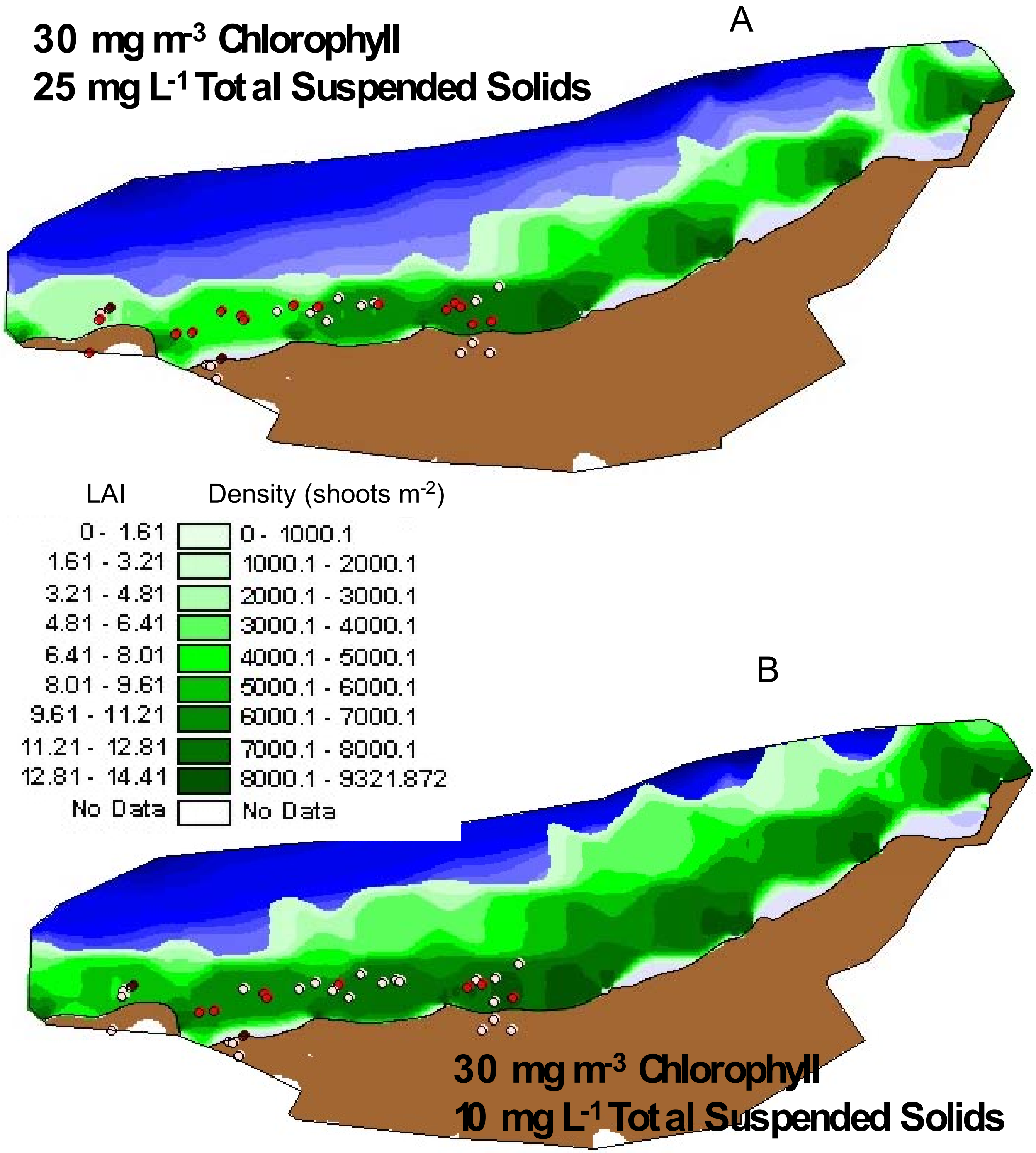
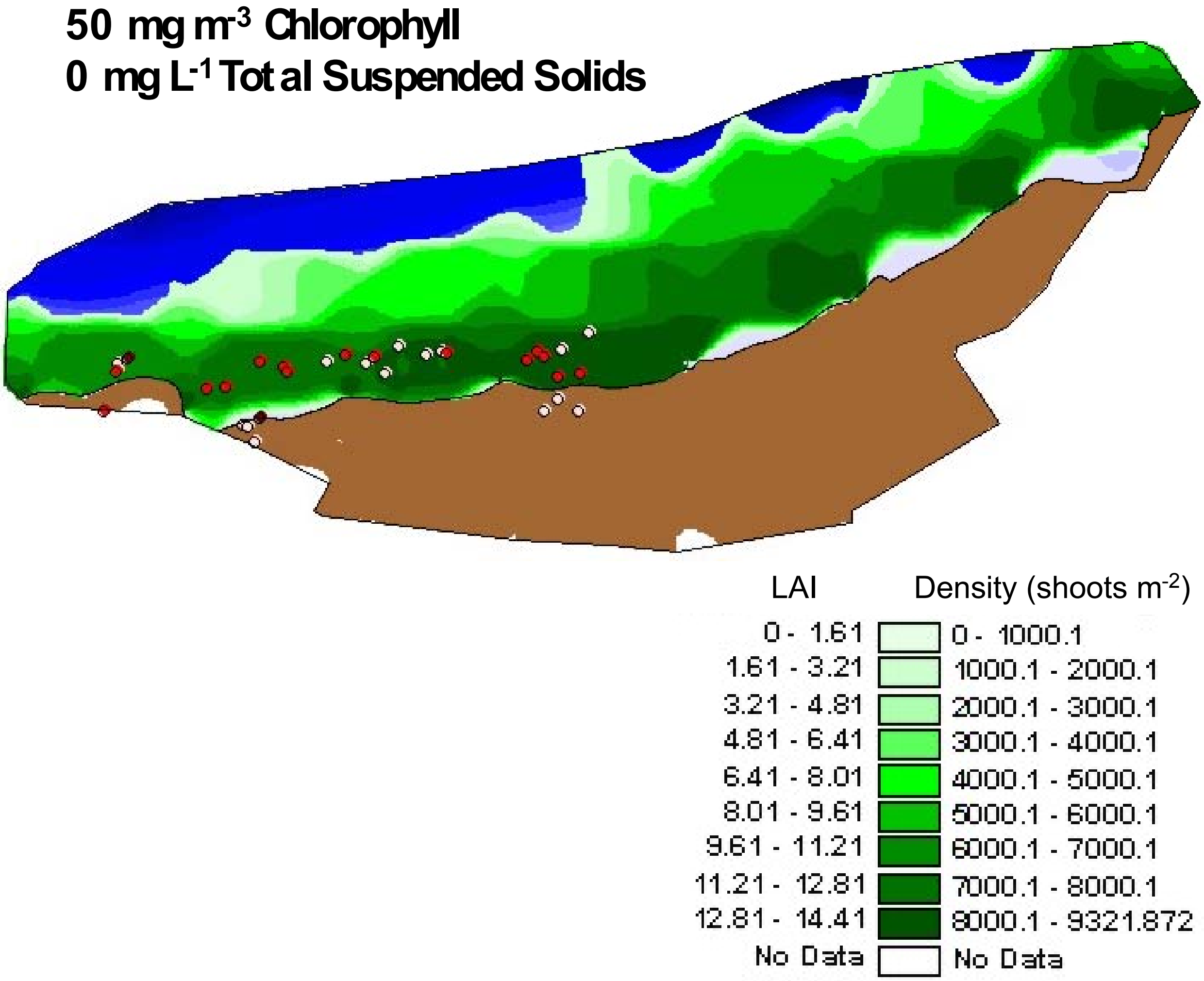


Figure 11. Potential eelgrass distribution under the maximum concentration of Chl but without TSS. Red dots indicate locations of grab samples with eelgrass, white dots indicate grab samples without eelgrass. Depth contours (blue isopleths) are from Fig. 5.



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