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Pacific Northwest Coastal Ecosystems Regional Study

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ANNUAL REPORT

May 2002

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RESEARCH PROJECTS

Interactions Between Human Communities and Biophysical Attributes of Pacific Northwest Coastal Ecosystems Chapter 1

Jessica Leahy, Daniel D. Huppert, Kathleen Bell, and Rebecca L. Johnson

Introduction

Human communities and coastal ecosystems are inextricably linked to each other. Feedback between the socioeconomic and ecological systems occurs in both directions. Human communities impact estuaries through residential, commercial, and recreational use. For example, residential housing development, commercial fisheries, and recreational crabbing impact the functions and processes of ecosystems. Coastal estuaries, in return, can influence human communities. Biophysical attributes of the estuaries near coastal communities can affect what industries are viable, where people live, how property is valued, and what recreation opportunities are available. The Pacific Northwest Coastal Ecosystems Regional Study (PNCERS) aimed to explore the linkages between biological, geophysical, and socioeconomic components of Oregon and Washington coastal estuarine ecosystems using an interdisciplinary research framework.

PNCERS was conducted primarily at five study estuaries: Coos Bay (Coos County), Yaquina Bay (Lincoln County), and Tillamook Bay (Tillamook County) in Oregon, and Willapa Bay (Pacific County) and Grays Harbor (Grays Harbor County) in Washington. The main goals of the PNCERS socioeconomic research were to gain an understanding of the human communities living or recreating in the PNCERS coastal estuaries, and to identify and understand the linkages between the biophysical environment of coastal estuaries and these communities.

To this endeavor, socioeconomic researchers initiated many different projects during the five-year long research study. In this article, five components of the socioeconomic research will be presented. First, the economic trends in the PNCERS area communities are discussed. These trends illustrate the feedback between biophysical attributes on the economies of coastal communities. In one direction, the environmental qualities of the area affect the resource dependency of coastal

economies. In the other direction, different types of economic systems influence the coastal ecosystem depending on whether the industries are consumptive (i.e., fishing) or non-consumptive (i.e., tourism). Next, demographic trends are considered. While these are strongly influenced by the economic system, they also indicate the different types of demands that various groups of people might place on coastal ecosystems. For example, rapid population growth can put pressure on sensitive lands for development, and environmental amenities can become increasingly valuable in the housing market. This connection between land values and the natural features of the coastal communities is explored using a hedonic model that shows how differences in land value can be explained by variations in environmental qualities. It can demonstrate that people do, in fact, place a value on environmental qualities related to estuaries since they are willing to pay more for land that has more abundant, or is nearer to, coastal environmental qualities.

Two specific types of human communities will be explored: residents and recreationists. The focus on residents concerns local resident perceptions of risks to the local environment and perception of changing local communities. The focus on recreationists concerns the connection between estuary-based recreation activities on both the natural features and economies of coastal communities.

Economic Trends in PNCERS Area Coastal Communities

Economic conditions in the PNCERS areas are linked to environmental conditions, as much of the economic activity in these areas rely on natural resources. The economic conditions are also a factor in determining the composition of coastal communities, producing the demographic characteristics discussed later. In all five of the PNCERS area counties, similar economic trends have occurred (Radtke and Davis 1999). Reduced tim-

ber supply and obsolete mills have led to a decline in the timber industry. Fishing has been hampered by reduced abundance and regulations, potentially due to overfishing, and habitat decline in ocean and freshwater environments. Recreation and tourism have been on the rise in all five counties, as is the influx of retirees who bring transfer payments (e.g., social security) into the local economy.

In Oregon, Coos County residents were heavily dependent on the timber and fishing industries. There have been many job losses in the last twenty years due to the decline in these industries. Lincoln County, on the other hand, has had the presence of the recreation/tourism industry for many years alongside timber and fishing industries. Timber employment in Lincoln County has been reduced by 82% in the last twenty years, yet overall employment has grown as a new industry mix has emerged. Employment in fishing has tended to be cyclical in nature. Manufacturing has declined from 20% to 7% of the industry mix over the past twenty years. Tourism accounts for about a quarter of current employment, about the same as twenty years ago (Rooney 2000). Tillamook County is unique from the other PNCERS areas because of the presence of a strong agricultural industry. While timber and fishing have declined in recent years, lumber and food products (dairy and meat) continue to be important in the local economy. Recreation and tourism have also increased in importance.

In Washington, Pacific County has many natural resource based industries including timber, fishing, seafood (oysters and crabs), and food products (meat, dairy, and cranberries). Even though timber and fishing have declined, they are still expected to be the mainstay of the local economy in the future. Grays Harbor County has traditionally been timber and fishing industry dependent. The port in Aberdeen is also Washington's main seaport, which provides opportunities for other

marine industries. The recreation and tourism industry has slowly begun to increase, and timber and fishing are expected to continue to be important to the local economy (Radtke and Davis 1999).

In Oregon, Coos and Lincoln Counties have experienced high unemployment rates (between 7-9%) for most of the 1990s. Tillamook County, however, has had unemployment rates near state levels (5.8%). Unemployment rates in the Washington counties, Pacific and Grays Harbor, are usually much higher than state levels (10.5% vs. 5.9%). Per capita income in the PNCERS areas have historically been lower than state levels. The gap has been increasing in recent years, especially for the Washington PNCERS areas. Radtke and Davis (1999) attribute some economic trends, in part, to resource-based economies. Natural resource harvests, from fishing and timber, are sensitive to shifts in supply and demand of the resources, thus influencing unemployment rates over time.

To understand the reliance of local residents on natural-resource based industries, it was useful to look at the percentage of total personal income that comes from these industries. Five natural resource industries were identified: marine (fishing and other seafood), agriculture, timber, tourism, and "other resource based." The "other resource based" category included sectors such as paper and paperboard mills, water transportation, marine cargo, boat and ship building, and other identifiable state and federal government sectors related to natural resources. In the five counties, the economic reliance on these natural resource based industries range from 21.34 to 37.83%. Many of the economic trends mentioned above can be seen in Table 1.1: Tillamook's major industry is agriculture. Grays Harbor, Pacific, and Lincoln counties all continue to have a high reliance on timber resources, and tourism provides the largest percentage of personal income in Lincoln county compared to tourism in other counties¹.

Table 1.1. Sector percentages of total personal income. Source: Radtke and Davis (1999) and Radtke and Davis (1994).

Sector	Coos County	Lincoln County*	Tillamook County	Grays Harbor County	Pacific County
Marine	2.34%	9.18%	0.95%	3.86%	10.14%
Agriculture	2.50%	0.67%	12.40%	1.22%	2.37%
Timber	6.64%	12.15%	5.97%	11.20%	13.87%
Tourism	3.98%	10.00%	3.76%	3.88%	3.08%
Other Identified	5.88%	5.83%	0.19%	5.56%	0.11%

Demographic Trends in PNCERS Area Coastal Communities

Demographic characteristics and trends in coastal communities can impact the linkages between biophysical and human systems. Population growth trends can indicate emerging demands and predict magnitude of changes in demand on estuaries by human communities. Depending on economic and environmental conditions, different groups of people will be attracted to living in the coastal communities. Diverse groups of people will also place different demands on coastal estuaries, for example, depending on their sources of income or availability of leisure time to pursue recreation.

Population growth rates for the counties in the PNCERS areas tend to fluctuate more than state growth rates. Radtke and Davis (1999) noted that episodes of out-

Table 1.2. Population changes. Source: Portland State University Population Research Center, Washington State Office of Financial Management Forecasting Division.

Area	2001 estimate	% change (1990-2000)
Oregon	3,471,700	20.40
Coos	62,950	4.20
Lincoln	44,650	14.40
Tillamook	24,600	12.50
Washington	5,974,900	21.10
Pacific	21,000	11.13
Grays Harbor	68,500	4.70

migration are especially pronounced in these counties because they are more impacted by downturns in the economy. For example, Coos Bay and Grays Harbor lost 6-8% of their population during the 1980s recession. In the last decade, the coastal counties have been increasing in population, although at less than the overall rate for the states of Oregon and Washington (Table 1.2). For all of the counties, except Grays Harbor, increases in the population are coming from new migrants into the communities and not natural increases. In the

2001 population estimates, the populations of Tillamook and Grays Harbor Counties were growing at a similar rate as the states.

The age distribution of residents in these coastal counties reflects the population changes that have occurred (Table 1.3). Many of the new migrants to these communities are "retirees." In general, there are more people of retirement age, 65 or older, in the PNCERS areas than state averages. Likewise, there tend to be

Table 1.3. Age distribution. Source: Census 2000.

Area	% ≤18 years	Median Age
Oregon	24.7	36.3
Coos	21.9	43.1
Lincoln	21.4	44.1
Tillamook	22.2	43.5
Washington	25.7	35.3
Pacific	21.4	45.8
Grays Harbor	25.7	38.8

Table 1.4. Educational attainment. Source: Census 1990.

Area	High School Graduate (%)	College Graduate (%)
Oregon	53.2	13.4
Coos	51.4	8.4
Lincoln	56.9	11.8
Tillamook	54.0	9.3
Washington	53.8	14.7
Pacific	52.0	7.9
Grays Harbor	48.2	7.1

fewer young people in these communities (Radtke and Davis 1999). Pacific County has the most dramatic difference from the demographic profile of Washington state residents (4.3% less young people, and 11.4% more older people).

Compared to the state demographic profile, the residents of the coastal counties studied have slightly less educational attainment compared to their entire state (Table 1.4). In all counties the percentage of people

¹Information for Coos, Tillamook, Grays Harbor, and Pacific counties originated from Radtke and Davis (1999) using 1995 data. Information on the resource reliance of Lincoln County came from Radtke and Davis (1994) using 1991 data. While this information was not as current, it should be representative of the modern situation. The economic composition of Coos and Tillamook counties were presented in both documents. These counties show a trend of either holding steady or slightly shifting away from resource-based industries. The same can be expected for Lincoln County.

who had graduated college was less than the state average (Radtke and Davis 1999). However, when looking at high school graduates, both Lincoln County and Tillamook County had rates higher than the state of Oregon.

These demographics trends have implications for estuarine management. It appears that the PNCERS areas, in terms of population growth, are slow growing. This implies that there will not necessarily be large increases in the demands placed on coastal ecosystems immediately. New coastal residents are likely to be older "retirees." On one hand, this creates a situation where they bring transfer payments to the community and do not rely on natural resources as a source of income. By this it means that residents are not as directly tied to the extractive industries in terms of employment; they derive their income from other sources. However, they may rely on the natural features of their communities for other reasons, such as scenic beauty, a sense of community character, and recreation.

Land Values and Coastal Ecosystems

Population growth, even at slow rates, increases demand for scarce developable land in coastal areas. Because many of the new residents are drawn to this area because of the natural amenities, properties with good environmental characteristics will be increasingly valuable. The linkages between human communities, and the natural features of the coastal communities can be explored through land values modeling. This method of determining the economic value of non-market goods and services takes differences in land values, or market prices, and determines the amount that can be explained by variations in environmental qualities. People exhibit their value for environmental qualities related to estuaries by being willing to pay more for land that has more abundant, or is nearer to, coastal environmental qualities.

Hedonic land value modeling quantifies the relationships between property prices and physical, ecological, and community variables. Lot size, proximity to an estuary, and proximity to shopping are examples. Past literature has shown that environmental quality influences housing prices (Palmquist 1991). In this model, the objective was to demonstrate the relationship between ecologi-

cal factors, including proximity to the estuary, and the market prices of properties in the PNCERS area. By including physical, ecological, and community variables, it was possible to compare the contribution of the ecological factors with the other variables in determining property values.

To date, a hedonic land value model has been prepared for only one of the PNCERS estuaries, Grays Harbor in Washington. The primary data were residential property transactions. The Grays Harbor County Department of Assessment Taxation provided this information. Between the years of 1994 and 1998, there were 3,108 market transactions. Information about each transaction included date of transaction, price of transaction, acreage of property, and assessed value of structures and improvements. Additional data were used from parcel-level geographic information system (GIS) coverages. These data included land use or type (developed, agriculture, wetland, forest, and water), and distances to major roads, city and town locations, sewage treatment plants, pollution emission sites, superfund sites, the coast, and the estuary. In a hedonic land value model, the price of the transaction was regressed using different functional forms on a set of explanatory variables, which include physical, ecological, and community factors. In this model, three functional forms were used: linear, log-log, and semi-log.

The results from the Grays Harbor hedonic land value model are presented in Table 1.5. The R^2 for all three functional forms were relatively high, indicating that the independent variables explained a large part of the variation in residential property transaction prices. While there were slight differences between each of the functional form results, there were commonalities between them all. First, there was a set of explanatory variables that consistently had a significant positive influence on property values. These were lot size, assessed value of structures and improvements, and proximity to cities and towns. Secondly, there was another set of variables that seemed to have a significant negative influence on property values. These were, not surprisingly, proximity to pollution emission sites, superfund sites, and major roads.

One avenue for discerning the contribution of the ecological resources of the estuary to property values was to evaluate the land use variables related to wetlands and water. In general, the greater the percentage of

Table 1.5. Hedonic land value model results. Parameter estimates, standard errors in parentheses below; *, **, and *** indicate significance at the 0.10, 0.05, and 0.01 levels, respectively.

Dependent Variable : Market Price			
Variable	Linear	Double-Log	Semi-log
Intercept	6145.7671***	3.6275***	10.2456***
	-1392.1782	-0.0584	-0.0251
Lot size	3238.7274***	0.0872***	0.0276***
	-140.811	-0.003	-0.0025
Lot size ²	-25.7367***	-0.0078***	-0.0002***
	-3.2763	-0.0019	-0.0001
Value of Structure	1.0699***	0.7040***	0.000012***
	-0.007	-0.005	0
Distance to CBD	1093.1679***	0.0467***	0.0173***
	-167.8169	-0.0089	-0.003
Distance to CBD ²	-42.3709***	-0.0129***	-0.0006***
	-7.0839	-0.0031	-0.0001
Industrial Emitter	-989.929	-0.0295*	-0.0212
	-1379.688	-0.0173	-0.0248
Hazardous Waste Site (NPL)	-3884.4718***	-0.0551***	-0.0638***
	-1071.9151	-0.0143	-0.0193
Sewage Treatment Plant	150.1682	0.0222	0.0088
	-3459.2757	-0.0433	-0.0622
Percent Developed	5042.9360***	0.0213	0.1352***
	-1549.8887	-0.0185	-0.0279
Percent Agriculture	873.6774	0.0228	0.0631
	-2166.2118	-0.0274	-0.039
Percent Wetland	5325.2507**	0.0323	0.0585
	-2191.6313	-0.0272	-0.0394
Percent Forest	5654.2293**	-0.0031	0.0900**
	-2503.0822	-0.0315	-0.045
Percent Water	4957.5052	0.0060*	0.2102***
	-3653.692	-0.0458	-0.0657
Distance to Major Road	-898.4263***	-0.0025	-0.0187***
	-267.3225	-0.0027	-0.0048
<i>R-squared</i>	0.9027	0.8937	0.7782
<i>F Value</i>	2050.582	1858.884	775.434
<i>Observations</i>	3108	3108	3108

land in wetlands and water use, the greater the market price for property. While not significant in all of the functional form results, these variables were consistently positive and significant in some cases. The value of living near the estuary is represented by these positive variables.

Hedonic land value modeling of Grays Harbor explored the connection between land values and estuaries. Consistently positive and significant values in some functional forms reinforced the fact that human communities place value of the biophysical attributes of coastal

estuaries and other natural features. It appeared that people consider many aspects, including social and biophysical attributes, when purchasing a property.

Residents and Coastal Ecosystems

The values that residents have about the environmental attributes in their coastal communities can be found in housing prices, but there are other ways of determining their values for environmental amenities. For instance, residents' perceptions of the state of their communities

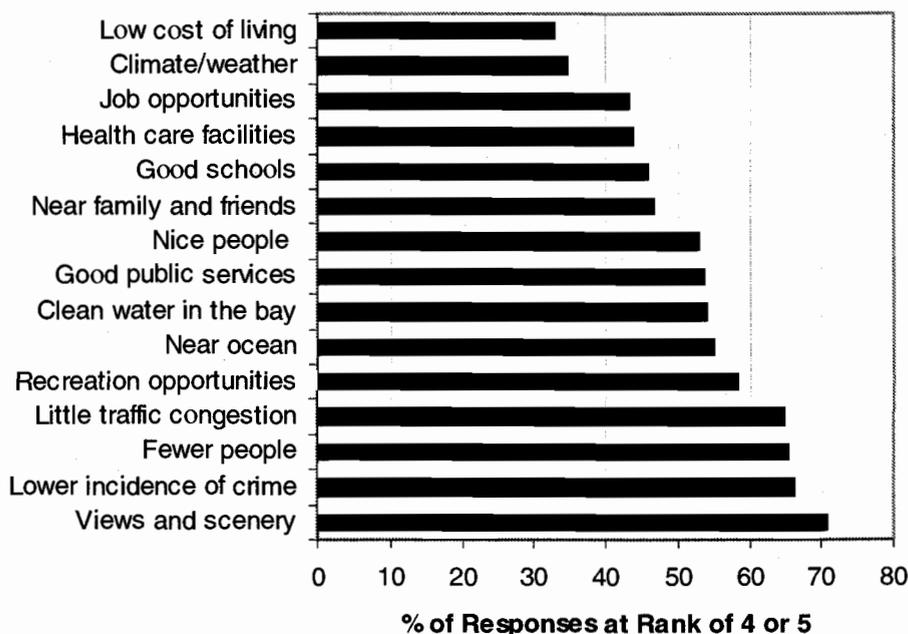


Figure 1.1. Community characteristics rated as very important by coastal residents.

coastal communities, the survey asked each respondent to indicate the importance of 15 characteristics in their decision to live near a bay. Each community characteristic was rated on a scale of 1 (not important) to 5 (extremely important). The percent of respondents who rated each of the fifteen characteristics to be very important (ratings 4 or 5), averaged across all five bays, are indicated in Figure 1.1. Some characteristics viewed as very important by at least a 50% of the respondents pertain to the surrounding environment. These include “views and scenery,” “recreation opportunities,” “being near the ocean,” and “clean water

and estuarine ecosystems reflect important aspects of human communities near estuaries. A partial and exploratory compilation of these perceptions was captured in the Coastal Residents Survey conducted by the PNCERS project. The objectives of the survey were: (1) to assess how residents value specific aspects of their communities and surrounding natural landscapes, and to understand what aspects of the communities and landscapes are perceived as changing — for better or worse; (2) to document the degree to which residents in these areas participate in outdoor recreation activities that are tied to the natural environments of the bays; (3) to determine what the residents think are threats to their local bays; and (4) to understand what management approaches residents prefer and where they acquire information about the management and health of their local bay. During the winter/spring of 2000, mail-back surveys were sent to 5,000 addresses located within 30 miles of the five PNCERS estuaries: Coos Bay, Yaquina Bay, and Tillamook Bay in Oregon, and Willapa Bay and Grays Harbor in Washington. Overall, fifty six percent of the 3,928 surveys successfully delivered were completed and returned. Information pertaining to items (1) and (3) are most relevant to assessing the status of communities.

To assess the importance of various community characteristics in residents’ decisions to live in or move to

in the bay.” Most of the remaining very important characteristics pertain to characteristics typical of rural communities: low crime, low density of people, and low traffic congestion. In addition, respondents were asked to note whether they believe these same community characteristics are getting worse, getting better, or staying the same. The trends perceived by survey respondents, again averaged over the five bays, are depicted in Figure 1.2. For the most part, the communities are getting worse in those aspects relating to economic conditions and congestion: higher housing costs, higher costs of living, more traffic congestion and crime, and fewer job opportunities. Characteristics associated with the bay ecosystems are generally not perceived as changing by a significant portion of the survey respondents. About a quarter of the respondents thought that public services and health care facilities were improving.

Residents’ perceptions about community characteristics were not uniform across the five bays. For example, “Job opportunities” were rated more highly (by more than 10% over the average) in Grays Harbor and Coos Bay, but it was rated highly by fewer residents (by about 7-8%) in Willapa and Yaquina Bays. “Low cost of living” was more highly rated in Grays Harbor and Tillamook Bays. The “climate/weather” rating exhibited a north-south trend, with the lowest importance ratings (about 25%) in Washington and the highest rat-

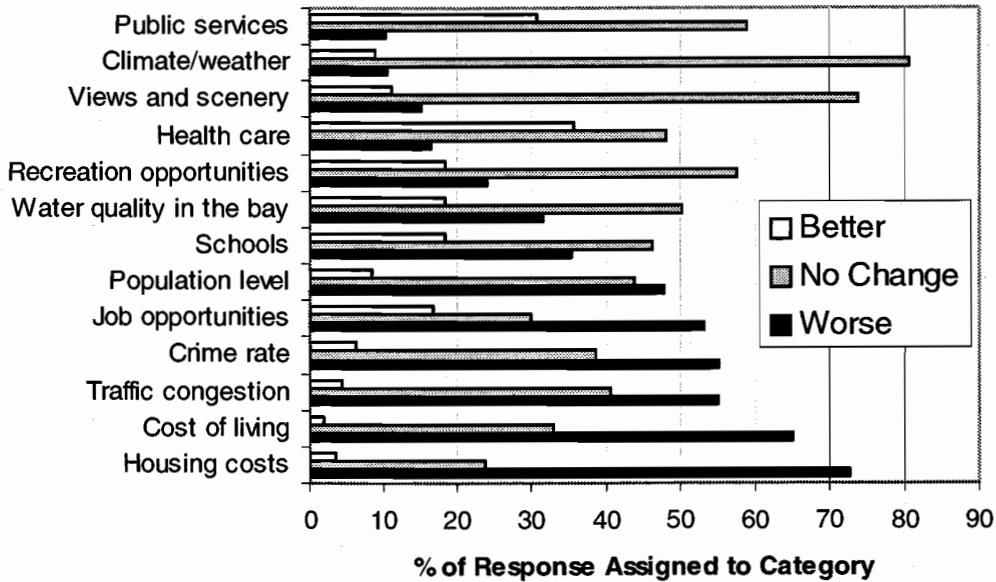


Figure 1.2. Community characteristic categorized as getting worse, getting better, or no change.

ings (53%) in Coos Bay. This latter result may reflect the warmer winters on the southern Oregon coast. Perceptions of trends also differ among bays. Tillamook residents had the greatest perception of worsening crime rate (12% above the average), and Coos Bay had by far the greatest perceived worsening of job opportunities (73% vs. the overall average of 48%). Traffic congestion was perceived less as a worsening problem in Willapa Bay, and much more of an increasing problem in Tillamook and Yaquina Bays. Finally, while water quality was perceived as worsening by 25% of the overall respondents, more Tillamook residents (38%) and fewer

Coos Bay residents (15%) registered this concern. Whether these perceptions accord with actual water quality measurements, or health-related risks, is unclear.

Another indication of residents' perceptions of the bay/estuarine ecosystems was elicited in a question asking the respondent to rate 12 "threats to the bay ecosystem" on a scale of 1 (not a threat) to 5 (extremely severe threat). As shown in Figure 1.3, while none of the indicated threats were rated as very severe (rating of 4 or 5) by even 50% of the respondents, five threats – decline in fish habitat, oil spills, shoreline development

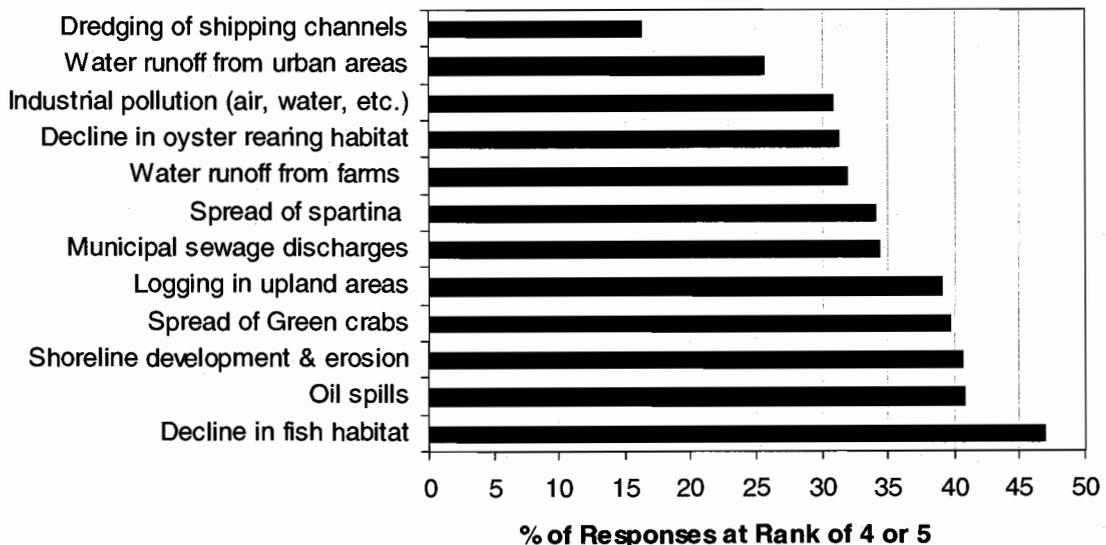


Figure 1.3. Rating of threats to bay ecosystems by coastal residents.

and erosion, the spread of green crabs, and logging in upland areas—were considered very severe threats by roughly 40% or more of the respondents in the five bays. Generally, the threat ratings were uniformly lower in Coos Bay. Further, individual ecosystem threat perceptions varied widely among the bays. For example, the invasive species, green crabs and spartina, were rated as strong threats by over 60% of respondents in Willapa Bay, by about 40% in Grays Harbor, but by only 20 – 33% of residents in the Oregon bays. Upland logging and shoreline development/erosion were most strongly rated as threats in Yaquina Bay and least strongly indicated by Coos Bay residents.

These perceptions concerning community characteristics and bay ecosystems augment the economic and demographic data to provide a more complete picture of human communities surrounding the five Pacific Northwest bays studied. The stagnant economies and slow population growth for most coastal communities are reflected in the perceptions that job opportunities and cost of living are worsening. This is most strongly registered in Coos Bay. Further, the local residents have definite perceptions about threats to the local bay ecosystem and, more specifically, to native salmon runs. Invasive species are considered important threats in those bays that are currently heavily infested, and oil

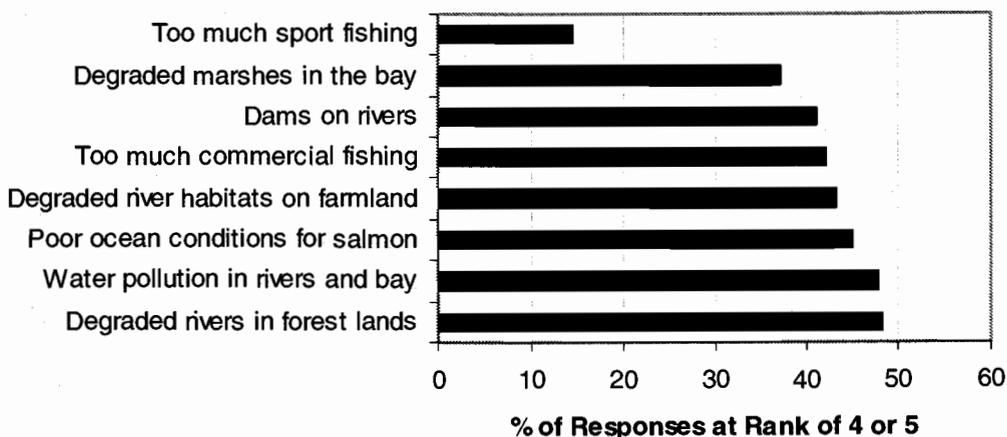


Figure 1.4. Rating of threats to native salmon runs by coastal residents.

Finally, focusing on the plight of native salmon runs, the survey asked residents to rate on a scale of 1 (not important) to 5 (extremely important) several known factors implicated in the decline of salmon stocks. As shown in Figure 1.4, none of the listed factors were rated highly (4 or 5) by 50% or more of the respondents. However, six of the eight causes listed were considered highly important by at least 40% of the respondents from the five bays combined. The most consistently high rating was assigned to degraded river habitats in forest lands—with more than 50% of respondents assigning a high rating, except in Coos Bay where only 38% gave this cause a high rating. Similarly, water pollution in the bay was rated highly by 48 to 58% of respondents from the four bays north of Coos Bay, while only 38% of Coos Bay residents considered water pollution to be a very important cause of salmon decline. Generally, respondents from Coos Bay assigned lower rating to all causes of salmon decline.

spills are rated highly in bays near recent oil spill events. Further, residents hold perceptions that appear well-balanced among the known threats to salmon.

Recreation/Tourism and Coastal Ecosystems

Natural-resource based recreation opportunities abound in Oregon and Washington, especially in coastal areas. These recreation opportunities are important to recreationists, residents, and communities. Recreationists, nonresident tourists and local residents alike, gain welfare and enjoyment from pursuing activities on the coast. Residents and communities benefit from the economic revenue generated by natural resource-based recreation. Recreation also contributes to the character of coastal communities and a sense of place. This aspect of the PNCERS socioeconomic research was focused on better comprehending the connection between coastal rec-

recreation and natural resources, especially estuaries. Specifically, the aim of this study was to understand the nature of recreation demand for different types of activities in estuary areas and to measure the contribution of recreation in estuaries to local coastal economies. To achieve these objectives it was necessary to gather information about recreationists' participation in different types of recreation, preferences for different types of recreation sites, and economic impact from expenditures during recreation trips.

Research interviewers administered a coastal recreation survey on-site from July through September of 2000. Eleven sites in two estuaries (Grays Harbor and Willapa Bay) in Washington and 12 sites in three estuaries (Nehalem, Tillamook, and Yaquina Bays) in Oregon were selected for interview locations. The Washington sample included 260 recreationists, while the Oregon sample contained 140 recreationists. The six-page survey covered the following topics: participation in recreation activities, preferences for recreation sites, visitation patterns to Oregon and Washington, information about the current recreation trip including trip expenditures, and demographics. Sites were chosen to achieve a broad representation of recreation sites that were available in the PNCERS estuaries. Fishing was not specifically addressed because that would have duplicated the coverage provided by the NOAA Marine Recreation Fisheries Statistics Survey (MRFSS). The MRFSS study, along with tourism studies conducted by Dean Runyan and Associates (2000a and 2000b) for Oregon and Washington, provide sources with which to compare our estuary recreation results.

In many respects the demographic and visitation patterns of Oregon and Washington coastal recreationists were similar (Tables 1.6 and 1.7). Sixty-four percent of the Oregon respondents were male, while in Washington there was a nearly even division between male and female recreationists. The mean age for both the Oregon and Washington samples was in the early 40s. The majority of respondents (82-84%) were visiting the coast of their home state. Both samples had an average household size of approximately three people, and both samples were

highly educated, with more than 50% having attained a college degree. Finally, retirees comprised a significant portion of the respondents (21% in Oregon and 15% in Washington).

Oregon and Washington respondents were fairly active participants in coastal recreation (Table 1.7). In the summer prior to being contacted, Oregon recreationists said

Table 1.6. Demographic results from the Coastal Recreation Survey.

	Oregon	Washington
Male (%)	63.9	46.9
Age (avg. years)	42.7	39.8
Household Size (avg. people)	2.8	2.7
In-State Resident (%)	82.2	84.2
<i>Educational Background</i>		
Some High School (%)	3.0	5.4
High School Diploma (%)	16.7	23.2
Some College (%)	29.5	23.2
College Diploma (%)	34.8	39.8
Post-Graduate (%)	12.1	8.1
<i>Employment Status</i>		
Student (%)	3.8	8.5
Employed Full-Time (%)	41.2	55.0
Employed Part-Time (%)	22.9	14.6
Retired (%)	20.6	15.0
Unemployed (%)	3.8	2.3
<i>Income</i>		
Under \$10,000 (%)	5.8	0.8
\$11,000 - \$30,000 (%)	21.7	28.3
\$31,000 - \$50,000 (%)	23.3	36.5
\$51,000 - \$100,000 (%)	35.9	29.9
Over \$100,000 (%)	13.3	4.5
	N=140	N=260

Table 1.7. Visitation/trip results from the Coastal Recreation Survey.

	Oregon	Washington
<i>Visitation Levels</i>		
Trips to Coastal WA during previous summer (avg. trips)	0.68	6.94
Trips to Coastal OR during previous summer (avg. trips)	10.40	1.26
Repeat Visitor to Coast (%)	94.80	86.30
<i>Trip Length</i>		
Day-trip (%)	49.60	40.40
Time at recreation site (avg. hrs)	8.00	2.78
<i>Catch Levels</i>		
Crab Catch (avg. # of crabs)	6.20	--
Clam Catch (avg. # of clams)	7.70	--
	N=140	N=260

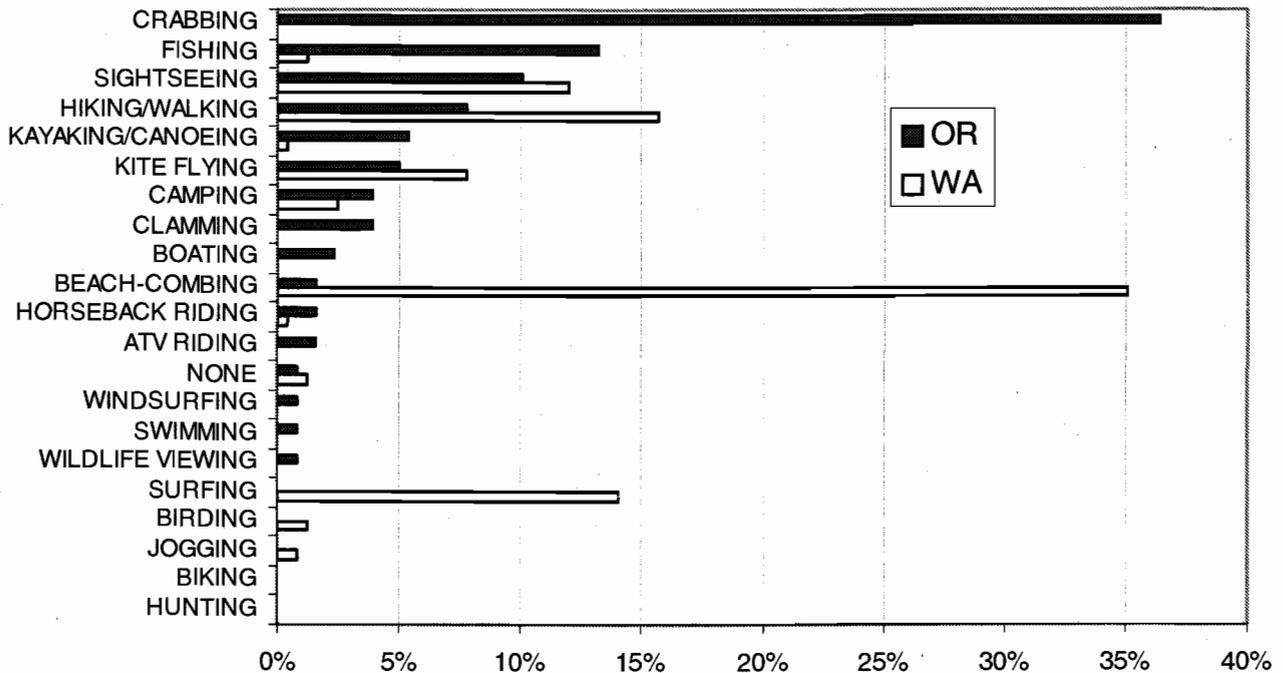


Figure 1.5. Recreation participation results from the Coastal Recreation Survey.

that they took an average of 10 trips to the Oregon coast and 1 trip to the Washington coast. Likewise, Washington respondents reported taking an average of 7 coastal Washington trips the summer before, and 1 trip to the Oregon coast. Respondents were quite familiar with, or repeat visitors of, the recreation site where they were contacted. Ninety-five percent of Oregon respondents and 87% of Washington respondents had previously visited the recreation site before. Finally, respondents were asked about the length of their trip. In Oregon, 50% were on a day trip, while in Washington, this percentage was slightly lower (40%).

Recreation participation, in terms of activities engaged in, at sites in coastal Oregon and Washington was quite different (Figure 1.5). In this recreation survey, Oregon recreationists were found evenly on both outer coastal beaches and on inner estuary areas. However, in Washington the majority of the recreationists were found on the outer coastal beaches. Furthermore, many of the most common recreation activities pursued by respondents in Oregon were resource dependent, such as crabbing, clamming, boating and wildlife viewing. Washington visitors were more likely to be engaging in less resource-dependent activities. These activities were beach combing, sightseeing, and walking. The differences in recreation activity participation were likely due to a combination of biophysical attributes and social in-

frastructure. The estuaries differ in terms of size, depth, and bottom characteristics, thus influencing the types of opportunities that are available. Furthermore, social infrastructure and the spatial distribution of roads, parking lots, and developed sites can influence the types of recreation activities available.

Differences in site preference factors were also present between Oregon and Washington respondents (Figure 1.6). Site preference factors were divided into three groups: site infrastructure (i.e., parking, boat ramps), social influence (i.e., favorite place, convenient), and environmental characteristics (i.e., good fishing, good crabbing). In both states, the individual factors of convenience and good facilities rated highly important as reasons for visiting a particular site. Oregon recreationists mentioned environmental characteristics as a factor in their decision 51% of the time (Table 1.8). This included such responses as good crabbing, good fishing, and good views. Washington recreationists, on the whole, mentioned social influences most often (51%).

Site preferences differed by type of recreation activity (Table 1.8). Respondents were grouped into three categories depending on their primary activity at the recreation site: active (surfing, horseback riding, ATV riding, etc.), passive (sightseeing, beach combing, camping, etc.), and consumptive (crabbing, clamming, fishing,

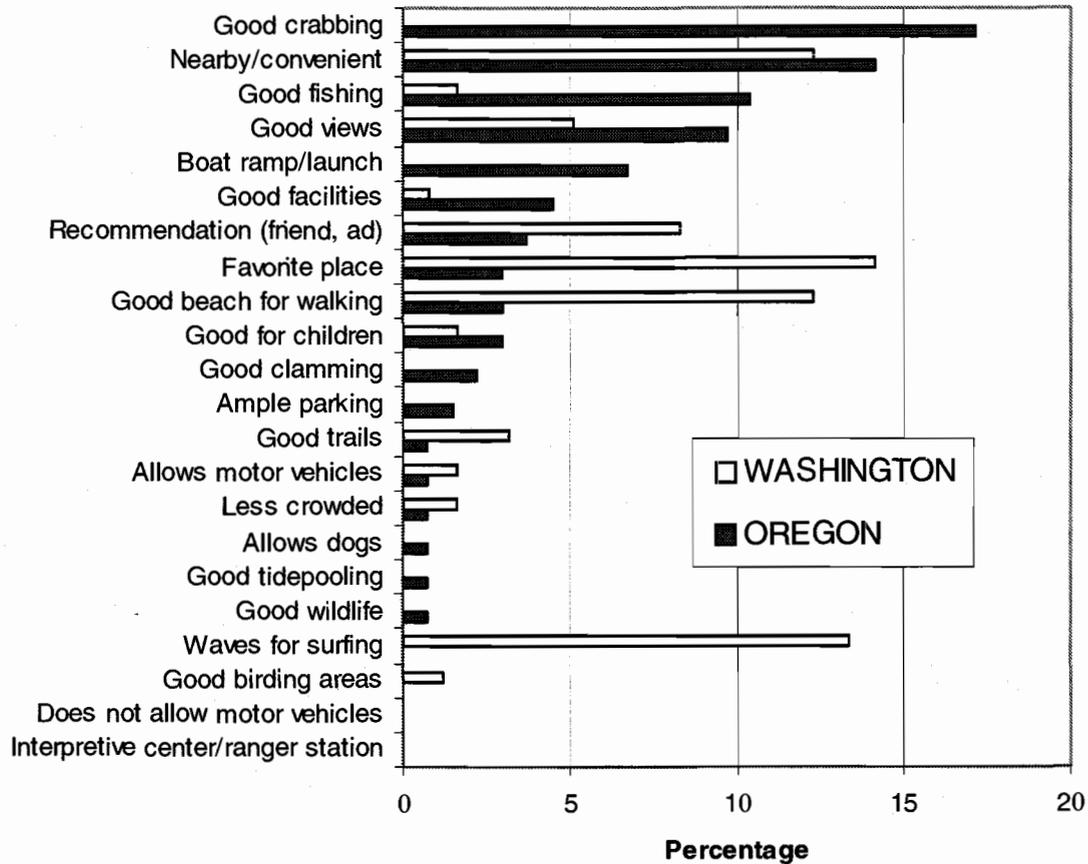


Figure 1.6. Site preference results from the Coastal Recreation Survey. Respondents selected one most important site factor which influences their decision to visit the recreation site.

etc.). In Oregon, people engaged in active recreation were evenly divided between infrastructure and environmental characteristics as the primary reason for visiting the recreation site. Passive recreationists tended

Table 1.8. Site preference by activity type from the Coastal Recreation Survey.

Type of Activity	Primary Site Preference		
	Infrastructure	Social Influence	Environmental Characteristics
Active			
OR	37.5%	25.0%	37.5%
WA	0.0%	2.9%	97.1%
Passive			
OR	22.6%	51.6%	25.8%
WA	24.4%	64.1%	11.5%
Extractive			
OR	10.2%	23.7%	66.1%
WA	50.0%	0.0%	50.0%
Overall			
OR	16.3%	32.7%	51.0%
WA	19.8%	50.9%	29.3%

to cite social influences (58%), while consumptive recreationists were likely to mention environmental characteristics (66%) as the primary site factor. Results were slightly different in Washington. Active recreationists were strongly influenced by environmental characteristics (97%) in their site preferences. Passive recreationists in Washington were similar to the Oregon sample in listing social influences as a primary factor for using the recreation site. Finally, consumptive recreationists were evenly divided between infrastructure and environmental characteristics of the site.

Coastal recreationists can have significant economic impacts in local communities. The first step in determining the economic impact of estuary-based recreation in coastal Oregon and Washington was to collect trip expenditure information (Table 1.9). Oregon recreationists reported spending an average of \$193.23 in the local area per group per day (range: \$0-2900) on the recreation trip. In Washington, the average trip expenditure was \$148.54 (range: \$0-1090). Groceries, restaurants and taverns, and lodging accounted for the ma-

Table 1.9. Average local trip expenditures by estuary-based recreationists.

Category	Oregon		Washington	
	Average	Range	Average	Range
Recreation Activity-Related Equipment	\$25.50	\$0-500	\$7.62	\$0-100
Gasoline	\$30.66	\$0-1000	\$14.26	\$0-125
Groceries (Food and Beverage)	\$39.28	\$0-700	\$22.27	\$0-200
Restaurants/Taverns	\$27.63	\$0-500	\$37.00	\$0-240
Lodging	\$48.84	\$0-1100	\$54.46	\$0-450
Retail Shopping	\$12.63	\$0-500	\$7.87	\$0-150
Licenses/Permits	\$1.17	\$0-30	\$0.27	\$0-38
Entrance Fees	\$4.23	\$0-100	\$0.12	\$0-30
Other	\$3.29	\$0-200	\$4.67	\$0-800
Total	\$193.23	\$0-2900	\$148.54	\$0-1090

majority of trip expenditures. These values are slightly higher than those reported in travel impact analyses for Oregon and Washington (Dean Runyan and Associates 2000a and 2000b). The average travel expenditure for pleasure travelers in Oregon in 1997 was \$122 per party per day. In Washington, this average expenditure was \$105.91 per party per day. The Oregon Tourism Commission figures are from all types of pleasure travelers, not just natural resource-based recreationists. It was also possible to compare the PNCERS trip expenditures to those from the MRFSS Angler Expenditures 2000 Survey (Gentner et al. 2001). The MRFSS surveyed marine anglers, and would not include all recreation activities that may be occurring in an estuary. In Oregon, the MRFSS average trip expenditure (\$96.74) was less than the PNCERS result. However, in Washington, the results were opposite; the MRFSS average expenditures were a much higher \$202.99.

These results from the Coastal Recreation Survey augment the socioeconomic data and Coastal Resident Survey to provide a more complete picture of human communities in the PNCERS coastal ecosystems. The survey provided information about coastal recreationists and their visitation patterns, activity participation, and site preferences. Results also indicated that recreationists spend a significant amount of money in local coastal communities while participating in estuary-based recreation activities. In addition to this, analysis revealed that coastal recreation in Oregon and Washington is quite diverse. Recreation participation on the Oregon and Washington coast is not the same, perhaps

caused by the biophysical conditions of the estuaries or demographic trends affecting these areas. These different uses suggest that there may be different linkages between recreationists and the coastal environments in Oregon and Washington.

Discussion and Conclusion

These five projects, which touched upon the economic trends, demographic trends, land values, resident perception, and recreation impacts of human communities in Pacific Northwest coastal ecosystems, all concern the interactive role of humans in the dynamics of estuary environments.

The local economies in the five PNCERS areas had a similar structure, history, and trends. There has been a movement away from extractive natural resource industries and other manufacturing, while tourism, retail, services, and transfer payments are increasing. Demographic changes also were similar in the five coastal counties, especially in terms of “retirees” comprising the majority of population growth. Results from the hedonic land value modeling, resident survey and recreation survey supplement our understanding of the socioeconomic baseline of these five coastal counties. The hedonic land value modeling results indicated that coastal estuaries and other natural features positively influence market prices for residential properties. The resident survey showed that residents were aware of economic and demographic trends, and possessed perceptions concerning resource conditions including declining salmon runs. The recreation survey concerned both the use of coastal environments by recreationists, which differs between states, and the economic impacts of recreationists on local coastal communities. Future data analysis plans include completing hedonic land value models for additional coastal communities near PNCERS estuaries, weighting the Coastal Resident Survey with newly released Census information, and integrating economic impact results from other coastal tourism projects with PNCERS data.

As stated earlier, the main goal of the socioeconomic research component of PNCERS was to analyze the linkages between the biophysical aspects of coastal estuary ecosystems and the human aspects of communities, recreation, and management. Through develop-

ing knowledge of demographic and economic trends, connections between property values and estuaries, resident perceptions of risks and changes to coastal environments, and interactions between recreationists with the estuary resource and communities, we have a better picture of the interactions between the residents, recreationists, and the biophysical coastal environment. This information, in particular, will help natural resource managers make more informed decisions. Improved knowledge of human values and behavior will enable us to better understand future socioeconomic dynamics, anticipate likely human interactions with the biophysical environment of coastal estuaries (both positive and negative), and facilitate effective management of the coastal ecosystems and marine resources of the Pacific Northwest.

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Applications

Publications:

Bell, K., R. Johnson, D. Huppert, and C. Farley. 2001. Coastal Resident Survey Basic Summary of Responses: Coos Bay, Coos County, Oregon.

Bell, K., R. Johnson, D. Huppert, and C. Farley. 2001. Coastal Resident Survey Basic Summary of Responses: Yaquina Bay, Lincoln County, Oregon.

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Presentations:

Daniel Huppert, "Summary of Findings from the PNCERS Coastal Resident Survey." PNCERS Eat and Learn Seminar Series, January 17, 2001, University of Washington, Seattle, WA.

Rebecca Johnson, "Importance of biophysical attributes on PNCERS residential location decisions" PNCERS Eat and Learn Seminar Series, February 14, 2001, University of Washington, Seattle, WA.

Daniel Huppert, Rebecca Johnson, Kathleen Bell, Jessica Leahy, and Chris Farley, "Assessing the Status of Human Communities on Pacific Northwest Estuaries." PICES X Annual Meeting, October 9, 2001, Victoria, B.C., Canada.

Rebecca Johnson, Kathleen Bell, Daniel Huppert, and Jessica Leahy, "Importance of biophysical attributes on

coastal residents' location decisions." Poster presentation at PICES X Annual Meeting, October 10, 2001, Victoria, B.C., Canada.

Workshops:

Rebecca Johnson, Chris Farley, Daniel Huppert, and Kathleen Bell attended the PNCERS All-Hands Meeting, January 11-12, 2001, University of Washington, Seattle, WA.

Partnerships:

Melissa O'Neill, Communications Manager, Washington Sea Grant. Socioeconomic research team supplied Washington Sea Grant with mailing lists of coastal residents to distribute summary report of Grays Harbor and

Willapa Bay workshops. Washington Sea Grant is preparing publications of coastal resident surveys for socioeconomic research team.

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Oceanography of the Pacific Northwest Coastal Ocean and Estuaries with Application to Coastal EcosystemsChapter 2

Barbara M. Hickey

Introduction

In this paper recent results on the physical oceanography of the U.S. Pacific Northwest (PNW) coastal region are integrated with new information on ecosystem variation. The coastal region important to the regional ecosystem includes both the nearshore zone and the coastal estuaries. These regions may be utilized by different species or for different life stages. For example, many Dungeness crab utilize coastal estuaries for the first year of their life, reentering the ocean to become part of the fishery as juveniles. Salmon, on the other hand, utilize the estuary at both the beginning and end of their life cycles.

As we will demonstrate, ocean variability in nearshore regions of the U.S. west coast and, in particular, its coastal estuaries, are distinctly different than estuaries and nearshore regions of the U.S. east coast. The West Coast is embedded within an Eastern Boundary Current System; the East Coast is embedded within a Western Boundary System. Thus, whereas the west coast is dominated by upwelling, the east coast is not; whereas upwelling provides plentiful nutrients to the coast and its estuaries, on the East coast nutrients are more commonly supplied by river outflow.

Ocean variability along the West Coast is generally very large scale, a result of large scale atmospheric systems. Nevertheless, we will show that smaller scale features may play important and even critical roles in ecosystem function.

In many ways, coastal estuaries in the PNW may be considered as extensions of the coastal ocean. Thus, like the ocean processes, variability from place to place in the growing season may be very similar, although absolute values of water properties will differ depending on the estuary configuration.

In the following, the large scale processes acting on the PNW coastal zone are first described. This is followed by a discussion of nutrient variability. Within this setting, the effects of important mesoscale features such

as submarine banks, canyons, and river plumes are presented. Last, the interaction of the coastal ocean with the coastal estuaries is described.

Large scale processes in the Pacific Northwest coastal ocean

The U.S. Pacific Northwest coastal zone is embedded within the California Current System, a system of currents with strong interannual, seasonal, and several day (event) scale variability (Hickey 1998). The California Current System (CCS) includes the southward California Current, the wintertime northward Davidson Current, the northward California Undercurrent, which flows over the continental slope beneath the southward upper layers, as well as "nameless" shelf and slope currents with primarily shorter-than-seasonal time scales. The PNW includes one major river plume (the Columbia), several smaller estuaries, and numerous submarine canyons (primarily in the north). The dominant scales and dynamics of the circulation over much of the CCS are set by several characteristics of the physical environment; namely, 1) strong winds; 2) large along-shore scales for both the winds and the bottom topography; and 3) a relatively narrow and deep continental shelf. Because of these characteristics, coastal-trapped waves (disturbances that travel northward along the shelf and slope) are efficiently generated and propagate long distances along the continental margins of much of western North America. Thus, much of the variability in the PNW is caused by processes occurring southward of the region. On several day time scales waves are created by gradients in alongshore wind stress, with contributions coming predominantly from northern California (Battisti and Hickey 1984). El Niño is the best known example of remotely forced feature on the interannual scale, producing enhanced northward flow in the PNW and warmer temperatures.

The California Current flows southward year-round offshore of the U.S. west coast from the shelf break to a distance of 1000 km from the coast. The current is strongest at the sea surface, and generally extends over

the upper 500 m of the water column. Seasonal mean speeds are $\sim 10 \text{ cm s}^{-1}$. The California Current carries colder, fresher Subarctic water southward along the coast. The California Undercurrent is a relatively narrow feature ($\sim 10\text{--}40 \text{ km}$) flowing northward over the continental slope of the CCS at depths of about 100–400 m as a nearly continuous feature, transporting warmer, saltier Southern water northward along the coast. The Undercurrent has a jet-like structure, with the core of the jet located just seaward of and just below the shelf break and peak speeds $\sim 30\text{--}50 \text{ cm s}^{-1}$. A southward undercurrent (the “Washington Undercurrent”) occurs over the continental slope in the winter season in the PNW (Werner and Hickey 1984; Hickey 1989). This undercurrent occurs at deeper depths than the northward undercurrent ($\sim 300\text{--}500 \text{ m}$). The existence of this undercurrent, like that of the northward undercurrent, likely depends on the co-occurrence of opposing wind stress and alongshore pressure gradient forces. The Davidson Current flows northward in fall and winter from Point Conception ($\sim 35^\circ \text{ N}$) to at least Vancouver Island (50° N). This northward flow is generally broader ($\sim 100 \text{ km}$ in width) and sometimes stronger than the corresponding subsurface northward flow in other seasons (the “Undercurrent”) and extends seaward of the slope. Northward shelf flow, in the sense of a monthly mean phenomenon, is sometimes described as an expression of “The Davidson Current”.

Currents and water properties of the CCS both over the shelf and in the region offshore of the shelf undergo large seasonal fluctuations. The southward flowing California Current and the northward flowing California undercurrent are strongest in summer to early fall and weakest in winter. The northward flowing Davidson Current is strongest in winter. Shelf currents are generally southward in the upper water column from early spring to summer and northward the rest of the year. The seasonal duration of southward flow usually increases with distance offshore and with proximity to the sea surface. A northward undercurrent is commonly observed on shelves during the summer and early fall. A strong tendency for northward flow throughout the water column exists over the inner shelf in all but the spring season. Off the coast of Vancouver Island a northward flowing buoyancy current exists year-round (the Vancouver Island Coastal Current) (Thomson 1981). This current opposes the southward shelf break jet current that connects to flow off the Washington shelf.

The transition of currents and water properties over the shelf and slope between winter and spring, the “Spring Transition”, is a sudden and dramatic event in the CCS. Along much of the coast, during the transition, sea level drops at least 10 cm, currents reverse from northward to southward within a period of several days and isopycnals slope upward toward the coast. The transition is driven by changes in the large scale wind field and these changes are a result of changes in the large scale atmospheric pressure field over the CCS. The transition includes both a local and a remotely forced (i.e., a disturbance that is forced by winds farther south and then travels northward as a wave) response to the change in wind conditions. A similar rapid transition between summer and fall oceanic characteristics does not occur.

Variability on Shorter-than-Season Time Scales

Seasonal conditions are often reversed for shorter periods of time in the PNW. Fluctuations in currents, water properties, and sea level over the shelf at most locations are dominated by wind forcing, with typical scales of 3–10 days. During periods of fair weather the stress of the southward winds at the sea surface accelerates the coastal currents, producing offshore and alongshore directed currents in the surface Ekman layer (45 degrees to the right of the wind), and alongshore currents elsewhere in the water column (geostrophically balanced with the cross-shelf sea surface height). Plumes of fresher water originating at coastal estuaries tend to spread offshore and to the south. Upwelling occurs within a few kilometers of the coast (typically, within one Rossby radius). During periods of poor weather the patterns reverse and freshwater plumes move back onshore.

In contrast to regions off southern Oregon and northern and central California, regions seaward of the shelf are not strongly dominated by jets and eddies. Satellite-derived patterns of sea surface temperature show only one region where upwelling appears to be enhanced off the Washington coast. Thus, the mid-shelf, mid water column, along shelf flow are primarily wind-driven and can be predicted with models that have been made available to the research community. However, the amplitude of current fluctuations is generally underpredicted, and the amount of variance predicted decreases toward the shelf break (Battisti and Hickey 1984). Predictive capability, and, therefore, understand-

ing, of both temperature fluctuations and cross-shelf flow is very poor at the present time. The alongshelf currents include a response to both local and remote wind forcing. At any given time and location, the ratio of remote and local forcing varies. In winter, local wind forcing dominates, especially in regions where winter storms are accompanied by strong northward winds that increase in the direction of propagating waves. In summer, free waves are more dominant in the Pacific Northwest, particularly at more northern latitudes and off the British Columbia coast (Hickey et al. 1991).

Nutrient supply in the Pacific Northwest coastal zone

The CCS contains waters of three types: Pacific Subarctic, North Pacific Central and Southern (sometimes termed "Equatorial"). Pacific Subarctic water, characterized by low salinity and temperature and high oxygen and nutrients, is advected southward in the CCS. North Pacific central water, characterized by high salinity and temperature, and low oxygen and nutrients, enters the CCS from the west. Southern water, characterized by high salinity, temperature and nutrients, and low oxygen, enters the CCS from the south with the northward undercurrent. In general, salinity and temperature increase southward in the CCS and salinity also increases with depth.

Upwelling along the coast brings colder, saltier, and nutrient richer water to the surface adjacent to the coast. In general, the strength and duration of upwelling (as seen at the sea surface) increases to the south in the PNW. Maximum upwelling occurs in spring or summer at most latitudes. Stratification in the CCS is remarkably similar at most locations and is largely controlled by the large-scale advection and upwelling of water masses as described above.

In contrast to most East Coast environments, the shelf is relatively narrow, so that nutrient-rich deeper water can be effectively brought to the surface by the wind-driven upwelling that occurs in the growing season along the entire coastal boundary. In contrast to most East Coast coastal areas, nutrient input from coastal rivers is negligible except in the associated estuary and right at the river mouth. Both seasonal and event-scale patterns of all nutrients on the continental shelf are domi-

nated by seasonal and event-scale patterns in the upwelling processes (Landry et al. 1989; Hickey 1989). Wind-driven upwelling of nutrients from deeper layers fuels coastal productivity, resulting in both a strong seasonal cycle and several day fluctuations that mimic changes in the wind direction and, hence, upwelling. During an upwelling event, phytoplankton respond to the infusion of nutrients near the coast and this "bloom" is moved offshore, continuing to grow while depleting the nutrient supply. When winds reverse (as occurs during storms), the bloom moves back toward shore where it can contact the coast or enter coastal estuaries. In the mean, coastal currents in near surface layers at most latitudes are northward in winter and southward in spring and summer, although direction reversals occur frequently in every season. In contrast to the East Coast, alongshore topography of the coastline is relatively straight and wind systems are large scale. Thus, currents and water properties (e.g., temperature, stratification, etc.) are similar over relatively large (>500 km) distances along the coast and are reasonably predictable, given information about the coastal wind field.

Some alongshore gradients in the larger scale environmental forcing do occur in the Pacific Northwest. For example, the duration of coastal upwelling decreases towards more northern latitudes. On the other hand, in winter and spring, the strength and occurrence of storms increases toward the north. Such differences may have important consequences on nutrient availability as well as larval transport along the coast.

The depth of the surface mixed layer in upwelling regions (the region in which water properties are uniform with depth) depends primarily on surface wind stress. Surface heat flux, which is important in the open ocean, does not contribute significantly to the depth of the mixed layer, and is likely balanced by horizontal advection of heat. Cross-shelf currents are uniform within the surface mixed layer, but strongly sheared below the mixed layer. A current spiral due to the earth's rotation (the "Ekman" spiral) is observed (currents to the right of the wind direction) but 25-50% of the net Ekman transport occurs in the transitional layer below the mixed layer; i.e., the surface mixed layer as defined by currents is thicker than that defined by water properties. Alongshore currents, unlike cross-shelf currents, decrease dramatically from the sea surface to the bottom of the mixed layer and the vertical structure is consis-

tent with the existence of a logarithmic near surface layer. The mixed layer near the sea floor is generally 5-15 m thick, and rarely exceeds one half the water depth. Like the surface mixed layer, its thickness of the bottom mixed layer increases offshore. The thickness of the bottom mixed layer is a function of stratification, current speed, and, most importantly, current direction, with thicker layers for northward flows than for southward flows. Ekman veering of about 20° is observed (to the left of the alongshore currents) and the veering occurs at the top of the mixed layer rather than within it. The veering decreases as the thickness of the mixed layer increases.

Mesoscale features and processes

Although the West Coast topography and forcing are generally large scale, several important mesoscale features such as river plumes, submarine canyons, and coastal promontories exist in the Pacific Northwest. Such features can modulate the local upwelling response, they can alter flow patterns, turbidity, mixed layer depth, and mixing rates. Such features are likely of particular importance to phytoplankton/zooplankton production, growth, and/or retention, as well as larval transport and/or retention.

Banks

On a coast-wide survey of domoic acid in surface waters in 1998, high values of the toxin were measured only in the vicinity of known topographic features such as banks or offshore islands (Trainer et al. 2001). The domoic acid is associated with the diatom *pseudo-nitzschia* spp. It seems likely that in regions where large coastal promontories occur such as off southern Oregon and northern and central California, plankton and larvae can be swept offshore and southward by the meandering jets and/or eddies that form where the coastal jets detach from the shelf. These plankton and larvae likely return to the coast rarely, if at all. On the other hand, in regions where banks and more complex mesoscale topography occur, such as offshore of the Strait of Juan de Fuca (the Juan de Fuca eddy) or Hacete/Stonewall bank off the central Oregon coast, retention areas are more likely. Maps of ocean pigment clearly show that chlorophyll is greater and located farther offshore in the vicinity of both of these features (Strub 2001). Under weak southward wind conditions

or during northward winds associated with storms, plankton and larvae in these retention areas can return to the coast to settle on the coast or enter coastal estuaries. For example, a relationship between toxic events in coastal razor clam populations due to toxic *Pseudo-nitzschia* and the Juan de Fuca eddy has been documented (Trainer et al. 2002). The toxin (domoic acid) reached the coast during the first significant storm of the year. Retention areas may also provide particularly favorable growth conditions for larval fish.

Submarine canyons

The entire Washington coast is indented by submarine canyons. Upwelling of nutrient-rich water is enhanced several-fold in the presence of such canyons. Thus overall we might expect higher nutrient levels off the Washington coast than off the Oregon coast where submarine canyons do not occur. This is consistent with chlorophyll patterns in Landry et al. (1989) as well as maps of sea surface color (Strub 2001). Alternately, the existence of the canyons may compensate for the generally weaker upwelling winds that occur off the Washington coast relative to Oregon. Submarine canyons such as Astoria canyon offshore of the mouth of the Columbia River, are also known to have retentive capabilities: each canyon tends to have a semipermanent counterclockwise eddy over and within the canyon. Zooplankton densities are frequently denser over the submarine canyons in the regions (Swartzman and Hickey, this volume).

Canyons also alter regional circulation patterns (Hickey 1997). In particular, counterclockwise circulation patterns are generally observed both within and over submarine canyons (although not extending to the sea surface necessarily). Such eddies provide an effective mechanism for trapping particles such as suspended sediment or food for the biomass.

The Columbia River Plume

The Columbia River provides over 77% of the drainage between the Strait of Juan de Fuca and San Francisco Bay. The plume from the Columbia River likely has major ecological effects in the PNW. River plumes are generally turbid, thereby providing less light for plankton growth, while at the same time providing better cover from grazing for higher trophic levels. Plumes provide retention areas: eddy like features are generated within a plume under both steady (Garcia-Berdeal et al. 2002)

and unsteady (Yankovsky et al. 2001) outflow conditions. Plumes provide a more stable upper layer overlying higher stratification: plumes alter regional current patterns in the upper layers, providing along-plume jets for rapid transport and convergences and trapping at frontal boundaries on the edges. Recent studies suggest that plume edges are preferred feeding sites for zooplankton. Inshore of the plume on the Washington coast, a retentive circulation pattern occurs (Hickey et al. 1998). The fact that juvenile salmonids are frequently found in this location may be due to this local retention pattern which might enhance food availability in this region.

On a seasonal basis, the plume from the Columbia River flows northward over the shelf and slope in fall and winter, and southward well offshore of the shelf in spring and summer. Most other smaller rivers on the Pacific Coast have significant river plumes only during major floods. In winter, the plume has a dramatic effect on the Washington coast, producing time-variable currents as large as the wind-driven currents. In summer, fresh water from the Columbia River gives rise to the low salinity signal and associated front used to trace the meandering jet that separates from the shelf at Cape Blanco. Both observational and modeling studies show that the plume is a "moving target", changing direction, thickness, and width with every change of local wind strength or direction (Hickey et al. 1998; Garcia-Berdeal et al. 2002). Thus the interaction of the plume with the local ecosystem is likely to be complex.

Other than the Columbia, river plumes on the PNW coast are relatively small, and their effects are likely confined to within one tidal excursion of the mouth of the river or estuary. Other river or estuarine plumes include those from Grays Harbor and Willapa Bay, Washington and Coos Bay, Oregon.

The structure and magnitude of the Columbia River plume have significant interannual variability. During years of high snowpack in the Pacific Northwest (such as 1999), very fresh water from the plume can flood the major coastal estuary just north of the Columbia estuary for prolonged periods, reversing the normal estuarine density and salinity gradients over much of the estuary. Because such plume intrusions would not occur in estuaries off the Oregon coast, the presence or absence of the plume may provide an important envi-

ronmental distinction between these estuaries as well as between nearshore coastal regions.

The Strait of Juan de Fuca

The counterclockwise cold eddy off the Strait of Juan de Fuca (also called the "Tully" eddy; Tully 1942) is situated southwest of Vancouver Island and offshore of northern WA. The eddy, which has a diameter of about 50 km, forms in spring and declines in fall (Freeland and Denman 1982). The eddy is a dominant feature of circulation patterns off the northern WA coast and is visible in summertime satellite imagery as a relative minimum low in sea surface temperature and, generally, a relative maximum in chlorophyll *a*. The seasonal eddy is a result of the interaction between effluent from the Strait, southward wind-driven currents along the continental slope and the underlying topography—a spur of the Juan de Fuca submarine canyon. A connection between the eddy and the Washington coast was demonstrated in July 1991, when oil that spilled in the eddy was found on the WA coast 6 days later (Venkatesh and Crawford 1993). Recent preliminary studies with drifters introduced into a diagnostic numerical model for a summer period in 1998 suggest that drifting particles can escape from the eddy to flow southeastward along the Washington shelf. During storms, onshore flow in the surface Ekman layer moves drifter pathways closer to the coast and even reverses the path to a northward direction. Pathways of drifters deployed this year in the field were consistent with these pathways; during a storm the drifter track reversed and the drifter moved backup the coast. Thus it seems likely that marine organisms residing in the Juan de Fuca eddy can, under certain ocean conditions, impact the WA coast.

Despite its potential importance as an area of high primary productivity and its unique status as a retentive site for diatoms, including *PN* (Forbes and Denman 1991; Horner et al. 2000; Trainer et al. submitted), the eddy has not been studied intensively. The photic zone in this area is characterized by high ambient macronutrients supplied by wind mixing, episodic wind-driven upwelling, topographically controlled upwelling (Freeland and Denman 1982), and the outflow from Juan de Fuca Strait where deep, nutrient-rich water is advected to the surface by estuarine circulation and tidal mixing (Mackas et al. 1980). Thus, although the ultimate source of nutrients for the eddy is the same as that in a nearshore coastal upwelling region (California

Undercurrent water), infusion of upwelled nutrients into the eddy likely occurs on different time scales and rates than in regions adjacent to the coast.

Pacific Northwest estuarine processes

Links to the coastal ocean

Recent studies show that water properties in PNW estuaries during the spring to fall growing season are controlled largely by processes occurring in the adjacent ocean rather than in situ estuarine processes. The type of water presented at the mouth of the estuary on flooding tides is governed by the water available near the coast at that time. The properties of that water (temperature, salinity, nutrient levels, and phytoplankton content) are governed by whether upwelling or downwelling is occurring along the coast at that time. During upwelling, surface waters move offshore and cold, saltier, nutrient rich water is moved upward within a few kilometers of the coast; during downwelling, surface waters move onshore and warmer, fresher, nutrient-poorer water moves inshore and downward within a few kilometers of the coast. In the Pacific Northwest, transitions between these two states occur at 2-10 day intervals. Water presented at the mouth of the estuary (for both upwelling and downwelling events) travels up the estuary at the rate of several km per day, modifying the circulation in the estuary as it passes. The modulations in estuarine circulation and water properties lag local wind stress fluctuations (hence, upwelling or downwelling) by more than a day.

The flushing rate of these estuaries, especially during the summer growing season, is likely to depend more on oceanic exchange processes than on river-driven ones. The dynamics of estuarine flushing will vary from system to system and also vary over time, but in general we can say that in contrast with most Eastern coastal-plain estuaries, West Coast estuaries are driven by strong tidal stirring and relatively weak summer riverflow. The efficiency with which tidal processes can flush a given estuary (and thus mix new ocean water into the system) will be largely controlled by the estuary's geomorphology, in particular, channel length, mean depth, cross-sectional area, and the presence and location of branch points and complex junctions. The distribution of open intertidal banks controls tidal flushing in both direct ways (i.e., through the geomorphological

parameters above) and also indirect ways (e.g., by frictionally retarding tidal flows and generating large residual tidal eddies).

During a coastal upwelling event on the coast, phytoplankton seed stock are also upwelled into the euphotic zone and, fueled by the high nutrient level, begin to grow. The growing phytoplankton move offshore as new seed stock is upwelled so that highest biomass may occur farther offshore of the coast rather than right at the coast. During the downwelling event that inevitably follows, the phytoplankton bloom is advected back to the coast.

Phytoplankton standing stock in coastal estuaries is of vital importance to the estuarine ecosystem and also provides the primary food source for commercial species such as oysters. Oceanically-derived phytoplankton can enter coastal estuaries by two routes. During upwelling events, just as on the coast, seed stock are also pulled into the estuary where they are fueled by the high nutrients brought in with the upwelled water. A local bloom may flow as this biomass moves up the estuary with the patch of water at a rate of about 10 km per day. Moreover, during downwelling events, just as on the coast, the phytoplankton from the upwelling-fueled bloom are pulled into the estuary and also move up the estuary (Roegner et al. 2002). This biomass, although nutrient poor and declining rather than growing, may provide a direct food source to the estuary, particularly near the mouth of the estuary.

Temperature in PNW estuaries is controlled not only by the temperature of adjacent shelf water (and hence, strength of upwelling) but also by local heating within the estuary. Local heating is also important in the shallow waters of a coastal plain estuary. We suspect that the water over the banks and possibly the muds on those banks also affect the temperature changes within the bay. Local heating of estuaries, being a function of bank to channel area as well as estuary flushing rate, can be expected to differ significantly between the several PNW estuaries. The local heating will directly affect areas on banks or in region where the estuary is poorly flushed. The overall heat content of an estuary can be affected indirectly as the heated bank water is mixed with the newer, cooler channel water. As a result of both ocean and atmospheric forcing, water in the estuary has a much larger seasonal variation than that on

the continental shelf just offshore (~ 16 °C vs. ~6 °C). Some heating of the estuary also occurs during the sunny weather typically associated with upwelling events (unless fog occurs). This effect is exactly in phase with the results of upwelling, which provides cooler water to the estuary. Thus, the resulting temperature signal would be masked by the upwelling signal (which is clearly stronger in most events).

As discussed in the first section, coastal processes in summer are large scale. Time series of temperature data collected simultaneously in three coastal estuaries demonstrate that in summer all three estuaries separated by over 400 km respond to upwelling/downwelling wind cycles in a similar manner and with similar timing. The magnitude of the response, on the other hand, can be expected to vary depending on the strength of the local wind and other local conditions as well as the flushing time for a particular estuary.

In winter and spring, weather patterns over the Pacific Northwest have more significant variability along the coast depending on the location of the jet stream; storms may occur off Washington, but not off southern Oregon, for example. In these periods, estuarine habitat may have greater differences due to the offshore forcing, but also due to the increased importance of riverflow to a particular estuary.

Nutrient-poor, fresher water from a major river plume (the Columbia) floods some estuaries during spring and summer, but not others. Intrusions completely reverse the normal estuarine salt gradient as well as eliminate the normal vertical salt gradient. Thus, changes in the volume and/or location of the Columbia River plume, such as result from changes in snowmelt due to conditions in a prior winter, or changes in wind during the spring and summer, will make significant differences in conditions in the physical environment in estuaries north and south of the Columbia River.

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Applications

Peer Reviewed Publications:

Yankovsky, A.E., B.M. Hickey, and A. Munchow. 2001. Impact of variable inflow on the dynamics of a coastal buoyant plume. *J. Geophys. Res.*, 106(C9):19,809-19,824.

Hickey, B.M., M. Zhang, and N. Banas. 2002. Coupling between the California Current System and a Coastal Plain Estuary (Willapa Bay) in Low Riverflow Conditions. *J. Geophys. Res.* (*in press*)

Garcia-Berdal, I., B.M. Hickey, and M. Kawase. 2002. Influence of wind stress and ambient flow on a high discharge river plume. *J. Geophys. Res.* (*in press*)

Roegner, G.C., B.M. Hickey, J.A. Newton, A. L. Shanks and D.A. Armstrong. 2001. Estuarine-nearshore links during a coastal upwelling-downwelling cycle: plume and bloom intrusions into Willapa Bay, Washington. *Limn. Oceanogr.* (*submitted*)

Other Publicity:

Radio Interview: National Public Radio. By Keith Seinfeld on the Columbia plume and its relation to the estuaries, September 2001.

Press release, University of Washington, on the Columbia plume research, August 2001.

University of Washington News, Article by Sandra Hines on the Columbia plume and relation to estuaries, August 2001.

Presentations:

Banas, N. and B.M. Hickey, "Seasonally varying physical controls on flushing and oceanic nutrient/phytoplankton

supply in Willapa Bay, WA." Estuarine Res. Fed. Meeting, Nov, 2001, St Pete Beach, FL.

Banas, N. and B.M. Hickey, "Seasonally varying controls on oceanic exchange in Willapa Bay, WA, Feb, 2002, AGU Ocean Sciences Meeting, Honolulu, HI.

Rooper, C.N., D.R. Gunderson, and B.M. Hickey, "Transport of eggs and larvae of English sole on the Oregon-Washington shelf." AGU Ocean Sciences Meeting, Feb, 2002, Honolulu, HI.

Roegner, C., D. Armstrong, B. Hickey, and A. Shanks, "Patterns of larval crab abundance in a Pacific Northwest estuary as determined by light traps." AGU Ocean Sciences Meeting, Feb, 2002, Honolulu, HI.

Banas, N., "Tidal and river-driven exchange between the coastal ocean and Willapa Bay, Washington." Masters presentation, School of Oceanography, Dec, 2001, University of Washington, Seattle, WA.

Hickey, B.M. and N. Banas, "Oceanography of the Pacific Northwest coastal zone and its coastal estuaries." PICES X Annual Meeting, Oct. 9, 2001, Victoria, B.C., Canada.

Workshops:

Barbara Hickey and Neil Banas attended the PNCERS All-Hands Meeting, January 11-12, 2001, University of Washington, Seattle, WA.

Barbara Hickey attended the PNCERS meeting in January, 2002.

Partnerships:

GLOBEC (NSF/NOAA supported research). Barbara Hickey has been awarded two contracts, one to maintain instrumented moorings off the coast near Grays Harbor, Washington and Coos Bay, Oregon for the next four years; the other (with G. Swartzman) to provide oceanographic interpretation for zooplankton and fish patches (from hydro-acoustic data all along the west coast on two triennial surveys). With GLOBEC support, data from these moorings will extend 7-15 years, allowing interannual comparison of environmental effects on the coast and in its estuaries. Data include ocean currents, temperature and salinity at a range of

depths. GLOBEC moorings will also include fluorometry and optical sensors to better examine biological variability.

COOP (Coastal Ocean Program). As a member of the National Science Foundation supported COOP steering committee Barbara Hickey has represented PNCERS at two semi-annual meetings this year. At these meetings, members of other groups (NSF, ONR and other NOAA programs) are kept informed of PNCERS efforts to assist in planning their own programs.

Washington Sea Grant. Neil Banas, a Ph.D. student working with Barbara Hickey, is supported by Washington Sea Grant. His ongoing physical oceanographic studies of biologically important intertidal areas supported by Washington Sea Grant complement the channel-oriented studies undertaken by PNCERS.

National Marine Fisheries (NMFS). We are providing oceanographic interpretation to V. Trainer (NMFS) and R. Horner (UW) to help understand HABS blooms off the Washington coast. A paper is in preparation. We have obtained funding from NOAA to continue these studies (the ORHAB program), with partners from the Washington State Department of Health and Washington Indian Tribes.

University of Oregon. Alan Shanks provided small boat support and lodging for our Coos Bay surveys and mooring refurbishments.

Washington State Department of Fish and Wildlife (WSDF). Brett Dumbauld has provided a small boat for many of our Willapa trips to clean or refurbish sensors and collect CTD data. We have provided Dr. Dumbauld with results from recent drifter and Doppler current surveys. We have undertaken surveys in intertidal regions of Willapa Bay of particular interest to WSDF.

Department of Ecology (DOE). We have been collaborating with Jan Newton in a number of analyses for Willapa Bay. In particular we have shared CTD data as well as data from moored sensors. These data are being incorporated into several papers describing biophysical interactions between Willapa Bay and the coastal ocean.

Personnel

Barbara Hickey, Professor, University of Washington
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Evidence for a Regime Shift After the 1997 El Niño, Based on Triennial Acoustic Surveys (1995-2001) in the Pacific Eastern Boundary Current (EBC)Chapter 3

Gordon Swartzman and Barbara Hickey

Introduction

The eastern Pacific coast ecosystem appears to be dominated by regime shifts which are reflected most strongly by changes in the year class strength of anadromous salmon (Francis and Hare 1994). The 1990s was a period of uniformly low recruitment of salmon stocks in the Pacific eastern boundary current (EBC: California, Washington, Oregon and British Columbia), while Alaskan stocks produced record runs (Beamish 1993). The picture that is emerging concerning regime shifts is that they are linked to a strengthening or weakening of the Aleutian low frontal system, a system which appears to set up for long periods of time (e.g., a decade) and be weak for similar time periods. (Polovina et al. 1996). The strengthening of the Aleutian low, which clearly occurred in a major regime shift in 1977-78 (Francis and Hare 1994), appears to be associated with increased winds in the EBC, cooler surface water temperatures offshore and an increased mixed layer depth (Beamish 1993; Polovina et al. 1996). The 1990s appeared to have the reverse condition, with weaker winds, and shallower mixed layer depths. There is additional evidence that the period from 1980-89 was a period of higher than average macrozooplankton (euphausiids and large copepods) abundance (Brodeur and Ware 1992). That regime shifts may be the cause of large-scale shifts in species composition in the EBC is supported by sediment core evidence on the shift in dominance between sardine and anchovy stocks over very long time scales (Baumgartner et al. 1992).

The major difficulty in detecting a regime shift in the biological part of the marine ecosystem, even when all environmental indicators suggest such a change has occurred, is the complexity of species interactions, the longevity of some of the fish species and their variable recruitment success (Myers and Pepin 1994). Nonetheless, we would expect that lower trophic levels respond more rapidly to regime shift than higher trophic levels, which depend on the lower levels for successful growth and recruitment. As such, we have examined the abundance and spatial distribution of large zoop-

lankton (e.g., euphausiid) patches and pelagic fish (dominated by Pacific hake (*Merluccius productus*)), from three acoustic surveys, transecting the EBC (mid California to at least the Canadian border) from nearshore to well beyond the shelf break at 10 n.mi intervals during the summers of 1995, 1998 and 2001. Image processing methods were used on the acoustic backscatter data at two frequencies (38 and 120 kHz) to extract locations of large patches of zooplankton and schools of pelagic fish. These data were also supported by net samples on a much coarser time scale and by synoptic CTD and ADCP data as well as surface temperature, salinity, and fluorescence data. Our aim is to examine whether the proposed regime shift in 1998 (Hare and Mantua 2000) has left any signal on the abundance and distribution, particularly of zooplankton schools, but also of fish, and if so when did this change occur (i.e., between 1995 and 1998 or between 1998 and 2001).

Methods

Data were provided by the National Marine Fisheries Service, Alaska Fisheries Science Center Marine Acoustics group from summer acoustic surveys in 1995, 1998 and 2001 (Wilson and Guttormsen 1997; 1998; Guttormsen 2001; Figure 3.1). These included acoustic backscatter data collected at 38 and 120 kHz using a SIMRAD EK-500 hull-mounted (at 9m depth) echosounder system, onshore-offshore and alongshore current estimates collected using a 150 kHz Acoustic Doppler Current Profiler (ADCP), CTD and XBT data collected during the cruise, fish data collected using an Aleutian Wing Trawl (midwater) and an otter trawl (bottom), and zooplankton data collected using a Methot net sampler.

We simultaneously mapped the distributions of both fish and plankton using morphological image processing methods applied to acoustic echograms at two frequencies (e.g., 38 and 120 kHz; Swartzman et al. 1999a). Fish schools were identified by applying a backscatter threshold to the 38 kHz images between -40 and -54

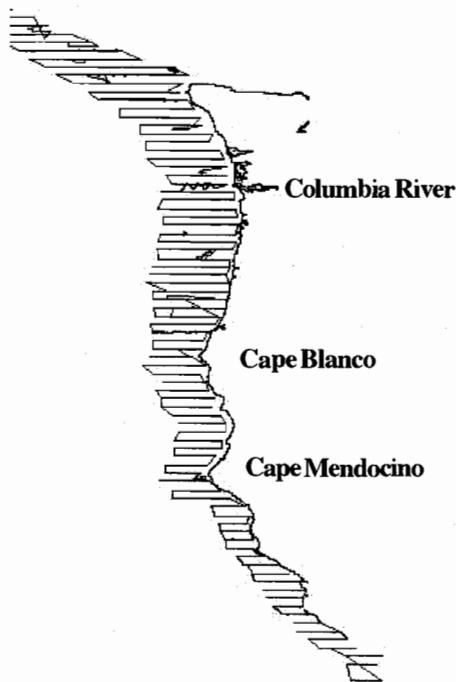


Figure 3.1. Transects followed during NMFS summer acoustic surveys in 1995, 1998, and 2001.

dB and then using a morphological opening and closing on the resultant image using a 3x2 pixel (horizontal x vertical) binary structuring element (Haralick and Shapiro 1992). Then the resulting image was multiplied by the original image and a connected component algorithm was used (Haralick and Shapiro 1992) to convert each fish shoal (contiguous group of non-background pixels after the algorithm) to a row of a table where each column is an attribute of the shoal. Attributes include location (center latitude longitude and depth), size (area, width, height), shape (fractal dimension, eccentricity, sinuousness, eight boundary points defining an enclosing polygon for the shoal), intensity (mean, maximum, and minimum backscatter, backscatter variance) and environment (bottom depth). Because Pacific whiting is dominant (80-90% of biomass in trawls) during the daytime (almost all transects were during the day) below the thermocline (Wilson and Guttormsen 1997), we assumed that the fish shoals below the thermocline are whiting.

Plankton patches were identified by applying a threshold between -62 and -54 dB to both the 120 and 38 kHz echograms. After taking the difference between the two images (120 kHz – 38 kHz images) a +5 dB

threshold was applied (all pixels having backscatter at 120 kHz less than 5 dB greater than that at 38 kHz were set to the background backscatter level). We then applied a morphological filter using a 3x3 binary structuring element to the resultant image. We then multiplied the resulting binary image by the 120 kHz echogram and used a connected component algorithm as with fish shoal identification (Swartzman et al. 1999b).

The morphological and differencing method uses the observation, based on in situ measurements and geometric models, that backscatter from most adult euphausiid species (15 – 25 mm in length) at 120 kHz should be significantly higher than backscatter at 38 kHz (Mitson et al. 1996; Stanton et al. 1993). The morphological filter provided a search for contiguous pixels in the echogram that were both in the expected backscatter range for euphausiids and had higher backscatter at 120 kHz, which identified patches of plankton independent of fish shoals (Swartzman et al. 1999a; Swartzman 2001). Exhaustive comparison of zooplankton net samples from the 1995 survey with acoustic backscatter at the two frequencies (McKelvey 2000) corroborated that the net samples were dominated by euphausiids when backscatter at 120 kHz was higher than that at 38 kHz.

The high resolution of backscatter images (9.0 m horizontal resolution and 0.5 m vertical resolution) made it possible to clearly identify patch and school boundaries.

Transect coverage for the three summers of acoustic survey data (1995, 1998 and 2001) followed an almost identical track (Figure 3.1). As such, we were able to line up the surveys transect-by-transect to provide for comparison by paired differences. Because the spatial region covered by the surveys was so large, and because there is evidence to suggest that both major capes along the survey track, Cape Mendocino and Cape Blanco as well as the Columbia River (Figure 3.1) provide oceanographic boundaries, we divided the survey region into four areas north to south. We split these four regions based on the well defined ocean boundaries (Hickey 1979). Additionally, we divided the cross-shelf transects into offshore, shelf break and nearshore regions. We used 200 meters as the boundary between shelf (nearshore) and shelf-break regions and 800 meters between shelf break and offshore regions. We

ended up specifying these regions by distance from the offshore end of each transect, because bathymetric differences between the transects, such as the possibilities of sea mounts and canyons along the transects made the regions occasionally noncontiguous, while we desired contiguous regions for comparisons.

The region splits are justified by oceanographic considerations. The regions north and south of Cape Blanco have significant differences with respect to the oceanographic environment. Wind forcing in summer is generally weaker north of Cape Blanco (Hickey 1979). However, the coastline north of Cape Blanco is relatively straight and shelf currents, upwelled water, and organisms tend to be confined to the shelf. South of Cape Blanco, on the other hand, the coastline is irregular, and wind-generated coastal jets tend to separate from the shelf at these promontories to form meandering jets that can extend hundreds of kilometers away from the coast (Strub et al. 1991). The jets provide a mechanism for carrying cold, salty, chlorophyll-rich recently upwelled water away from the coast. Meandering jets can sometimes be traced continuously from Cape Blanco, where

they separate from the shelf, to southern California (Strub et al. 1991).

Near-surface waters in the CCS are also affected by fresh water discharge, primarily from the Columbia River (Budinger et al. 1964). During winter months, the plume of the Columbia River generally tends north or northwestward from the river mouth, strongly modifying the currents and water properties over the Washington shelf in the upper 10-30 m of the water column (Hickey et al. 1997). During summer, ambient winds and currents cause the Columbia River plume to tend offshore and to the southwest off Oregon, although reversals frequently occur in late summer and early fall. The density front associated with the river plume, which can be traced as far south as San Francisco in summer (Huyer 1983), may provide a barrier and perhaps a conduit for zooplankton movement (Thomson et al. 1990).

We compared the three years graphically and statistically using boxplots and paired difference t-tests for density of fish shoal and plankton patch biomass (biomass per transect km) in each region, using the transects

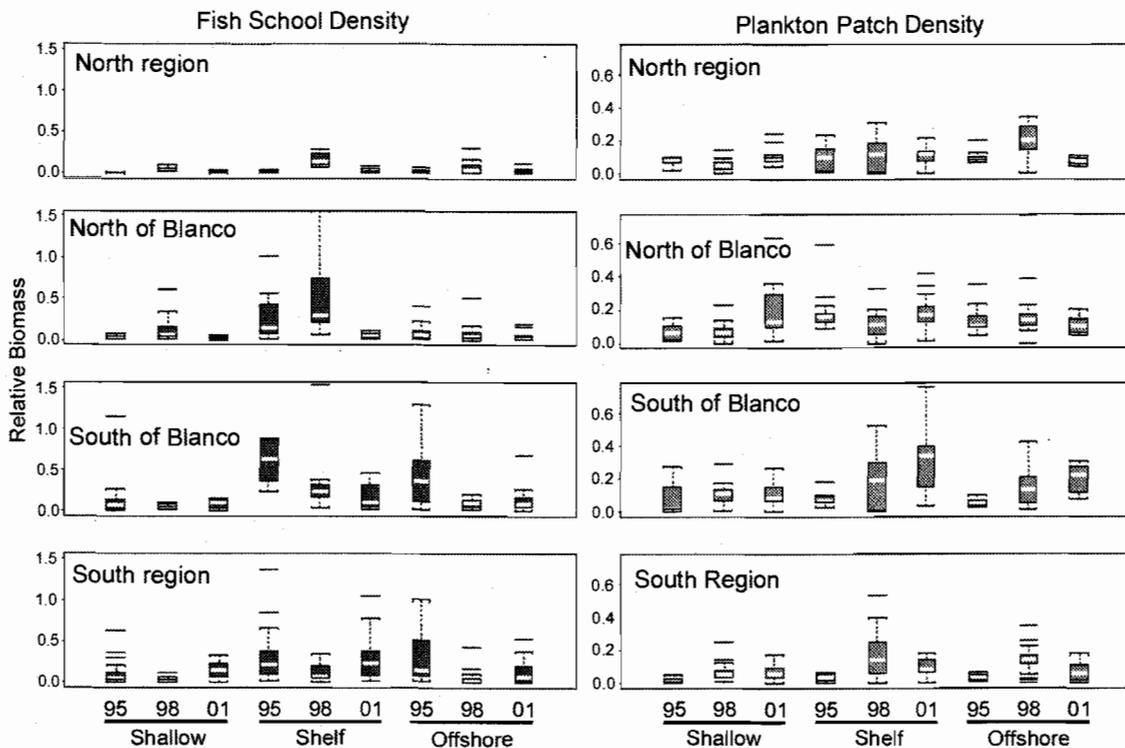


Figure 3.2. Boxplot comparison of acoustic biomass density (biomass/km) for fish shoals and zooplankton patches for nearshore (shallow), shelf-break, and offshore regimes in the region (from top to bottom) north of the Columbia River, north of Cape Blanco to the Columbia River, south of Cape Blanco to Cape Mendocino, and south of Cape Mendocino.

as replicates. The statistical comparison was done for all zooplankton patches, all fish shoals, and fish shoals deeper than 50 m, which are dominated by Pacific whiting (Wilson and Guttormsen 1997; 1998).

Results

Comparison of the fish shoal and plankton patch density between the three survey years is given, for each region and regime, in Figure 3.2. Results of the paired-difference t-tests are given in Tables 3.1-3.3 for zooplankton patches, fish shoals, and deeper fish shoals respectively.

The results in Figure 3.2 suggest that the shelf break was, in all three years, a regime of consistently high abundance of both fish shoals and zooplankton patches. In all years, except 1995 in the northern region, fish abundance was highest in the shelf break regime. Zoop-

lankton was highest in the shelf break region in all regions except in 1998 in the northern region and 1995 south of Cape Mendocino.

A regime shift would be expected to be reflected by a significant increase in the abundance of zooplankton, of which euphausiids by far dominate acoustic backscatter (McKelvey 2000). There appears to be a markedly strong increase in zooplankton patch abundance between 1995 and 1998, which was sustained in 2001 south of Cape Blanco (in both the region south of Cape Mendocino and between Mendocino and Blanco). This is supported by the t-test p-values in Table 3.1, which were, for all regimes in these regions, less than 0.057, implying rejection of the null hypothesis of no change in mean zooplankton abundance at least $\alpha=0.057$ (and usually at a much lower type-1 error; Table 3.1). North of Cape Blanco, the zooplankton picture is unclear, and there is no consistent pattern of change in zooplankton acoustic biomass between 1995 and 1998 (Table 3.1,

Table 3.1. P-values from paired differences t-tests for the null hypothesis that the mean acoustic biomass density (per km) for zooplankton patches was equal between years within each regime--nearshore (shallow), shelf-break, and offshore--and north south region. * means NS for $\alpha>0.2$.

	Nearshore-shallow			Shelf-break			Offshore		
	95-98	95-01	98-01	95-98	95-01	98-01	95-98	95-01	98-01
North	0.130	0.128	0.028	*	*	*	0.027	0.003	0.031
N. Blanco	*	0.012	0.025	*	*	*	*	*	0.107
S. Blanco	0.014	0.032	0.040	0.057	0.001	0.041	0.009	0.000	*
South	0.003	0.001	0.106	0.000	0.000	0.029	0.000	0.004	0.005

Table 3.2. P-values from paired difference t-tests for the null hypothesis that the mean acoustic biomass density (per km) for fish shoals was equal between years within each regime--nearshore (shallow), shelf-break, and offshore--and north-south region. * means NS for $\alpha>0.2$.

	Nearshore-shallow			Shelf-break			Offshore		
	95-98	95-01	98-01	95-98	95-01	98-01	95-98	95-01	98-01
North	0.0010	*	0.0010	0.0003	*	0.0009	0.1120	*	*
N. Blanco	0.0190	0.0030	0.0060	0.1200	0.0070	0.0090	*	0.0740	*
S. Blanco	0.1600	*	0.0110	0.1240	0.0220	*	0.0070	0.0060	*
South	0.0310	*	0.0000	0.0200	*	0.0130	0.0100	0.0160	0.0990

Table 3.3. P-values from paired difference t-tests for the null hypothesis that the mean acoustic biomass density (per km) for fish shoals was equal between years within each regime--nearshore (shallow), shelf-break, and offshore--and north-south region. * means NS for $\alpha>0.2$.

	Nearshore-shallow			Shelf-break			Offshore		
	95-98	95-01	98-01	95-98	95-01	98-01	95-98	95-01	98-01
North	0.0400	0.1600	0.0100	0.0050	*	0.0050	*	0.1100	*
N. Blanco	*	0.0030	0.0250	*	0.0400	0.0200	*	*	*
S. Blanco	*	*	*	0.0200	0.0240	*	0.0004	0.0030	0.0011
South	0.0500	*	0.0040	0.0400	*	0.0500	0.0100	0.0400	0.0020

Figure 3.2). The only discernible pattern is that north of Cape Blanco zooplankton abundance offshore was significantly smaller than in 1995 or 1998. Thus, while there is a strong regime-shift like signal of increased zooplankton abundance between 1995 and 1998, this signal is not apparent north of Cape Blanco.

One other prevalent distribution pattern for both zooplankton and fish was a relative increase or shift in abundance in 2001 toward the nearshore regime throughout the survey area (Figure 3.2). This does not imply that the nearshore regime had the highest fish and zooplankton densities, but that these densities were higher, relative to the shelf-break and offshore densities, than in other years. This was particularly noticeable for zooplankton north of Cape Blanco, where the nearshore densities were clearly higher than the offshore densities (Figure 3.2).

We would not expect a regime shift to reflect a predictable change in pelagic fish abundance, and this appears to be the case. While there is a strong difference between fish abundance patterns between the years, it is not reflective of a consistent change over time. In fact, both 1995 and 2001 had highest abundance of pelagic fish shoals south of Cape Blanco (Figure 3.2), while in 1998, abundance was highest in the north and was significantly higher than abundance in either 1995 or 2001. The strong northward migration of whiting in 1998 is thought to be due to the El Niño that preceded the sampling period (Wilson and Guttormsen 1998). South of Cape Blanco, the difference between 1998 deeper fish densities offshore and those in 1995 and 2001 was greater than the equivalent differences for all pelagic fish (Table 3.2, Table 3.3). This suggests that there were relatively more whiting offshore in the south in 1995 and 2001 than there were other pelagic fish.

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- Gordon Swartzman and Barbara Hickey. "Evidence for a regime shift after the 1997 El Nino, based on triennial acoustic surveys (1995-201) in the Pacific Eastern Boundary Current (EBC)" March 29, 2002, Newport, OR.

Workshops:

Gordon Swartzman attended the PNCERS All-Hands Meeting, January 11-12, 2001, University of Washington, Seattle, WA.

Partnerships:

Chris Wilson, Steven DeBlois, Michael Guttormsen, and Tania Honkalehto, NMFS AFSC. Provided acoustic data for 1995 and 1998. Provided CTD data for 1995 and 1998, including programs to contour and meld these data. Helped write and critique the manuscript under preparation.

Michael Kosro and Steve Pierce, Oregon State University. Provided 1995 and 1998 ADCP data in ASCII form.

Mark Saunders, Kenneth Cook, and Robert Kieser, Canadian Marine Fisheries Laboratory, Nanaimo. Meeting to discuss methods of identifying zooplankton patches.

Ric Brodeur, NMFS NWFSC, Newport, OR. Collaborate on processing data on BPA and GLOBEC sponsored cruises.

Applications

Publications:

Swartzman, G.L. 2001. Spatial patterns of Pacific hake (*Merluccius productus*) shoals and euphausiid patches in the California Current Ecosystem, pp. 495-512 In *Spatial Processes and Management of Marine Populations*. Alaska Sea Grant College Program. AK-SG-01-02

Presentations:

Gordon Swartzman, Barbara Hickey, and Chris Wilson, "Mesoscale biotic features of the coastal and nearshore environment." PICES X Annual Meeting, October 9, 2001, Victoria, B.C., Canada.

Personnel

Gordon Swartzman, Research Professor, University of Washington

Ocean Distribution and Estuarine Recruitment of Dungeness Crab *Megalopae* in Southern Washington Chapter 4

Curtis Roegner, Alan Shanks, and David Armstrong

Introduction

Pacific Northwest estuaries serve as important nursery grounds for commercially important invertebrate species such as the Dungeness crab, *Cancer magister*. With few exceptions, these crab species undergo larval development in the coastal ocean, and recruit back to estuary and coastal sites as the terminal larval stage known as the megalopae. While crab megalopae are relatively good swimmers, physical oceanographic processes on the shelf are energetic and dynamic and must play an important role in larval dispersion and eventual transport of larvae back toward shore. Variation in the abundances and timing of recruiting megalopae may have large consequences for subsequent population dynamics, and so understanding the patterns and processes affecting larval recruitment has been a major goal of our PNCERS research.

In this report we summarize observations from Washington studies in 1999, when we collected two sets of larval abundance data to understand larval transport and estuarine recruitment: 1) surveys of the coastal ocean during oceanographic cruises, and 2) daily time series at estuarine sites using light traps. These abundance data are related to physical data sets acquired from shipborne and moored oceanographic instruments. Several issues are investigated. On the ocean side, we wish to understand the spatial distribution and patch size of larvae in relation to environmental factors. From the estuary side, we are concerned with the temporal variation of larvae both within and between estuarine sites. The overall goal is to determine mechanisms controlling larval recruitment to estuarine systems.

In previous PNCERS reports, we demonstrated how variation in wind stress generated large changes in water prop-

erties and production in the coastal ocean over short time scales. Water properties in the nearshore zone were quickly transmitted to the Willapa Bay estuary. We follow up that research to include distribution of larvae in the ocean during the *Lady Kaye* cruise as well as time series of crab megalopae at three estuarine sites during a 90 day period in 1999.

Methods

Distribution of larvae in the nearshore zone

The study area comprises Grays Harbor (GH), Willapa Bay (WB), and the adjacent ocean bounded by 46.5° to 47.2° N and 125.0° to 124.3° W (Figure 4.1). Larvae were sampled in the ocean section of this area from the trawler *Lady Kaye*. Two scales of sampling arrays were investigated. A large spatial array consisted of a grid of

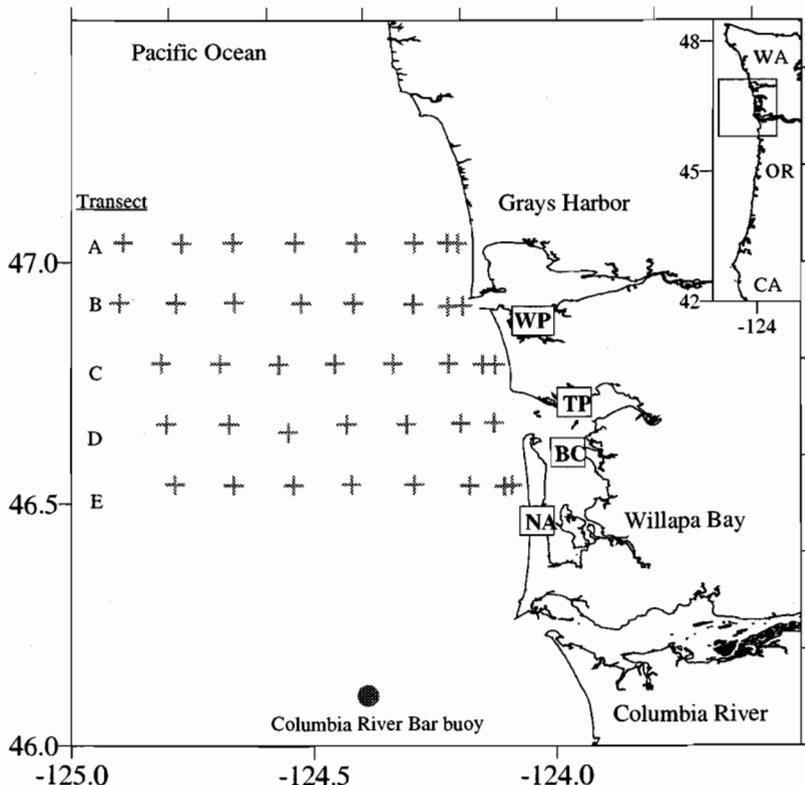


Figure 4.1. Study region. WP, Westport light trap; TP, Toke Point light trap and NOAA station; BC, Bay Center instrument mooring; NA, Nahcotta light trap.

five cross-shelf transects (A to E) extending from one to 80 km offshore. Stations were 1.8 to 9.25 km apart, and the transect lines bracketed the Willapa Bay and Grays Harbor estuaries. The large array was sampled twice in late May 1999: Survey 1 from 23-25 May and Survey 2 from 28-30 May. Each survey took ~1.75 days to complete and they were separated by a 4 day period.

The small arrays were positioned immediately adjacent to the mouths of Grays Harbor and Willapa Bay. Stations were 1.8 km apart, and the grid pattern was repeated at each locale to examine day/night differences in larval surface abundance. Each small survey consisted of 12-13 stations, required ~3.5 hours to complete, and were conducted in the period between Surveys 1 and 2. At present, these data are displayed in summary form only.

At each station, coupled biological and physical measurements were made. The surface concentration of larvae was sampled with a Manta style neuston net (1.5 x 0.5 m mouth dimensions, 300 μm mesh net). The neuston net was towed for 5 to 7 minutes at 2 knots, and the volume of water filtered through the net, averaging 202.4 m^3 , was measured with a General Oceanics flowmeter. Samples were preserved using a 7% buffered formalin solution. Larvae were sorted in the laboratory and concentration was standardized by tow volume to yield individuals m^{-3} (ind m^{-3}). During Survey 1, we also made vertical net tows (0.5 m^2 ; 300 μm mesh net); however, very few larvae were caught. Physical characteristics at each station were determined with a Sea-Bird 25 CTD equipped with fluorometer and oxygen sensor that was lowered to within 5 m of the bottom on the shelf and to 100 m elsewhere. During processing, CTD profiles were binned into 1.0 m intervals. The light field at deck height was measured with a light intensity meter (Onset Instrument Corp) at 0.5 hour intervals.

Time series of Cancer magister megalopae

Light traps were used to collect time series of larval Dungeness crab abundance. These devices function as behavioral samplers and depend upon the positive phototropism of organisms towards artificial illumination. The traps were constructed from semi-opaque 5 L plastic jugs, and plankton entered the trap through 1 x 3 cm openings cut into the apex of translucent plastic funnels. The light source was a 4 watt AC fluores-

cent bulb sealed in an acrylic tube. The traps were constructed to float with the uppermost two funnels just below the surface of the water, and thus sampled organisms in the upper 50 cm. Trapped specimens were concentrated in a cod end (250 μm mesh) attached to the base of the trap, fixed in buffered formalin, and sorted in the laboratory. Only *Cancer magister* megalopae were enumerated from the Washington samples.

Three concurrent sets of light trap time series were collected from 1 May to 30 July 1999. Three replicate traps were deployed at Westport (WP), Grays Harbor and Toke Point (TP), Willapa Bay sites. Traps at these sites were near the mouths of the respective estuaries and are used to evaluate ingress of megalopae to the estuary from the nearshore zone. The third site was at Nahcotta (NA), about half way down the north-south axis of Willapa Bay. Nahcotta data are used in conjunction with the TP time series to investigate transport of megalopae within the Willapa Bay estuary.

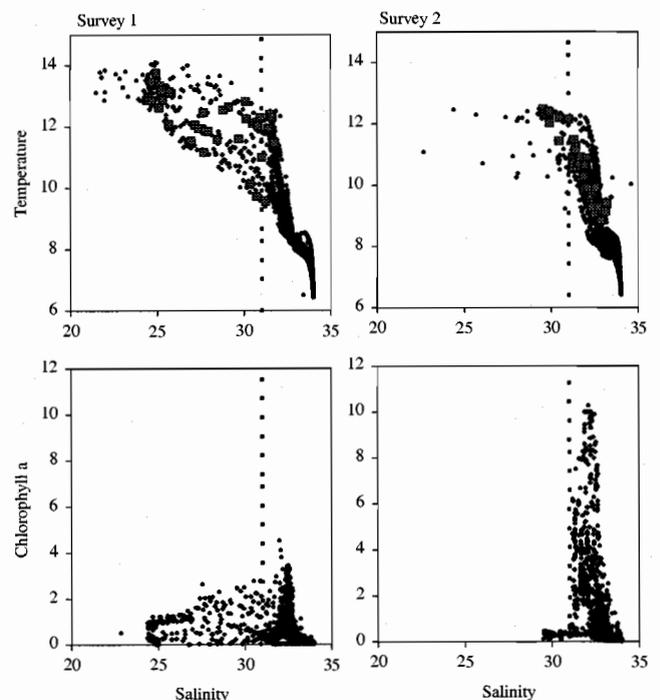


Figure 4.2. Temperature/salinity (top) and Chlorophyll/salinity (bottom) diagrams for Survey 1 (left) and Survey 2 (right) cruise periods. Crosses designate all data, while squares show properties at 4-5 m depth at the neuston net stations. Dotted vertical line at 31 psu distinguishes plume-influenced water.

Time series from instrument moorings

We used time series measurements of several biophysical variables to link atmospheric forcing on nearshore and estuarine hydrology and larval invertebrate abundance. Nearshore sea surface temperature (SST) was measured and the alongshore wind stress ($N\ m^{-2}$) was calculated from wind velocity vectors measured at the Columbia River Bar (CRB) weather buoy (Buoy 46029; $46.12^{\circ}\ N$, $124.50^{\circ}\ W$). Within Willapa Bay, time series of salinity and fluorescence were recorded at 0.25 hour intervals by a Sea-Bird 16 CT equipped with a WetLabs Wet Star fluorometer. The instrument was moored at Bay Center ($46.6^{\circ}\ N$, $123.9^{\circ}\ W$), near the mouth of the estuary, and the sensors sampled water at 1 m depth. We also utilized hourly temperature and water level records measured at the Toke Point NOAA station, located northeast of the estuarine mouth ($46.7^{\circ}\ N$, $123.9^{\circ}\ W$). The time series are plotted for the period 1 May to 29 July 1999.

Results

Oceanography of the nearshore zone

As we previously reported, wind stress had a dramatic effect on the nearshore water properties observed during the two large scale surveys, conducted just four days apart. Temperature/salinity (T/S) and chlorophyll/salinity (C/S) diagrams made from the CTD casts clearly show the existence of Columbia River Plume water (defined as $< 31\ psu$) containing low chlorophyll concentrations during Survey 1, and upwelled water supporting a phytoplankton bloom during Survey 2 (Figure 4.2). The squares in Figure 4.2 indicate the values at 4-5 m depth used to construct

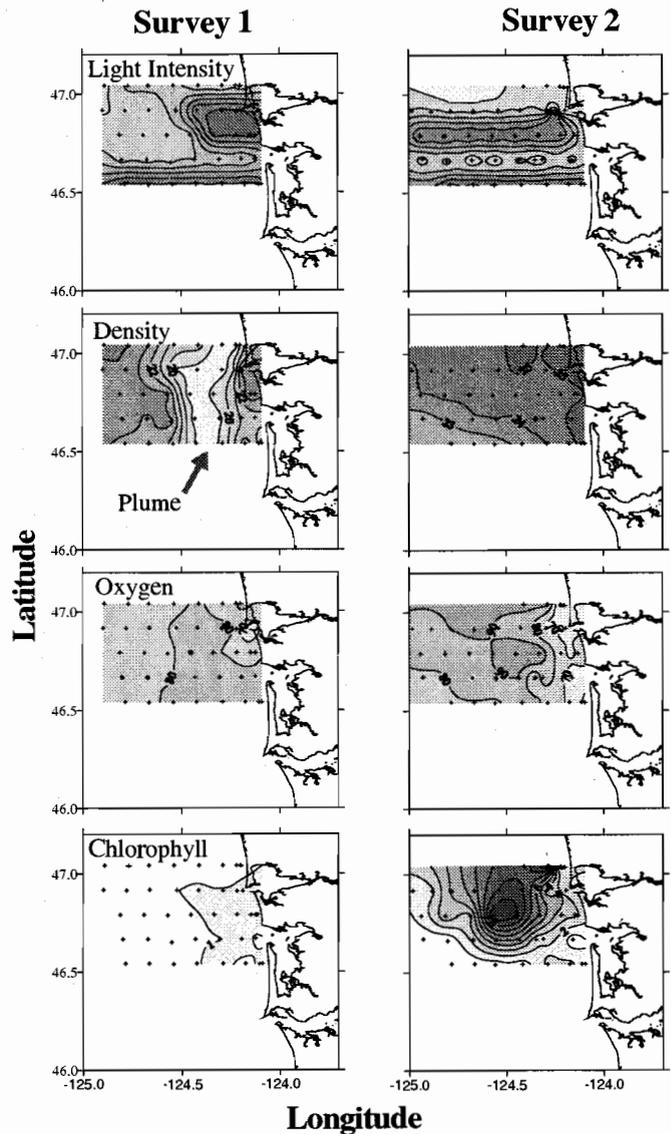


Figure 4.3. Surface environmental conditions during Survey 1 (left) and Survey 2 (right) periods.

Table 4.1. Summary statistics for plankton groups. %: percent of non-zero stations; N: total individuals sampled; Max: maximum concentration ($ind\ m^{-3}$). Number in parentheses denotes number of stations sampled.

Organism	All stations (171)			Survey 1 (39)			Survey 2 (42)		
	%	N	Max	%	N	Max	%	N	Max
Cyprids	69.0	5911	3.89	92.3	2566	3.89	78.6	2816	3.28
Cancer	61.4	1451	0.69	71.8	223	0.36	69.0	378	0.55
Pugettia	59.1	3924	5.80	30.8	49	0.06	64.3	557	1.09
Lepas	53.8	5563	4.46	79.5	628	0.71	83.3	4704	4.46
Pagurus	39.8	3165	9.95	28.2	41	0.07	33.3	688	1.90
Porc meg	32.7	768	10.05	17.9	8	0.01	28.6	67	0.20
Hemigrapsus	24.0	311	0.26	7.7	8	0.02	11.9	66	0.25
Porc zoea I	19.9	93	0.13	7.7	4	0.01	16.7	20	0.06
Porc zoea II	18.1	321	0.57	2.6	5	0.02	19.0	44	0.29

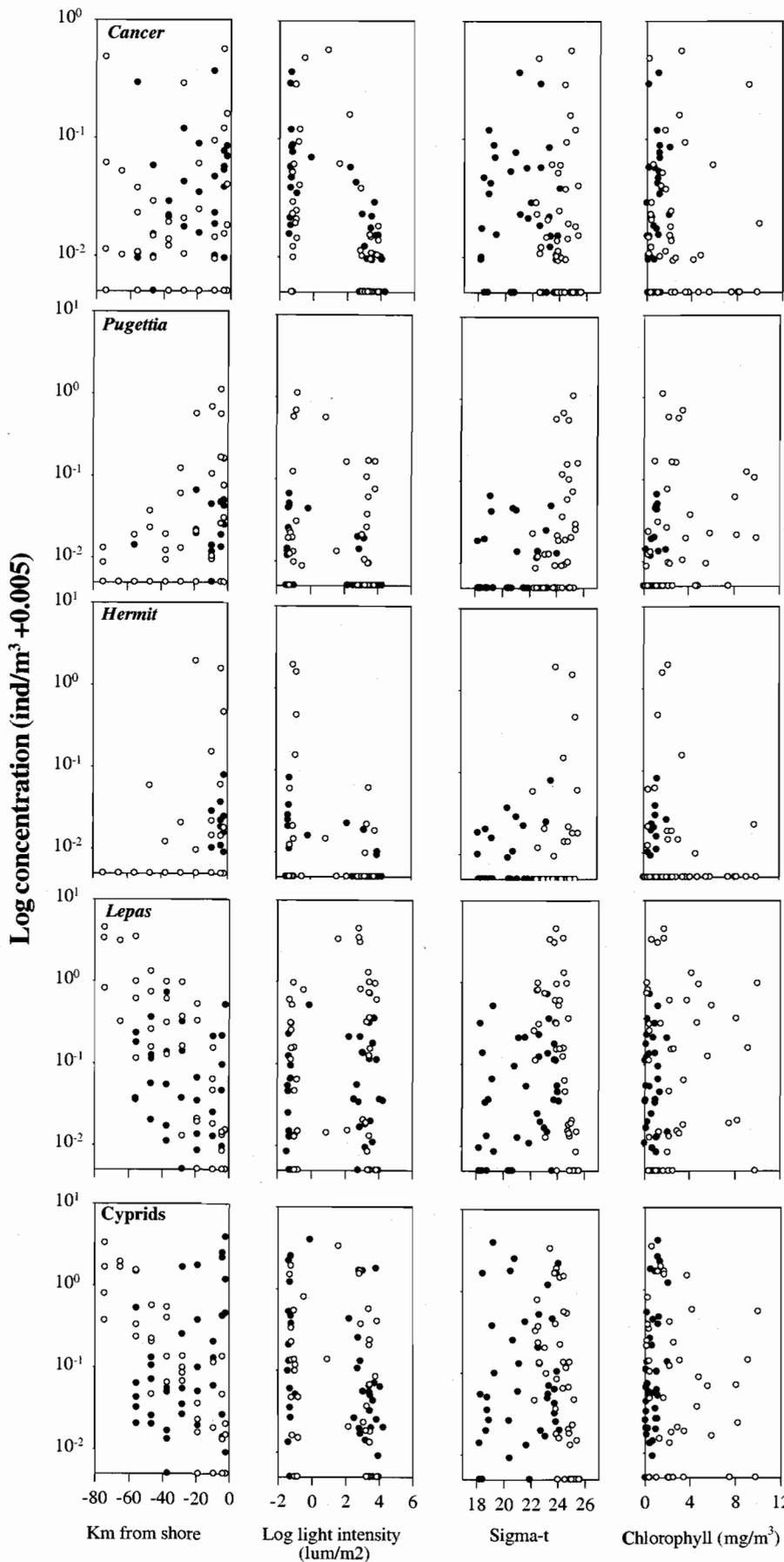


Figure 4.4. Scatterplots of larval concentration ($\log C + 0.005$) and environmental variables at 4-5 m. Filled symbols are Survey 1 stations; open symbols are Survey 2 stations.

surface plots shown in Figure 4.3. Note the strong horizontal gradients in density surrounding the plume water (Figure 4.3). During Survey 2, upwelled water was concentrated near the coast, and the remnant of the plume (23 sigma-t units) had moved to the southwest indicating a large advective event had occurred. The spatial variation of oxygen increased during Survey 2, with reduced O₂ in newly upwelled water and higher values with the chlorophyll maximum. Ocean productivity was dramatically enhanced by upwelling. The light field indicates we sampled reasonably representative light-dark and onshore-offshore station combinations.

Nearshore distribution of larvae

Prominent meroplankton sampled were megalopae and zoea of brachyuran crabs (*Cancer magister*, *Hemigrapsus nudus*, *Pugettia productus*), anomuran crabs (*Pagurus* spp and porcelain crabs), pelagic gooseneck (*Lepas anatifera*), and unidentified balanoid barnacle cyprids. Table 4.1 gives summary statistics on these groups and indicates differences in overall abundances between Survey 1 and Survey 2 cruises. With the exception of *Cancer* and balanoid cyprids, meroplankton were enhanced in overall abundance and maximum concentration during Survey 2 samples. However, porcelain crabs and *Hemigrapsus* megalopae were mostly collected during the small scale survey, and will be discussed elsewhere. Additionally, the small scale surveys collected extremely dense larval aggregations.

Scatter plots of log concentration by distance from shore, light intensity, water density, and chlorophyll a concentration for Surveys 1 and 2 reveal trends to specific environmental variables (Figure 4.4). Log values are used in the Figure because, overall, a few high-density areas tended to dominate abundance. *Cancer* megalopae were widespread and exhibited little change in cross-shelf distribution during the upwelling period. They were found throughout the range of density values. In contrast, *Pugettia* and *Pagurus* avoided plume water and exhibited increased concentrations near shore. All three of these groups tended to be more prevalent during periods of reduced

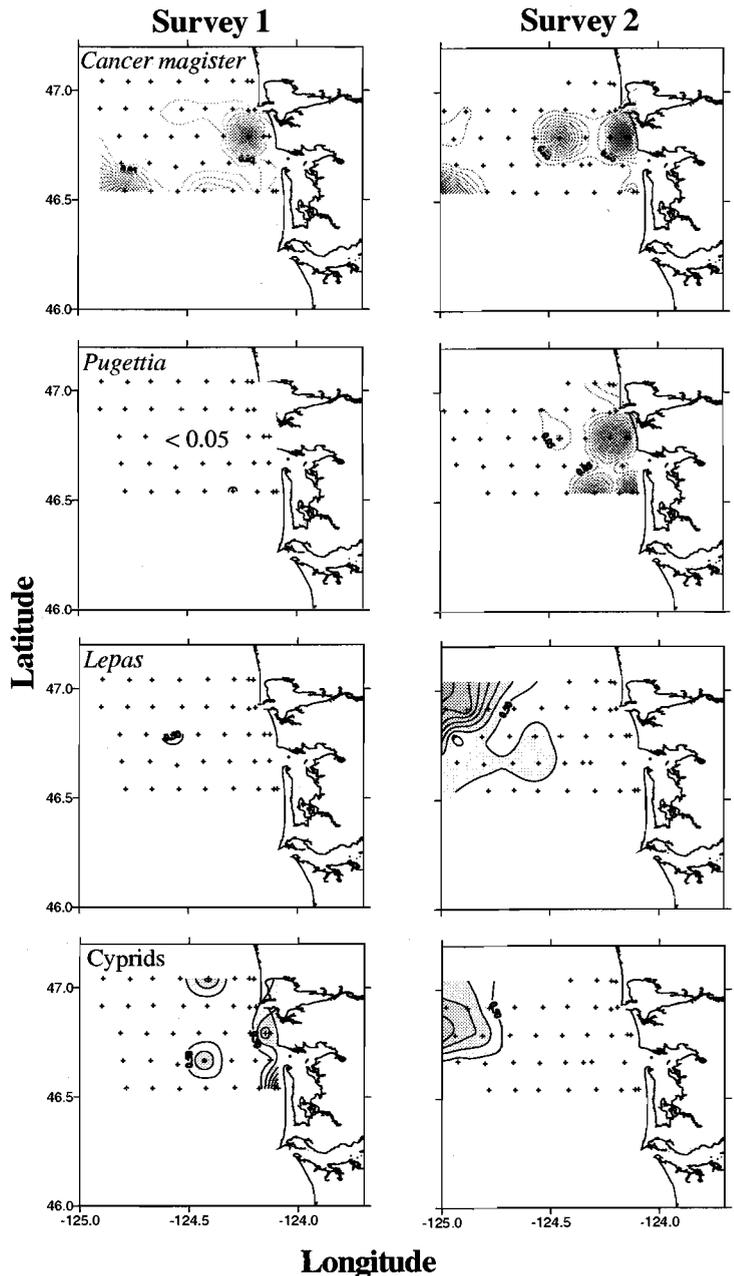


Figure 4.5. Surface plots of larval concentration (ind m⁻³) during Survey 1 (left) and Survey 2 (right) periods.

light intensities. Cyprids and *Lepas* were widespread and were less affected by light. Cyprids showed large changes in cross-shelf concentration consistent with passive offshore advection during upwelling, while *Lepas* had reduced concentrations in low salinity water and tended to be found off shore. No species exhibited increased concentrations with chlorophyll. However, despite these trends, larval concentration was not well correlated with the physical variables.

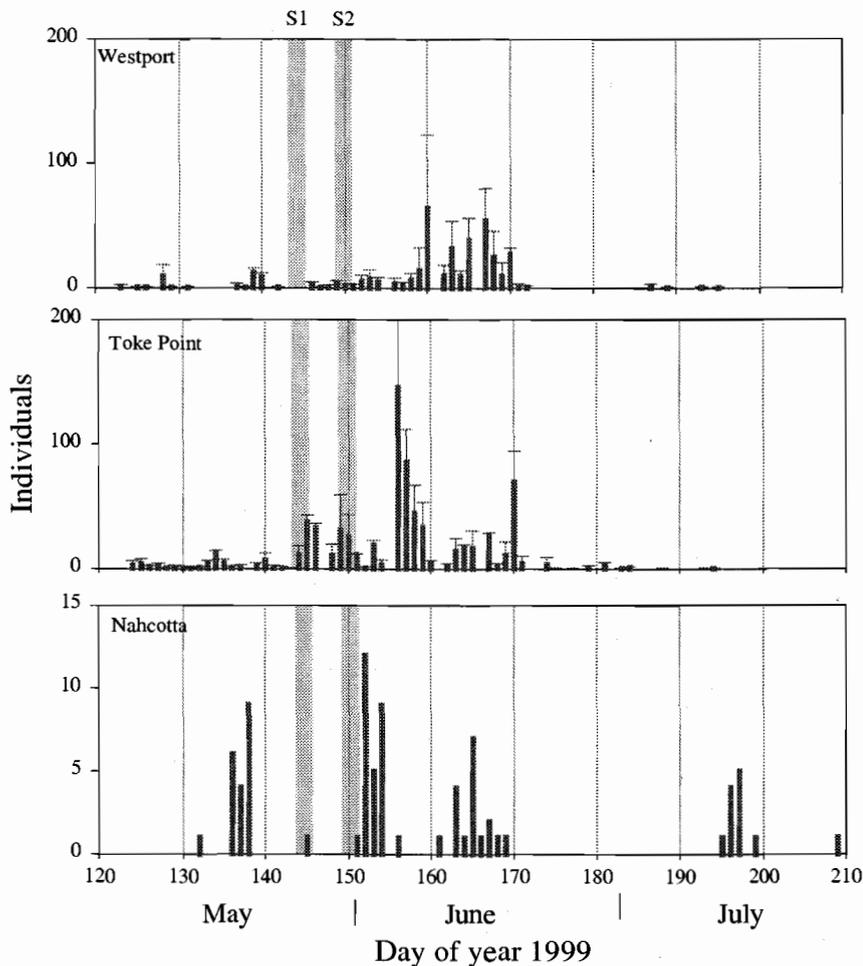


Figure 4.6. Time series of *Cancer magister* megalopae abundance (ind/night) for the 1999 recruitment period. Westport and Toke Point values are mean \pm sd ($n=3$). Survey 1 and 2 cruise periods are shown as shaded sections.

Surface plots of *Cancer*, *Pugettia*, *Lepas*, and cyprid concentrations during Survey 1 and Survey 2 illustrate the range of response patterns demonstrated by plankton groups to the upwelling cycle (Figure 4.5). Megalopae were patchily distributed, with the patch size often being defined by one or two stations. These patterns were in part caused by negative association to light. The *Cancer* distribution was remarkably similar between surveys despite the large change in ocean conditions. Note the high concentration between the mouths of WB and GH. In contrast, *Pugettia* and *Lepas* exhibited wider distributions but were much more abundant during Survey 2, with the crabs prevalent in the newly upwelled water nearshore and the barnacles distributed offshore. Cyprids and similar concentrations but distribution changed from nearshore to offshore as upwelling progressed. Thus, species distributions were

affected differently by the large-scale advective event. Larval swimming behavior is likely to cause some of this variance.

Estuary time series

Time series of light trap data for the three stations during 1999 show that, while low levels of megalopae were present for much of the time series, the bulk of annual recruitment occurred in distinct pulses (Figure 4.6). For the TP traps, megalopae abundance increased moderately during the cruise period, when the cruise transects detected high larval concentrations between the mouths of GH and WB. However, no corresponding peaks were observed for the GH site. This likely reflects the patch size of the larvae and the direction of coastal currents; these were observed during the cruise to be strongly southward in accordance with upwelling winds. Cross-correlation analysis between the WB and GH time series did not detect significant correlations at any lag, and recruitment between the estuaries was not coincident despite the likelihood that wind forcing was affecting both systems coincidentally. In contrast,

the NA and TP light traps had a maximum correlation coefficient (0.7) at a lag of 4 days, suggesting a link between ingress to the estuary and transport within it. Overall recruitment levels at NA were only 0.5% to 10% that measured from TP, itself very moderate compared to the Coos Bay time series (PNCERS 2000 Annual Report).

Crab abundance and oceanographic processes

The biophysical time series recorded by instrument moorings showed estuarine water characteristics were strongly influenced by oceanic processes. Wind stress was responsible for much of the event-scale variation (Figure 4.7). For the period encompassing the light trap time series, wind stress fluctuated from largely downwelling-favorable in May, to an upwelling event during the Lady Kaye cruise, then to an extended pe-

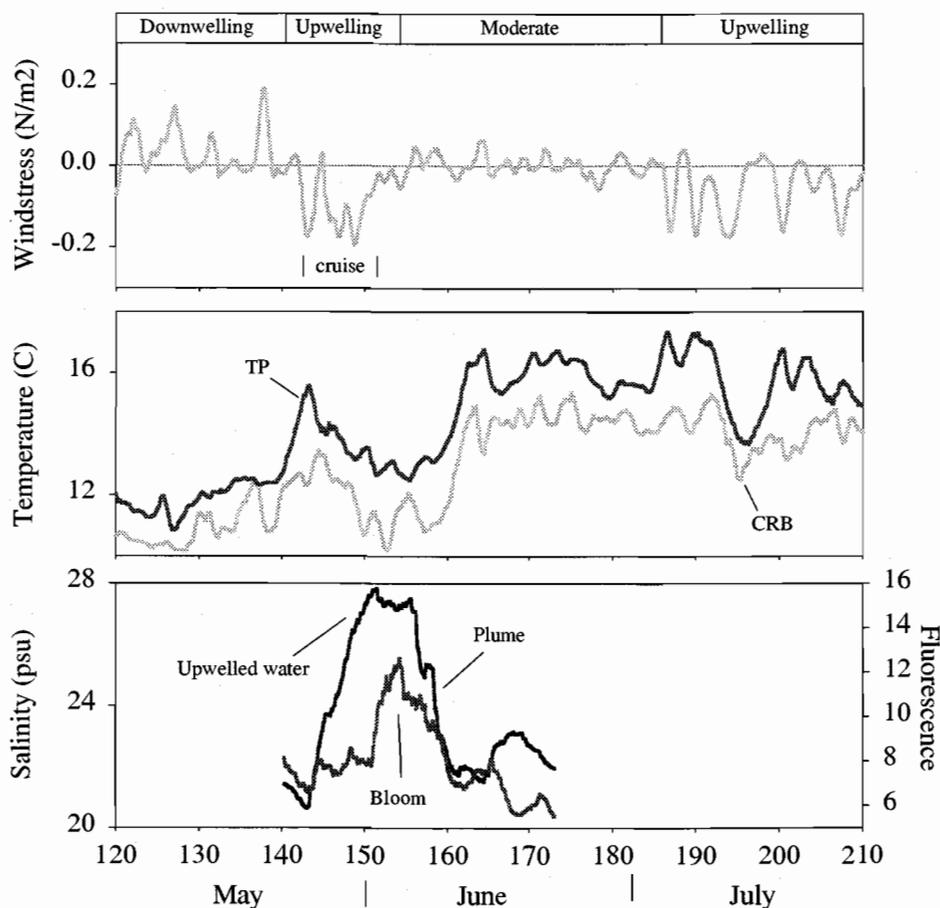


Figure 4.7. Time series of instrument mooring data for the 1999 recruitment period. Top, wind stress at the Columbia River Bar (CRB). Note designation of cruise period. Middle, temperature at Toke Point (TP) and CRB. Bottom, salinity and fluorescence at Bay Center.

riod of moderate (relaxed) wind stress, and finally to a period of upwelling/relaxation. These fluctuations influenced both estuarine and coastal (SST) temperature time series, which can be seen to track closely and supports close coupling of nearshore and estuarine water properties (Figure 4.7). The upwelling/relaxation cycle observed during the *Lady Kaye* cruise was responsible for large variation of salinity and chlorophyll in both nearshore ocean (Figure 4.3) and estuarine systems (Figure 4.7). Note especially the import of plume water to Willapa Bay, beginning around DOY 155, which resulted from relaxation from upwelling.

Megalopae recruited to WB and GH over a range of wind forcing and the resultant variation in water properties. In WB, two small pulses, corresponding to the increased nearshore concentrations measured offshore

during both Survey 1 and Survey 2, occurred when plume and upwelled water, respectively, were present in the estuary. The largest pulse of the WB recruitment season occurred in conjunction with the return of the plume (around DOY 155), and may reflect concentration of larvae in the plume front. Both GH and WB had a period of higher larval recruitment during moderate wind stress when plume water was entering the estuary. No large recruitment pulses occurred during the upwelling/relaxation period in July, despite evidence from the temperature time series suggesting advective transport had occurred. However, most of the annual recruitment is likely complete after June. For *Cancer* megalopae, the Columbia River plume was not a deterrent to estuarine recruitment and may have acted to concentrate larvae in the density front convergence zones.

Acknowledgments

Instrument mooring data from Bay Center was supplied by Jan Newton. We thank the crew of *Lady Kaye* for an informative voyage.

Applications

Publications:

Roegner, G.C., B. Hickey, J. Newton, A. Shanks, and D. Armstrong. (*in press*) Wind-induced plume and bloom intrusions into Willapa Bay, Washington. *Limnology and Oceanography*

Roegner, G.C. and A.L. Shanks. 2001. Import of coastally-derived chlorophyll *a* to South Slough, Oregon. *Estuaries* 24: 244-256.

Presentations:

Curtis Roegner, Barbara Hickey, Alan Shanks, David Armstrong, "Patterns of Larval Crab Abundance in Pacific Northwest Estuaries as Determined by Light Traps." *Ocean Sciences*, February 11, 2002, Honolulu, HI.

Curtis Roegner, David Armstrong, and Alan Shanks, "Measuring variation in larval supply to estuarine sites with light traps." Poster presentation at PICES X Annual Meeting, October 10, 2001, Victoria, B.C., Canada.

Jessica Miller, Alan Shanks, and Curtis Roegner, "Ocean-estuary coupling in the Coos Bay estuary: Nearshore and estuarine delivery of larval and juvenile fish and invertebrates." Poster presentation at PICES X Annual Meeting, October 10, 2001, Victoria, B.C., Canada.

Curtis Roegner, Barbara Hickey, Jan Newton, Alan Shanks, and David Armstrong, "Estuarine-nearshore links during a coastal upwelling-downwelling cycle: plume and bloom intrusions into Willapa Bay, Washington." PICES X Annual Meeting, October 9, 2001, Victoria, B.C., Canada.

Curtis Roegner, Barbara Hickey, Jan Newton, Alan Shanks, and David Armstrong, "Estuarine-nearshore links during a coastal upwelling-downwelling cycle: plume and bloom intrusions into Willapa Bay, Washing-

ton." Eastern Pacific Oceanography Conference, September 2001, Lake Tahoe, CA.

Jessica A. Miller, Alan Shanks, and Curtis Roegner, "Seasonal and interannual larval and juvenile fish use of Coos Bay, Oregon: A time series based on daily light trap collections." Pacific Estuarine Research Society, 17-19 May, 2001, Tacoma, WA.

Curtis Roegner, Barbara Hickey, Jan Newton, Alan Shanks, and David Armstrong, "Estuarine-nearshore links during a coastal upwelling-downwelling cycle: plume and bloom intrusions into Willapa Bay, Washington." Pacific Estuarine Research Society, 17-19 May, 2001, Tacoma, WA.

Curtis Roegner, "Nearshore-estuarine links in Pacific Northwest Estuaries: Plume and bloom intrusions in Willapa Bay." PNCERS Eat and Learn Seminar Series, February 5, 2001, University of Washington, Seattle, WA.

Jessica Miller and Alan Shanks, "Daily light trap collections of juvenile fish in Coos Bay, OR: A time series analysis." Western Society of Naturalists, 2001, Portland, OR.

Workshops:

Curtis Roegner, Alan Shanks, and David Armstrong attended the PNCERS All-Hands Meeting, January 11-12, 2001, University of Washington, Seattle, WA.

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Factors Influencing the Spatial and Annual Variability in Eelgrass (*Zostera marina* L.) Meadows in Pacific Northwest, USA, Systems Chapter 5

Ronald Thom, Amy Borde, Steven Rumrill, Dana L. Woodruff, Gregory D. Williams, John Southard, and Susan L. Blanton

Introduction

Purpose

The purpose of this paper is to examine factors influencing the spatial and annual variability in eelgrass (*Zostera marina* L.) meadows in Pacific Northwest estuaries. An understanding of these factors can be used to assess anthropogenic impacts on eelgrass within the context of natural spatial and temporal variation as well as increase knowledge needed for successful eelgrass restoration.

Background

Eelgrass is an ideal indicator of estuarine "health" because it forms meadows throughout much of all coastal estuaries in the region, harbors large numbers of fisheries species, is a nursery and feeding area for juvenile salmon and Dungeness crab, and responds to physical and chemical forcing factors through changes in its size, morphology, and distribution.

Objectives

The studies presented here are the culmination of several research programs, including the Habitat/Bioindicator Study as part of the Pacific Northwest Coastal Ecosystem Regional Study (PNCERS). The goal of this study was to provide resource managers and decision-makers with information about habitats that are useful in making management decisions in coastal estuaries of the Pacific Northwest. To achieve this goal, the study addressed two broad objectives: 1) to understand and document existing and historic patterns of primary benthic habitats in the target estuaries through geospatial analysis, and 2) to understand and document the factors responsible for spatial and interannual dynamics of selected habitats through directed field and laboratory studies. The latter objective is the focus of this paper.

Study Locations

The study sites were located in Puget Sound, the Strait of Juan de Fuca, Willapa Bay and Coos Bay (Figure

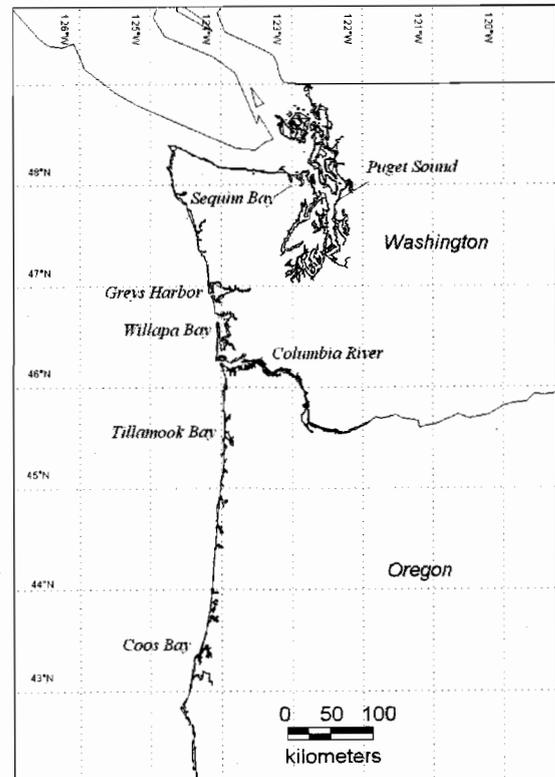


Figure 5.1. Location of study areas.

5.1). Depth distribution and light attenuation was documented at eight sites in Puget Sound (Figure 5.2). Puget Sound is a fjordal estuary with numerous rivers entering the system. Because of the steep nearshore morphology, eelgrass is confined to a narrow fringe of shoreline. Some deltas contain large expanses of eelgrass (e.g., Padilla Bay, 3000 ha). Surface salinities are generally 30 ppt or somewhat lower. A low salinity layer forms when river flows are great in winter and spring. Water temperatures fluctuate in nearshore areas where eelgrass occurs. Detailed studies on light requirements were conducted at Battelle Marine Sciences Laboratory (MSL) located at the mouth of Sequim Bay on the Strait of Juan de Fuca (Figure 5.2). Strong tidal currents flush this site with oceanic water entering the Strait. Field studies on depth distribution, annual variation in eelgrass standing stock, and temperature were conducted at six sites in Willapa Bay and four sites in Coos Bay (Figure 5.2). Sites in Coos Bay and Willapa Bay

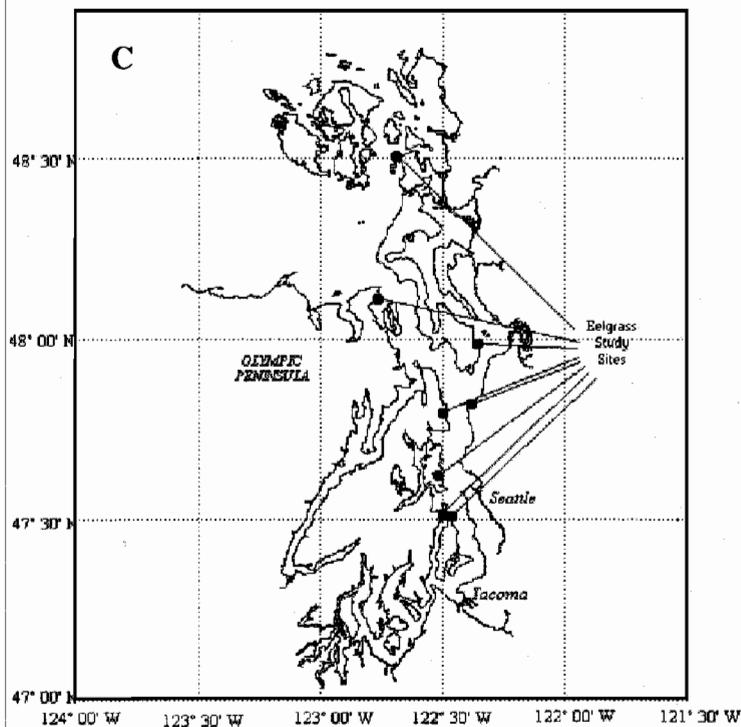
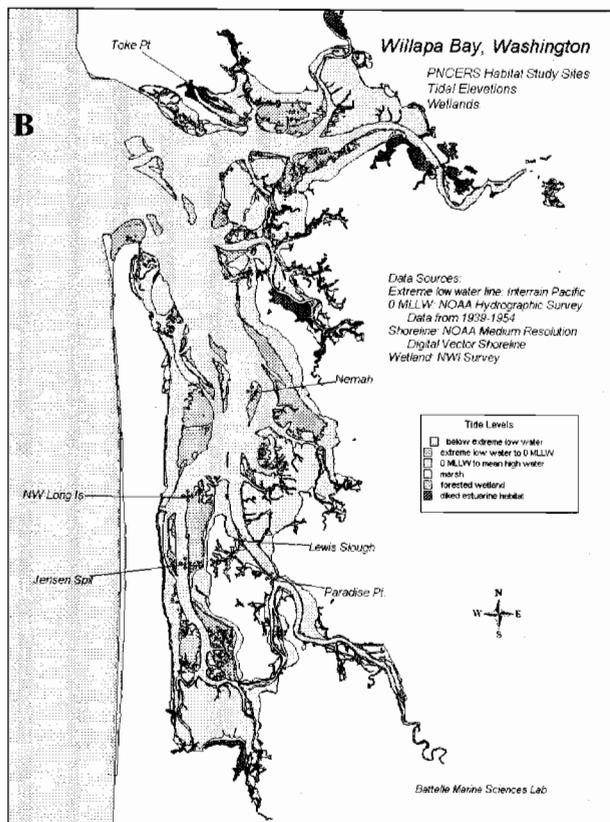
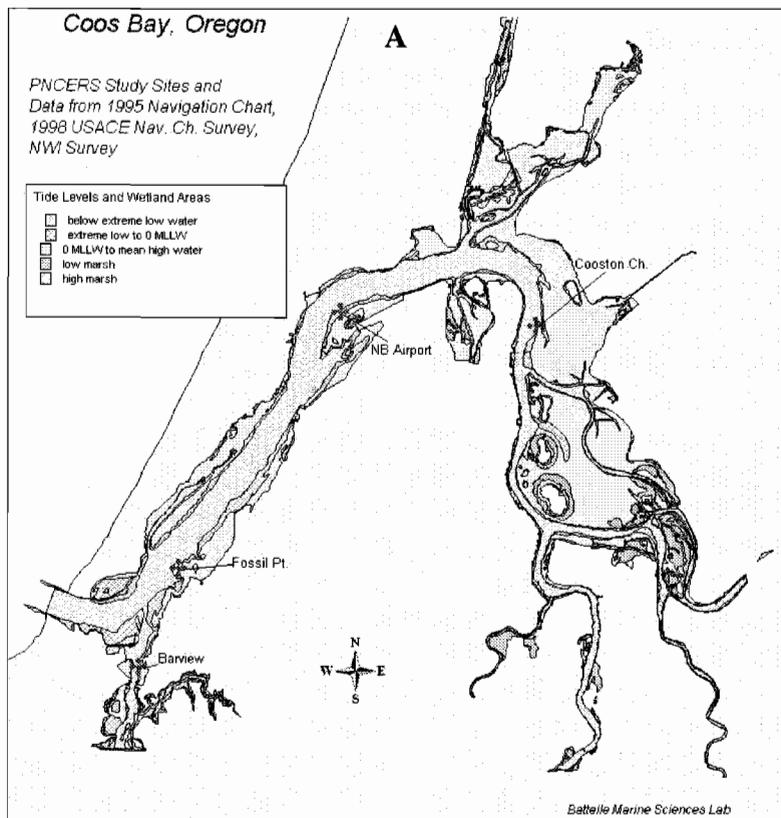


Figure 5.2. Location of study sites in Coos Bay (A), Willapa Bay (B), and Puget Sound (C).

were purposely established to span salinity-temperature gradient in these estuaries. Eelgrass covers approximately 58.1 and 5.1 km² in Willapa and Coos Bays respectively (Borde et al. in prep). All systems studied are subjected to mixed semidiurnal tides.

Materials and Methods

Light

Light requirements for eelgrass was investigated with field monitoring and laboratory studies. In the laboratory, we developed photosynthesis to irradiance (P vs I) relationships. We used three 10 cm long sections of clean (free of visible epiphytes or inorganic matter) and healthy portions of eelgrass leaves placed in glass jars. The jars were filled with filtered seawater taken from the mouth of Sequim Bay. The jars were placed on their side in a shallow (10 cm) flowing seawater bath that maintained water temperature near ambient. Dissolved oxygen was measured in the jars at the start and end of each run, and oxygen flux was used as a measure of photosynthesis. Five replicate jars were run containing eelgrass, and five jars were water-only blanks. The experiments were run outside under ambient sunlight, and photosynthetically active radiation monitored at 10-15 min intervals over a 1-3 hour incubation period. We ran two or three experiments each day taking advantage of varying natural light conditions. Experiments were conducted in summer (July, August), winter (January, February) and spring (March, April) spanning major variations in light as well as water temperature.

To investigate the effects of seasonal differences in light on eelgrass growth, we grew eelgrass in pots in a flowing seawater troughs over a 13 month period (November 1994-November 1995). Three healthy shoots with rhizome sections were planted into plastic flower pots containing sediment collected from the field where the plants were collected. The pots were placed in the flowing seawater tanks and various light treatments were created using layers of plastic screen. Four light levels were established in triplicate, with nine plants (three pots) subjected to each replicate within a treatment. Light was monitored continuously in one of the unshaded treatments, and light levels in the shaded treatments were established by periodically measuring light in these treatments relative to the unshaded treatment. We mea-

sured leaf growth on a weekly to biweekly basis depending on season, with less frequent measurements made during winter. To measure growth we trimmed the ends of all leaves extending beyond 30cm above the upper edge of the pot. All of the leaf tips trimmed from a treatment were pooled and dried and weighed to the nearest mg. Growth was recorded as change in biomass per treatment per unit time.

Light requirements were examined using field sampling of the depth distribution of eelgrass at sites in Puget Sound, six sites in Willapa Bay and four sites in Coos Bay. Using SCUBA in Puget Sound, we recorded shoot density within three 0.25 m² quadrats placed at 5m intervals along transects that spanned the depth distribution of eelgrass at the sites. The number of transects and sites varied among the sites depending on steepness of the gradient and lateral expanse of the meadow. Divers, using calibrated depth gauges, recorded the depth at each of the points where a density measurement was recorded. Overall, we recorded approximately 1,300 paired records of depth and density. PAR attenuation curves, mostly gathered in spring and summer at some of the sites, provided an indication of light penetration by depth in the central Puget Sound nearshore areas. Comparison of the density, depth, and PAR provided an indication of the effect of light on eelgrass abundance. Depth distribution in Willapa Bay and Coos Bay were sampled at low tide by recording eelgrass density within 1.0 m² quadrats placed along transects that spanned the depth gradient of eelgrass at the sites. Turbidity limits the lower depth of eelgrass in both bays to very shallow depths that were possible to sample during extreme low tides. We gathered samples in Willapa Bay and samples in Coos Bay in this manner. Depth was established by surveying (using a hand level and stadia rods) the elevation of the quadrat relative to the water's edge. The time of each sample was recorded and the depths were then calibrated to actual depths for the day of the survey using tide curves for NOAA tide recording stations nearest the site.

Salinity

We evaluated the effect of salinity on leaf section productivity of eelgrass by subjecting plants to 1 hour and 24 hour exposures to various salinities and then measuring oxygen flux in jars as described for light experiments. The plants used were collected from the Sequim Bay site and placed in 4 L jars containing salinity treat-

ments of 0, 10, 15, 20, 25, 30, 35, and 40 ppt. Hypersaline treatments were developed using brine from evaporated seawater. Three replicate leaf sections were cut from three separate plants within each salinity treatment and were then placed in jars containing the appropriate salinity for determination of oxygen flux rates. Five replicate jars of water-only controls (no leaf sections) were run for each treatment.

We also conducted growth experiments in three salinities: 10, 20 and 30 ppt. About 150 plants were planted in each of three flowing seawater troughs, which contained sediment from the field. Each trough had a different salinity treatment, and hence treatments were not replicated. Salinity was maintained by continuous dilution of water entering the troughs. Growth was measured at weekly intervals for three weeks during April 1999 using the leaf trim method described above for light experiments.

Temperature

We evaluated the effect of temperature on net primary productivity and respiration using the oxygen flux methods described above. In this set of experiments we incubated leaf sections in five replicate jars in temperature treatments ranging from about 3 to 30 °C. Because of difficulties at maintaining temperatures, we had fewer treatments above about 20 °C. Experiments were run in saturating light intensities. Following the incubations in light, we measured leaf respiration by incubating the same leaf sections under various temperature treatments for several hours in the dark.

Nutrients

We evaluated the effect of nutrient enrichment on eelgrass productivity using the oxygen flux methods described above. Plants were collected from four sites in Willapa Bay. In a series of experiments spanning four days (one site each day), three 1-cm leaf sections were placed in 500-ml glass jars with 500 ml seawater (taken from the site) and 0.6 ml ammonium stock solution. Random samples were extracted from the spiked seawater and ambient seawater for nutrient analysis prior to initiation of the experiment. The set of five replicate jars were placed in a freshwater bath which was renewed to maintain approximately 20 °C. Three additional sets of five replicates each were also placed in the freshwater bath. These treatments were eelgrass with no ammonium spike and seawater-only, with and

without the ammonium spike. Experiments were conducted outside in ambient sunlight. After 3-4 hours the experiment was terminated and four random samples were extracted from each of the four treatments. The samples were frozen and shipped to the University of Washington oceanography lab for nutrient analysis. Nitrate (NO_3), nitrite (NO_2), ammonia (NH_4), and phosphate (PO_4) concentrations were determined using an autoanalyzer (Technicon AAI) following UNESCO (1994). Total nitrogen (TN) and total phosphorus (TP) concentrations were determined following the methods in Valderrama (1981).

Sediment Respirometry

We conducted incubation experiments at six sites in Willapa Bay to evaluate sediment-associated respiration rates following the methods outlined in Thom et al. (1994).

Substrata

To evaluate the effect of substrata type on eelgrass growth, we planted three shoots with rhizome segments in plastic flower pots containing the sediment treatments. The pots were placed in the flowing seawater troughs. Growth was measured weekly for 13 weeks using the leaf trim method described above. The sediment treatments included the qualitative range of sediment types in which eelgrass occurs in the Pacific Northwest (i.e., medium to fine sand, fine sand-silt), as well as two sediment types outside this qualitative range (coarse organic-poor sand, and gravel-rock; Phillips 1984). The sediments from which eelgrass plants were acquired for the experiment were included as a treatment.

Erosion

To evaluate bottom velocities and erosion of eelgrass, a small (ca 0.1 m² x 10-cm deep) patch of eelgrass sod with associated sediment (a medium to fine sand, with moderate organic matter) collected at the Sequim Bay site was established in a flume and subjected to increasing current velocities. Care was taken to minimally disturb the sediment and eelgrass during removal and positioning of the patch. The edges of the patch were contoured to create a very gentle slope between the bottom of the flume and the top of the sod. This was done to reduce eddies that may have been created by an abrupt edge. The sod, which contained 38 healthy eelgrass shoots, was left undisturbed in the flume for a week prior to testing. A reference sod was held in a

trough with gently flowing seawater. Water was piped through a 10-cm diameter pipe into the flume in a manner to allow incremental increases in current speed, and a baffle was positioned between the source of water and the eelgrass patch to create a laminar flow field. Velocities were measured using a hand-held digital water velocity meter (Global Water). Ten velocities, ranging from 0 to 325 cm s⁻¹ were used in the experiment.

Experiments were conducted outside, under natural light in July. Each run consisted of gradually bringing currents up to the target velocity (i.e., over a period of approximately one minute) and maintaining the velocity for 2-3 minutes. Following the run, water was partially drained from the flume to facilitate measurements. The measurements and observations included: (a) depth of sediment at nine points spread evenly over the surface of the sod; (b) number of shoots with rhizomes exposed (i.e., no surrounding sediment); and (c) number of shoots lost. Depth of the sediment was measured to the nearest mm by inserting a thin, pointed, plastic ruler into the sediment until it touched the bottom of the flume. Sediment lost was not replaced prior to the next run. Hence, the experiments reveal the effect of incrementally increasing bottom currents on erosion of sediments and plant loss. Following the experiments, the sod was maintained in gently flowing ambient seawater for 10 days. Observations were subsequently made on the condition of plants in the flume and the reference patch.

Field Monitoring

We conducted two primary field efforts to document seasonal, annual, and spatial variation in eelgrass.

Seasonal Monitoring. The first consisted of monitoring eelgrass growth rate on a biweekly basis along with PAR at the Sequim Bay site. Monitoring of growth and light was conducted during several separate studies. Taken together the studies covered all months except September. During each study, growth over a two-three week interval was measured using the leaf marking method described by Thom et al. A number of shoots were marked and measured from plots in the middle of the eelgrass meadow at an elevation of about 0 to -0.3 m MLLW (mean lower low water). PAR was recorded continuously using an underwater spherical quantum sensor (LI-COR) suspended at the depth of the plots from a dock located approximately 200m from the plots. Water temperature was continuously measured using a

recording thermometer which recorded seawater flowing into the seawater system at MSL.

Annual Monitoring. The second field effort measured annual variability in midsummer (July-August) eelgrass assemblages in Willapa Bay and Coos Bay (Figure 5.1). The six sites in Willapa Bay and the four sites in Coos Bay spanned a salinity gradient from oceanic near the mouth to a zone of highly variable salinity which ranged from 13 ppt to 32 ppt driven by variations in river flows. Temperature varied over this gradient also because of the dynamic nature of tidal-forced currents, winds, upwelling events, and river flows. The plots at each site consisted of 100 m-long transects that were established parallel to the waters edge. The elevations of the plots ranged between 0.0 and -1.0 m MLLW, which was generally in the middle of the eelgrass depth range within these systems. Eelgrass at these low intertidal sites served as an indicator of the variation of the eelgrass populations in the estuaries. We sampled eelgrass within 20 equally spaced 1.0 m² quadrats along the transects. In the field, we recorded percent surface cover of vegetation, substrata, and animals using qualitative categories of 5% cover increments (e.g., eelgrass 80%, seaweed 5%, bare substrata 15%). Next, we recorded the number of eelgrass shoots within the quadrat. Finally, we recorded the number of shrimp (ghost shrimp, *Neotrypaea californiensis* and mud shrimp, *Upogebia pugettensis*) burrows. Because we resampled these plots in four consecutive years, we implemented a protocol to minimize disturbance of the vegetation and sediments.

For above ground biomass determination, we collected 30 shoots in a nonselective manner in a location adjacent to the plots, but containing plants appearing similar to those found in the plots. To measure below ground biomass, we collected 10-cm diameter cores to a depth of 10 cm at five points adjacent to the plots. We sieved these cores through a 2-mm mesh screen and placed the material retained on the screen into labeled plastic bags.

In the laboratory, visible epiphytes were cleaned from the plants by gentle scraping with a fingernail. We recorded if the shoot was flowering. The width of the second or third oldest (and healthy) leaf, on nonflowering shoots only, was measured in the approximate middle of the leaf. Eelgrass leaves have a constant width over the vast majority of their length. Finally, we dried each

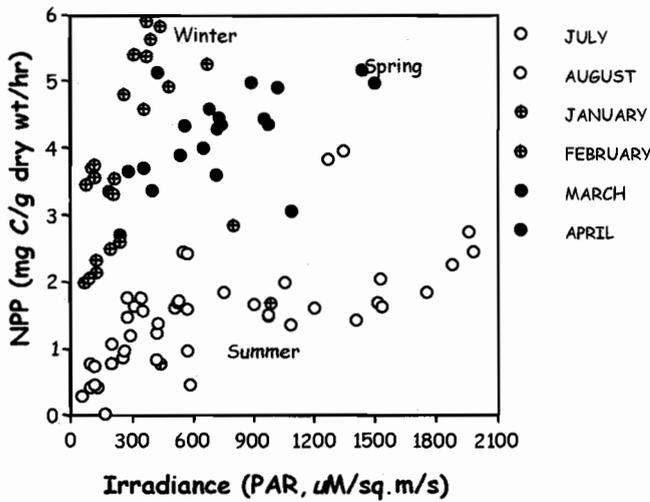


Figure 5.3. Productivity vs. irradiance relationships for eelgrass leaf segments.

of the shoots and recorded their weights to the nearest mg. Above ground biomass was calculated by multiplying mean shoot density by mean shoot weight. All live root and rhizome material from the core samples were similarly dried and weighed.

We recorded sedimentation by measuring the surface of the sediment relative to a fixed point above the sediment surface. To do this, we drove two heavy PVC plastic pipes sections, spaced 1 m apart, as far as possible into the sediment, and cut their tops approximately 30 cm above the surface of the sediment. We suspended a heavy wooden meter stick between the tops of the two stakes, and measured the vertical distance between the meter stick and the sediment surface at five points along the meter stick. Two of these sedimentation stations were established within 1 m of each plot.

Temperature was recorded at 1.1 hour intervals using a continuous temperature logger (HOBO from Onset Computer Corporation) at each site in Willapa Bay and Coos Bay. The sensors were firmly attached at the sediment surface to a stake located at one end of each transect. Sensors were downloaded annually during field trips. We also collected water temperature and salinity data within 0.5 m of the surface and at the bottom immediately offshore from each site using a multiprobe (YSI 600XLM). This latter sampling was conducted only during the annual field trips to the Willapa Bay and Coos Bay sites.

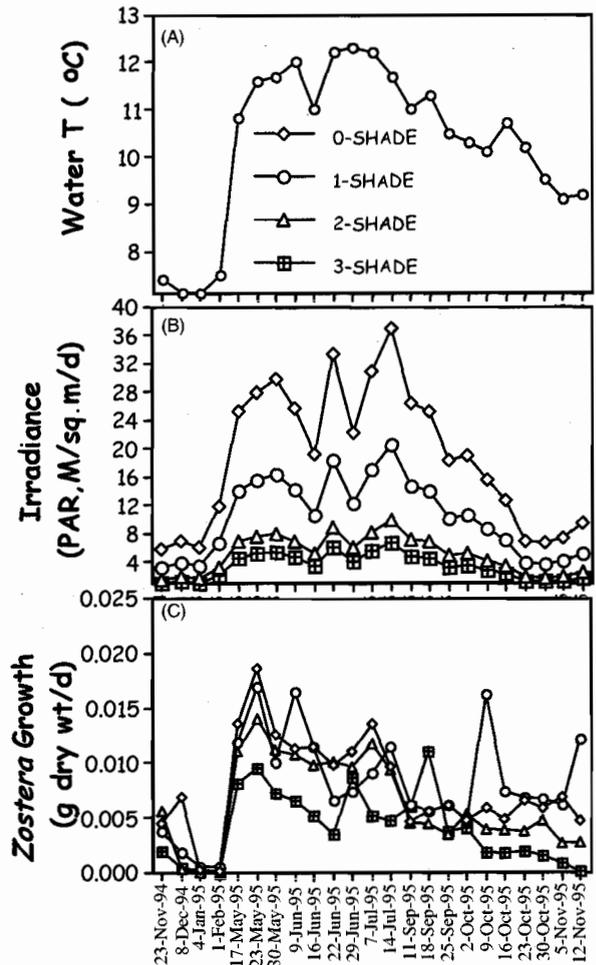


Figure 5.4. Eelgrass growth relative to irradiance and water temperature in shading experiments.

Results

Light

Maximum photosynthesis rates for leaf sections appeared to generally occur at 300-500 $\mu\text{M m}^{-2} \text{s}^{-1}$ PAR independent of the season of the experiment (Figure 5.3). However, rates within this irradiance range varied among seasons. Experiments conducted in winter months showed rates on the order of three times greater than summer rates. Spring rates were intermediate between summer and winter rates.

The long-term growth experiments conducted under various shade treatments showed that growth in May through September was generally supported by all irradiances evaluated (Figure 5.4). However, there was slower growth during this period, and there was a noticeable decline in growth in October-November, among

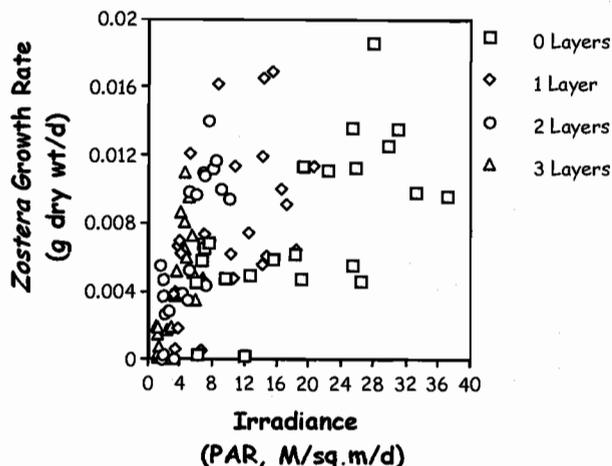


Figure 5.5. Eelgrass growth from shading experiments plotted against irradiance for various shade layers.

plants subjected to the greatest shade. In fact, plants died in the lowest light treatment by the end of the experiment in November, whereas plants in other treatments remained alive although growth was reduced. A scatter plot of growth vs. average integrated daily irradiance indicated that growth maximized at approximately 4-8 $M\ m^{-2}\ d^{-1}$ (Figure 5.5). Temperature probably had an influence on growth (Figure 5.4), and variation in temperature throughout the year may have been responsible for much of the scatter in Figure 5.5.

Eelgrass was found between about -1 and -7m relative to mean sea level (MSL) in Puget Sound, with maximum shoot densities recorded between -2 and -3 m MSL (Figure 5.6). Irradiance curves near the sites where

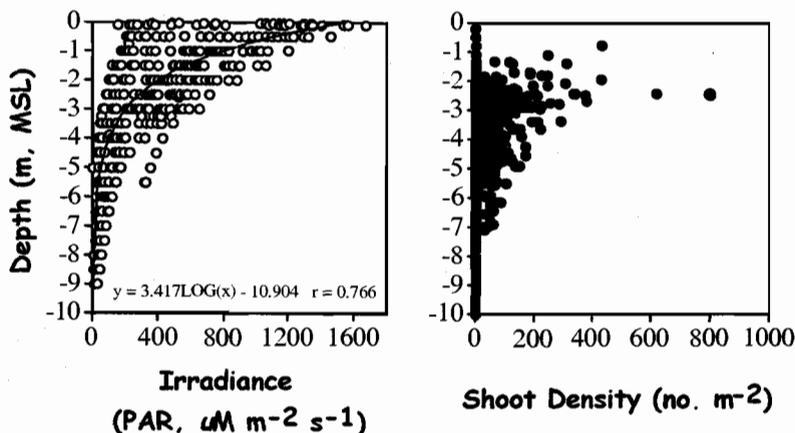


Figure 5.6. Depth distribution of eelgrass shoot density and associated light attenuation profiles for sites in Puget Sound.

eelgrass was sampled indicated that PAR averaged approximately $400\ m^{-2}\ s^{-1}$ at the depth where eelgrass densities were maximum, and about $50-100\ m^{-2}\ s^{-1}$ at the deepest point where eelgrass was observed. Eelgrass was restricted to much shallower depths in Willapa Bay and Coos Bay (Figure 5.7). Attenuation coefficients showed that water clarity was greater in Puget Sound than the two outer coast estuaries.

Salinity

Net primary productivity varied with salinity treatments, with greatest NPP associated with salinities of 30 and 35 ppt (Figure 5.8). There appeared to be no consistent difference between treatments lasting 1 hour or 24 hours. Eelgrass grew in all three salinity treatments over a three-week period (Figure 5.9). It was apparent after two weeks that plants grew substantially slower at 10 ppt salinity as compared to 20 and 30 ppt.

Temperature

Net primary productivity peaked at about 11-15 °C (Figure 5.10A), with negative (oxygen uptake) rates recorded at 19 °C and above. Respiration increased linearly with increasing temperature. Using this relationship, we calculated R for all temperatures that were run for NPP experiments to produce the plot of NPP:R (Figure 5.10B). This ratio showed a dramatic peak between about 5-7 °C. The ratio was low but positive at greater temperatures.

Substrata

Eelgrass grew in all sediment treatments (Figure 5.11). As expected, lowest growth occurred in a mixture of

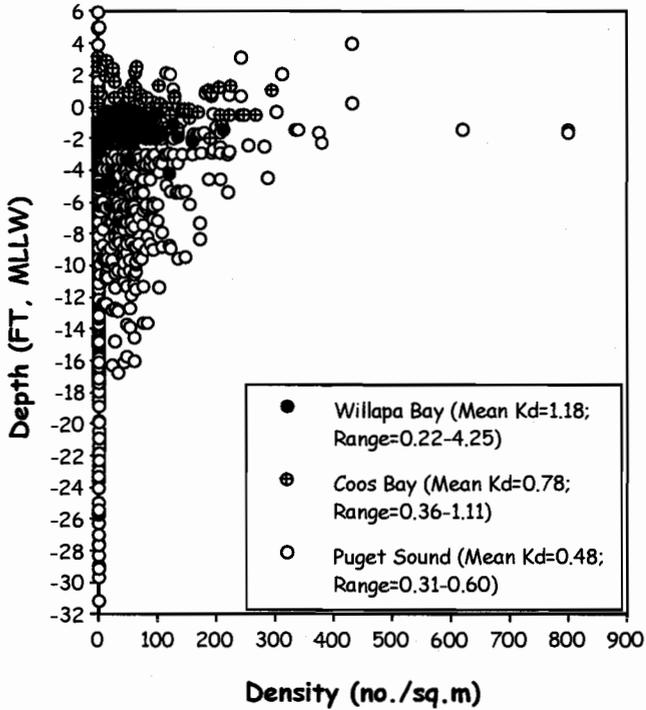


Figure 5.7. Depth distribution of eelgrass shoot density for Puget Sound, Willapa Bay, and Coos Bay sites. The mean attenuation coefficient measured for the three areas is shown.

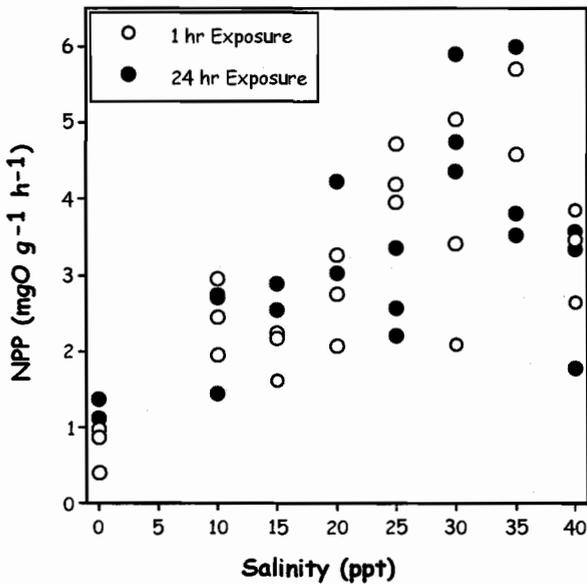


Figure 5.8. Net primary productivity (NPP) versus salinity for eelgrass exposed to each treatment for 1 and 24 hours.

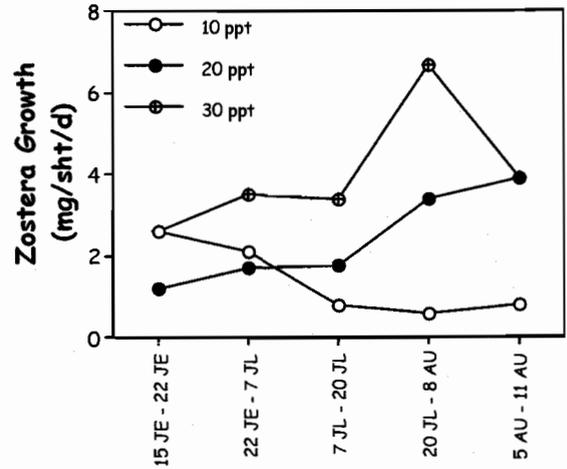


Figure 5.9. Growth rate of eelgrass in three salinity treatments.

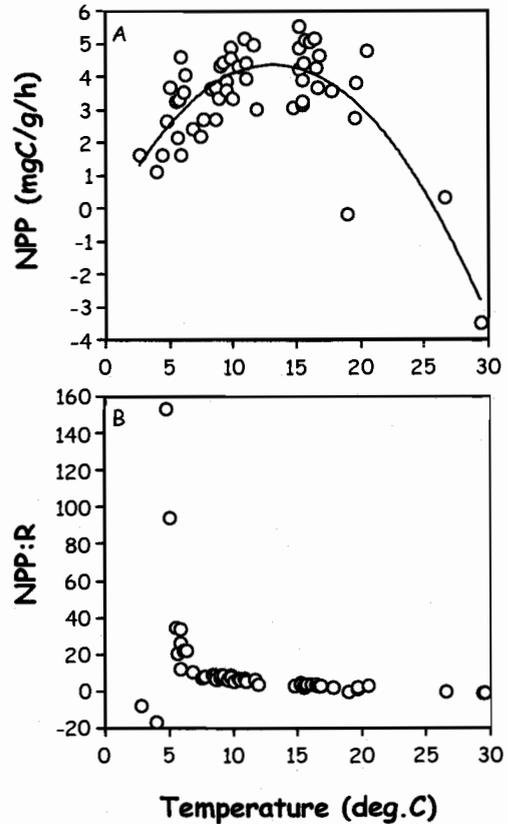


Figure 5.10. Net primary productivity (NPP) and NPP:Respiration (R) ratio versus temperature.

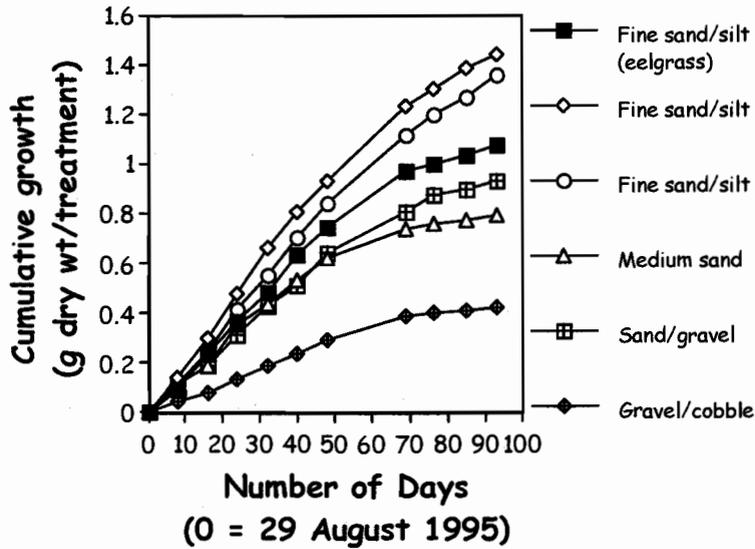


Figure 5.11. Cumulative growth rate of eelgrass in various sediment types.

gravel/rock. Greatest growth occurred in finer grained sediments containing organic matter. Coarse-grained sand and the sand/gravel mixture produced intermediate growth rates.

Field Monitoring

Seasonal Monitoring. The monitoring at the Sequim Bay site showed that eelgrass net shoot production occurred all seasons and exhibited a seasonal pattern (Figure 5.12), with a low period in winter and a maximum in spring. Net growth was intermediate during summer.

Water temperature peaked in midsummer, showed a small increase between January and February, and a greater rate of increase between February and June (Figure 5.12). Integrated daily PAR was very low between January and April, and showed an substantial increase in May through July (Figure 5.12). This pattern in PAR is partially explained by sea level variations. Very low tides (i.e., those falling below MLLW) begin to occur during daylight hours in April. During autumn, winter, and early spring, these low tide events occur during periods of very low light or darkness. The increase in net shoot production (Figure 5.12) corresponded more closely with the increase in temperature than with the increase in PAR between January and April.

Annual Monitoring. Mean shoot density at Willapa Bay showed an increase between 1998 and 2000 at all sites,

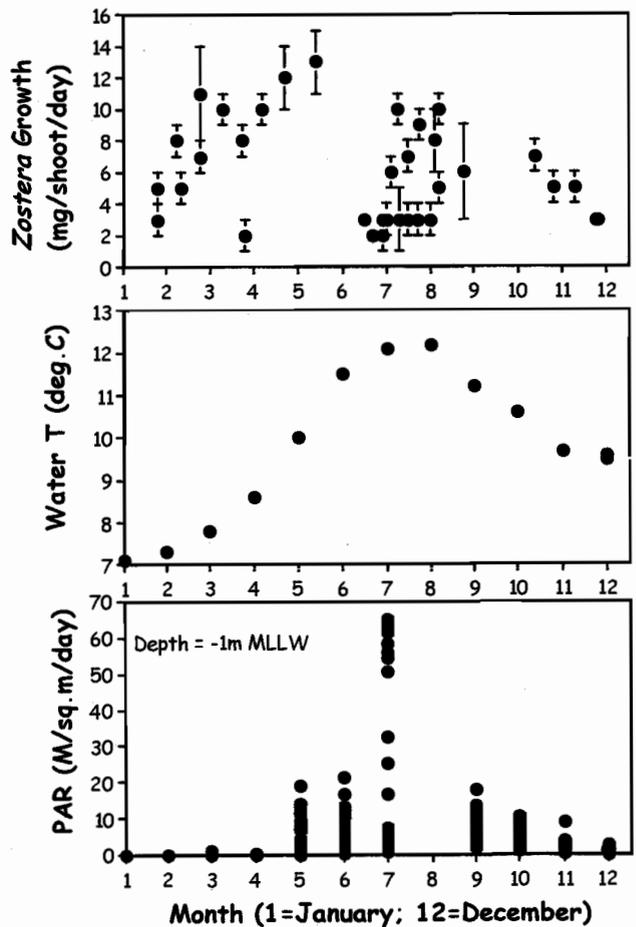


Figure 5.12. Eelgrass growth rate, mean water temperature, and daily integrated PAR at the mouth of Sequim Bay.

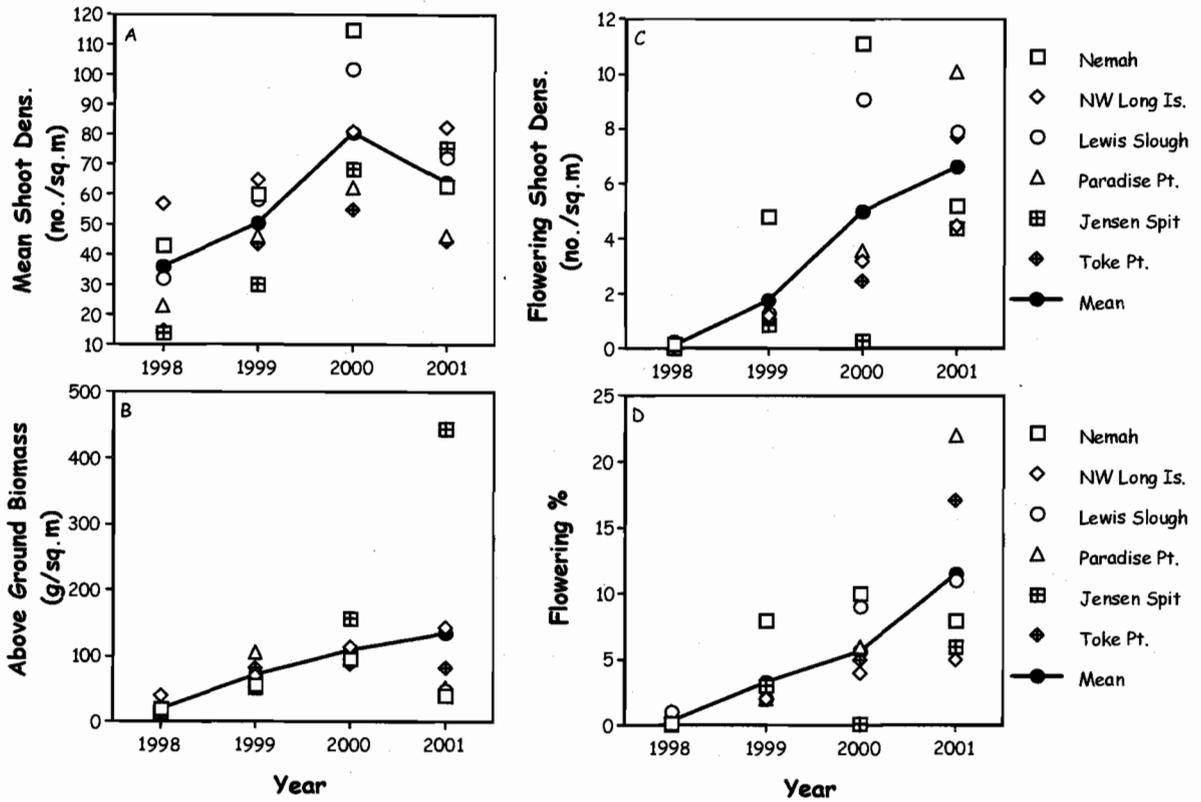


Figure 5.13. Annual values of eelgrass shoot density (A), above ground biomass (B), flowering shoot density (C), and percent flowering (D) at sites in Willapa Bay.

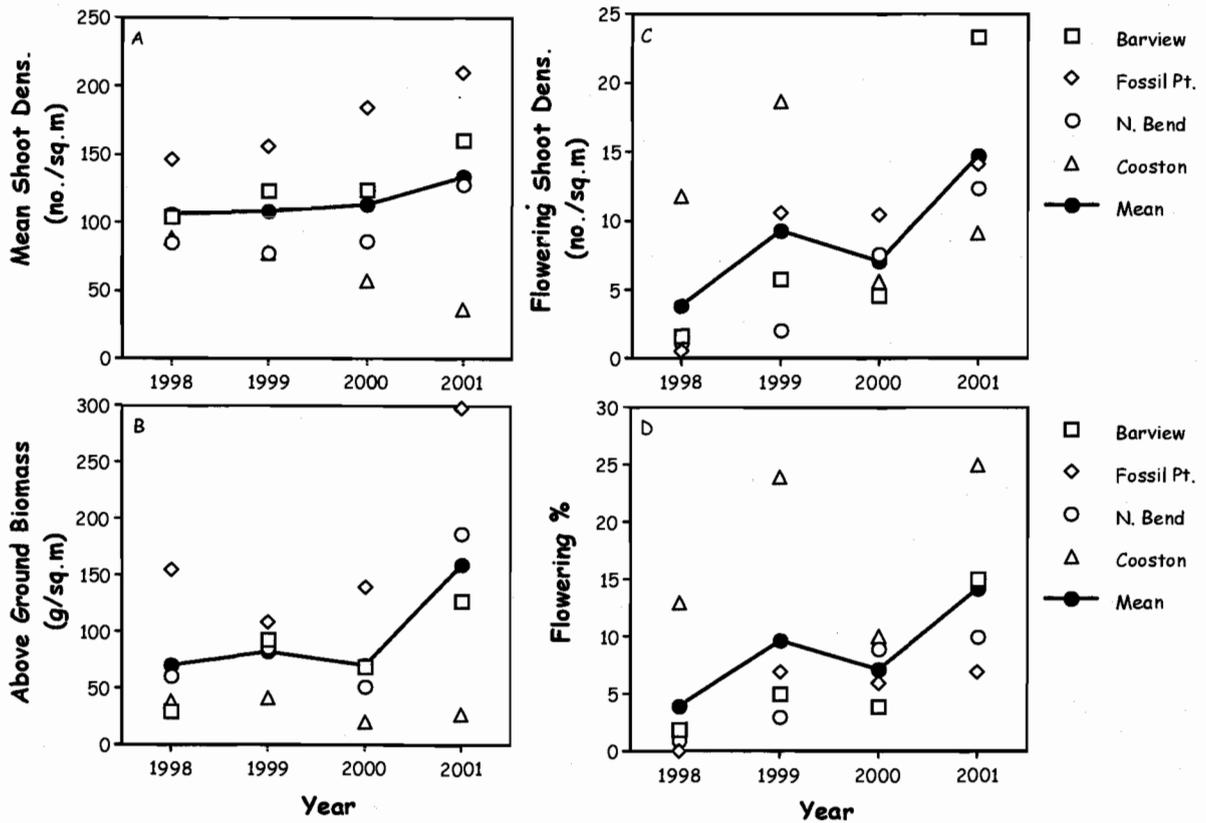


Figure 5.14. Annual values of eelgrass shoot density (A), above ground biomass (B), flowering shoot density (C), and percent flowering (D) at sites in Coos Bay.

and declined between 2000 and 2001 (Figure 5.13A). Eelgrass density tripled and more than quadrupled at the Nemah and Jensen Spit sites, respectively, between 1998 and 2000. The most oceanic site, Nemah, had the greatest mean densities recorded over the study period in Willapa Bay. Mean shoot density overall increased approximately 2.6 times between 1998 and 2000. Above ground biomass varied in conjunction with shoot density, with an average fivefold magnitude increase between 1998 and 2000 (Figure 5.13B). There was a decline in biomass between 2000 and 2001 except at Jensen Spit. There were a few very large generative shoots that skewed the biomass at this site in 2001.

Average generative shoot density and percent of shoots flowering steadily and dramatically increased between 1998 and 2001 on average over all sites in Willapa Bay (Figure 5.13C). The percent of the population that flowered increased from less than 1% on average to 12% (Figure 5.13D). Paradise Point plants showed the most change and had the greatest flowering percentage recorded (~22%). Plants at NW Long Island exhibited the least variability.

Annual variation in shoot density and biomass was less pronounced in Coos Bay as compared to Willapa Bay (Figures 5.13A, B, 5.14A, B). In contrast to Willapa Bay, there were considerable differences among sites in the degree of annual variation. The most oceanic sites (Fossil Point, Barview) showed steady increases in density on the order of 40-45%, whereas the mid-estuary site (North Bend) was stable 1998-2000 and increased (~60%) in 2001. Density declined steadily at the most up-estuary site at Cooston Channel between 1998 and 2001, with density in 2001 being only about half that in 1998. Biomass was greater at the two outer estuary sites as compared with mid and inner estuary sites (Figure 5.14B). There was an approximate doubling of biomass between 2000 and 2001 at three of the sites, with little change at Cooston Channel.

Flowering varied in Coos Bay with a low point in 1998 on average and a peak in 2001 (Figures 5.14C, D). Generative shoot density was over three times greater in 2001 as compared with 1998 on average with the greatest change documented at Barview (Figure 5.14C). In three of four years, the highest proportion of flowering shoots was consistently recorded at the most up-estuary site.

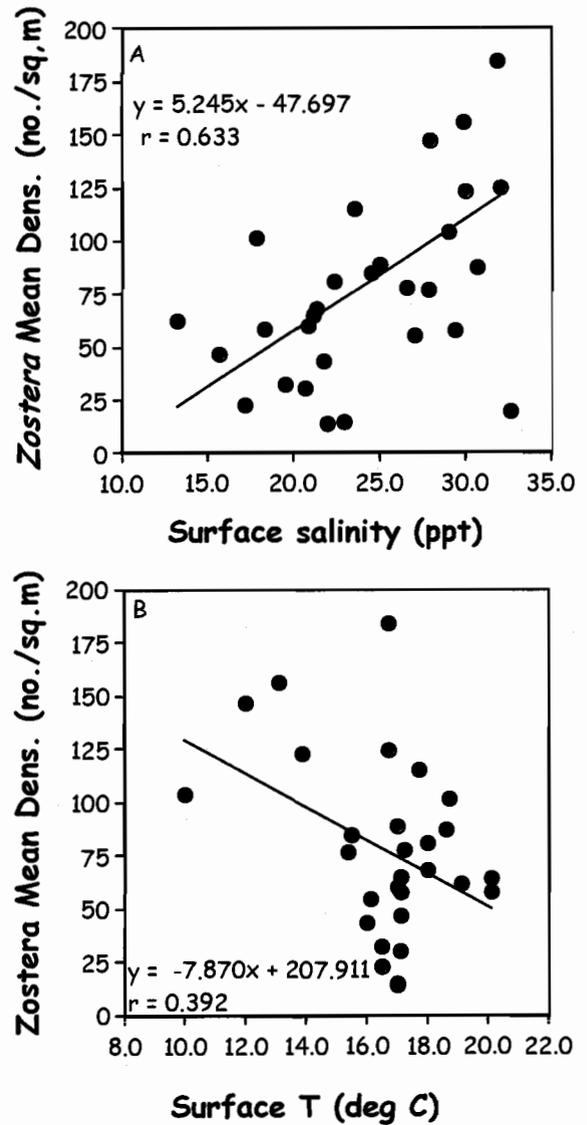


Figure 5.15. Eelgrass density versus surface salinity (A) and temperatures (B) at Willapa and Coos Bay sites.

Eelgrass density was about twice as great in Coos Bay (~115 m⁻²) as compared to Willapa Bay (~55 m⁻²) when averaged over the four years (Figures 5.13A, 5.14A). Mean biomass in Coos Bay substantially exceeded that in Willapa Bay in 1998, but was either similar or slightly less in the other years (Figures 5.13B, 5.14B). Average percentage flowering was 1% to 6.5% greater in Coos Bay as compared to Willapa Bay in 1998-2001. Between 4% and 14.5% of the population flowered on average in Coos Bay as compared to 0.5% and 12% in Willapa Bay. The two highest values (24% and 25%) for percentage flowering among all sites were recorded at Cooston Channel.

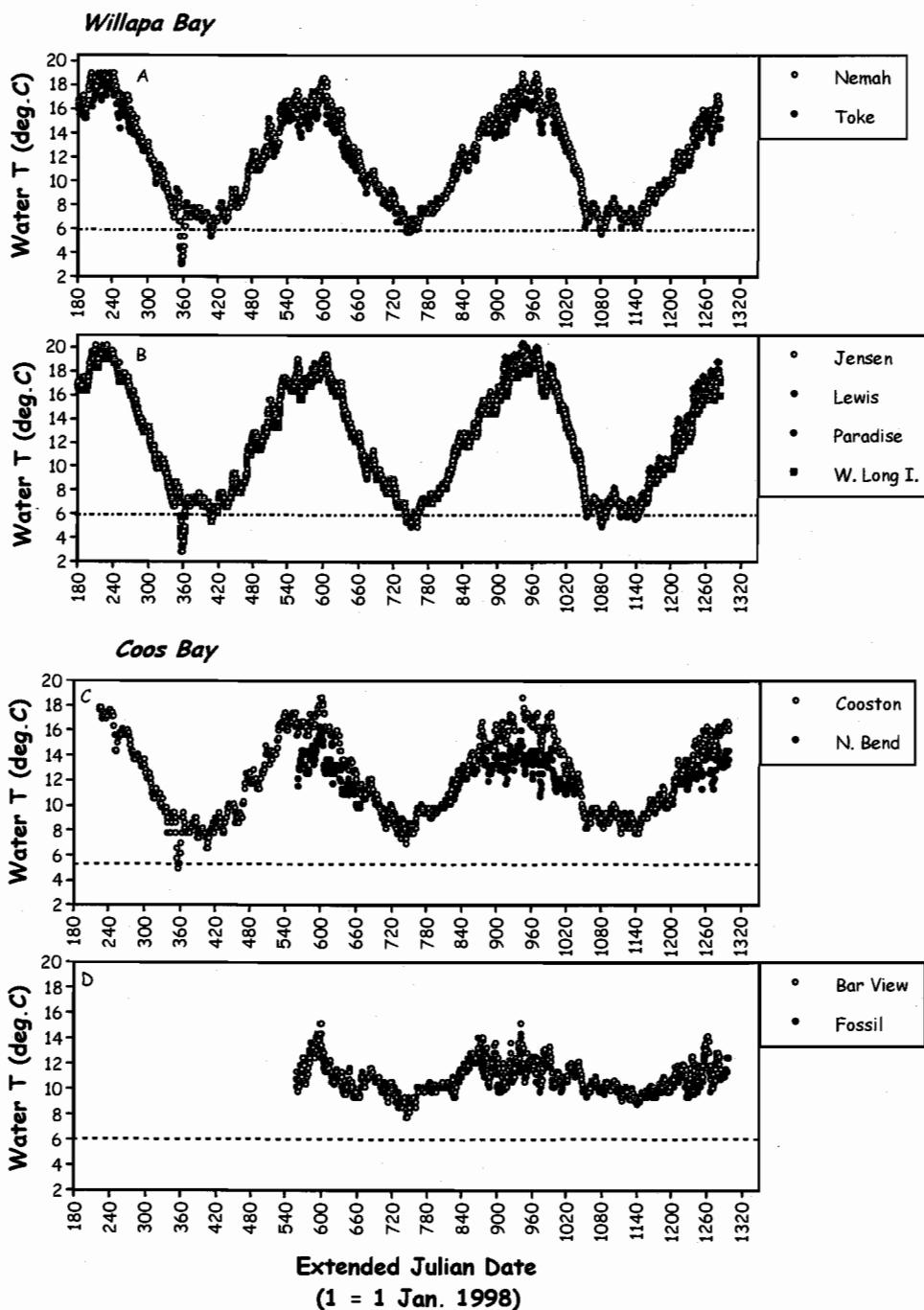


Figure 5.16. Median daily temperatures at Willapa Bay (A, B) and Coos Bay (C, D) sites between summer 1998 and summer 2001.

Eelgrass Density versus Salinity and Temperature. Using eelgrass data from all four years at all sites, shoot density showed a positive relationship with summer surface water salinity (Figure 5.15A). Density showed a negative and weaker relationship to summer surface water temperature (Figure 5.15B). Data on water properties were from spot samples collected during the sampling period, and are only somewhat indicative of the gradients exhibited in the estuaries. These two water properties, taken together, indicate that areas of greater salinity and lower temperatures tend to have greater shoot densities.

Temperature Monitoring. Because of instrument loss, we did not acquire full data sets at all sites. However, the temperature monitoring showed the dynamic seasonal patterns at all sites (Figures 5.16A-D). The patterns that emerge are as follows:

- Oceanic sites in both estuaries show a smaller range in temperature than up-estuary sites (Figures 5.16A, D).
- Coos Bay sites tended to have cooler summers and warmer winters than Willapa Bay sites.
- Water temperatures appeared to trend toward somewhat cooler in summer and warmer in winter beginning in 1999.

Acknowledgments

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is sincerely appreciated. We thank the PNCERS management team, and the other members of the PNCERS study team, for their help throughout this study.

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Applications

Publications:

None.

Presentations:

Ronald Thom, Amy Borde, Steven Rumrill, Gregory Williams, Dana Woodruff, and John Southard, "Spatial and Interannual Variability in Eelgrass Abundance and Biomass in Willapa Bay, Washington and Coos Bay, Oregon." Estuarine Research Federation Biennial Conference, November 4-8, 2001, St. Pete Beach, Florida.

Amy Borde, Ronald Thom, and Steve Rumrill, "Geospatial Habitat Analysis in Pacific Northwest Coastal Estuaries." Poster presentation at PICES X Annual Meeting, October 10, 2001, Victoria, B.C., Canada.

Ronald Thom, Amy Borde, Steven Rumrill, Gregory Williams, Dana Woodruff, and John Southard, "Historical Changes and Short-term Spatial and Interannual Variability in Marshes and Seagrass Meadows in Willapa Bay, Washington and Coos Bay, Oregon." PICES X Annual Meeting, October 9, 2001, Victoria, B.C., Canada.

Amy Borde, "Annual Variability in Eelgrass Abundance and Biomass in Willapa Bay, Washington and Coos Bay, Oregon". Pacific Estuarine Research Meeting, May 17-19, 2001, Tacoma, Washington.

Ron Thom, "Carbon Sinks in Nearshore Marine Vegetated Ecosystems". First National Conference on

Carbon Sequestration, May 14-17, 2001, Washington, D.C.

Ron Thom, "Eelgrass Meadows as Indicators of Estuarine Condition". PNCERS Eat and Learn Seminar Series, March 7, 2001, University of Washington, Seattle, Washington.

Ron Thom, "The Influence of Climate Variation and Change on Structure and Processes in Nearshore Vegetated Communities of Puget Sound and Other Northwest Estuaries". Puget Sound Research Conference, February 12-14, 2001, Bellevue, Washington.

Workshops:

Ronald Thom, Steve Rumrill, and Amy Borde attended the PNCERS All-Hands Meeting, January 11-12, 2001, University of Washington, Seattle, WA.

Partnerships:

Dr. Brett Dumbauld provided laboratory space at the Nahcotta Laboratory of the Washington Department of Fish and Wildlife for processing samples during our field trip to Willapa Bay.

The Oregon Institute of Marine Biology provided laboratory space for processing samples during our trip to Coos Bay.

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Survival Rates of Coho (*Oncorhynchus kisutch*) and Chinook Salmon (*O. shawytscha*) Released from Coastal Washington and Oregon HatcheriesChapter 6

Arni Magnusson and Ray Hilborn

Introduction

Coho (*Oncorhynchus kisutch*) and chinook (*Oncorhynchus tshawytscha*) salmon have been released from hatcheries on the U.S. and Canadian Pacific coast since the late 1800s, but it was not until the 1960s and 1970s that the number of hatcheries and their release output increased dramatically. This was in response to dwindling spawner returns, and today more than half of the salmon catches in the Pacific Northwest are of hatchery origin. However, in Alaska the opposite is true, where most runs consist of wild spawners in pristine watersheds (NRC 1996).

The number of returning spawners, wild and hatchery-reared, fluctuates considerably between years and the dynamics behind those changes are often far from understood. Due to the complex salmon life cycle their survival can be impacted by a multitude of physical and biological factors in local watersheds and the ocean. Macdonald et al. (1988) approached this problem with a direct experiment and found that chinook smolts are subject to considerable mortalities in estuaries and in the ocean just outside estuaries, but in recent years much of the research effort has been directed towards coho survival rate and its relationship with oceanic conditions (Ryding and Skalski 1999; Cole 2000; Hobday and Boehlert 2001). In this paper, temporal patterns of coho and chinook survival rate are compared between regions in an attempt to separate watershed-specific changes from interregional trends. If regions separated by hundreds of kilometers show similar fluctuations of survival rate it seems likely that large-scale effects such as climate play a dominant role in determining salmon survival rate. If the temporal patterns of coho and chinook survival rates look similar within a region, it seems likely that the two species are subject to the same kind of mortalities.

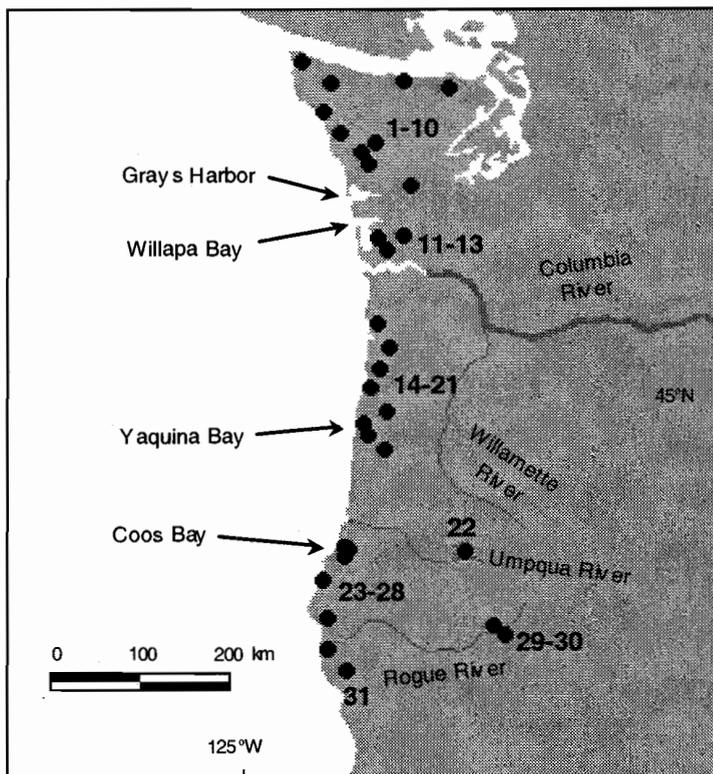


Figure 6.1. Map showing the 31 hatcheries releasing coho and fall chinook in coastal Washington and Oregon. The Columbia River divides coastal Washington and Oregon.

Methods

Survival rate, defined as the proportion of individuals surviving from smolt release to adulthood, was estimated from coded-wire-tag (CWT, Jefferts et al. 1963; Johnson 1990) recoveries obtained from the CWT database of the Pacific States Marine Fisheries Commission (Gladstone, Oregon). The analysis included 15,136 coho and fall chinook CWT groups, tagged and released from 189 hatcheries in Alaska in the north to California in the south. The coho groups were released in the years 1972–1998 and the fall chinook groups were released 1972–1996. Survival rates of spring chinook (Magnusson 2002) are not reported here, as relatively few of them are released from coastal hatcheries in Washington and Oregon.

Coho are released at age two and fall chinook during the first year following their brood year. Both species generally return at age three, but the age distribution at recovery varies between regions, and because of this variation, standardization of the number of fish recovered (Coronado and Hilborn 1998) was necessary to compare survival rates between regions:

$$N_3^* = C_2s_2 + C_3 + \frac{C_4}{s_3} + \frac{C_5}{s_3s_4} + \frac{C_6}{s_3s_4s_5}$$

where N_3^* is the number of 3-year-olds from a particular release group that would be alive if none were recovered at an age different from age three, C_a is the

number of fish recovered at age a , and s_a is the adult ocean survival rate from age a to $a + 1$. For coho, $s_a=0.5$ across all ages, but for chinook $s_2=0.6$, $s_3=0.7$, $s_4=0.8$, $s_5=0.9$ (Argue et al. 1983). This assumed adult ocean survival rate plays a minor role in the computations, since most individuals are recovered at age three, and should not be confused with the estimated smolt-to-adult survival rate which depends primarily on the first few months after release. Survival rate of each CWT release group was estimated as:

$$\text{Survival} = \frac{N_3^*}{\text{No. released}}$$

Table 6.1. List of the 31 hatcheries releasing coho and fall chinook in coastal Washington, Oregon and California. "Label" refers to the map labels, "Grps" stands for number of CWT groups released and "Surv" stands for average survival rate.

Label	Hatchery	State	Estuary	Coho		Fall chinook	
				Grps	Surv	Grps	Surv
01	Dungeness	WA	Dungeness Bay	50	4.19%		
02	Lower Elwha	WA	Freshwater Bay	28	1.28%	31	0.31%
03	Makah	WA	Mukkaw Bay	43	3.66%	46	0.26%
04	Solduc	WA	Quillayute River	115	1.42%	25	0.37%
05	Chalaat Creek	WA	Hoh River	13	1.03%		
06	Salmon River (WA)	WA	Queets River	46	1.00%	11	0.70%
07	Quinault	WA	Quinault River	54	1.30%	55	0.81%
08	Quinault Lake	WA	Quinault River	53	1.15%	43	0.71%
09	Humptulips	WA	Grays Harbor	62	2.20%	10	1.23%
10	Bingham Creek	WA	Grays Harbor	61	1.55%	14	0.51%
11	Forks Creek	WA	Willapa Bay	26	2.87%	17	1.13%
12	Nemah	WA	Willapa Bay			18	1.06%
13	Naselle	WA	Willapa Bay	10	5.96%		
14	Nehalem	OR	Nehalem Bay	52	1.26%		
15	Trask	OR	Tillamook Bay	53	1.31%	139	0.75%
16	Cedar Creek	OR	Nestucca Bay			17	0.62%
17	Salmon River (OR)	OR	Salmon River	50	0.81%	59	2.28%
18	Siletz	OR	Siletz River	30	1.27%		
19	Yaquina Bay	OR	Yaquina Bay	628	0.75%	85	1.14%
20	Wright Creek	OR	Yaquina Bay	59	0.38%		
21	Fall Creek	OR	Alsea Bay	122	1.09%	14	0.90%
22	Rock Creek	OR	Umpqua River	37	1.47%	33	0.56%
23	Coos Bay (Anad Inc)	OR	Coos Bay	239	1.91%	135	1.07%
24	Domsea Farms	OR	Coos Bay	13	0.95%	10	0.35%
25	Coos Bay (Oreg Aqua)	OR	Coos Bay	22	0.73%		
26	Bandon	OR	Coquille Bay	12	0.72%	10	0.25%
27	Elk River	OR	Elk River			146	1.82%
28	Indian Creek	OR	Rogue River			14	0.53%
29	Cole Rivers	OR	Rogue River	59	2.77%	280	2.23%
30	Butte Falls	OR	Rogue River	54	1.76%	15	0.99%
31	Burnt Hill Creek	OR	Chetco Bay			19	0.92%

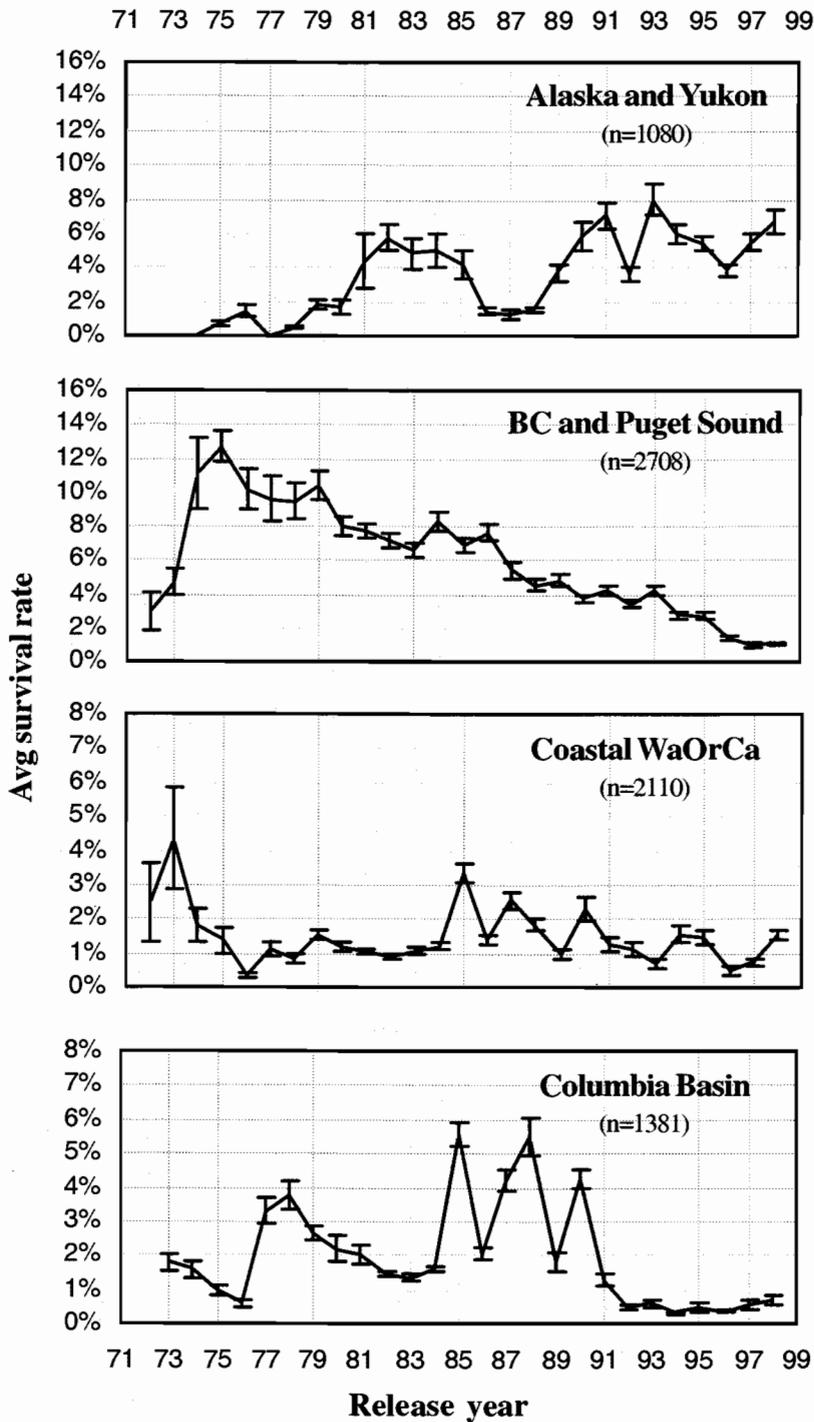


Figure 6.2. Coho survival rates by release year in each geographical domain. The number of CWT groups released is shown within parenthesis and the error bars show the standard error of the mean.

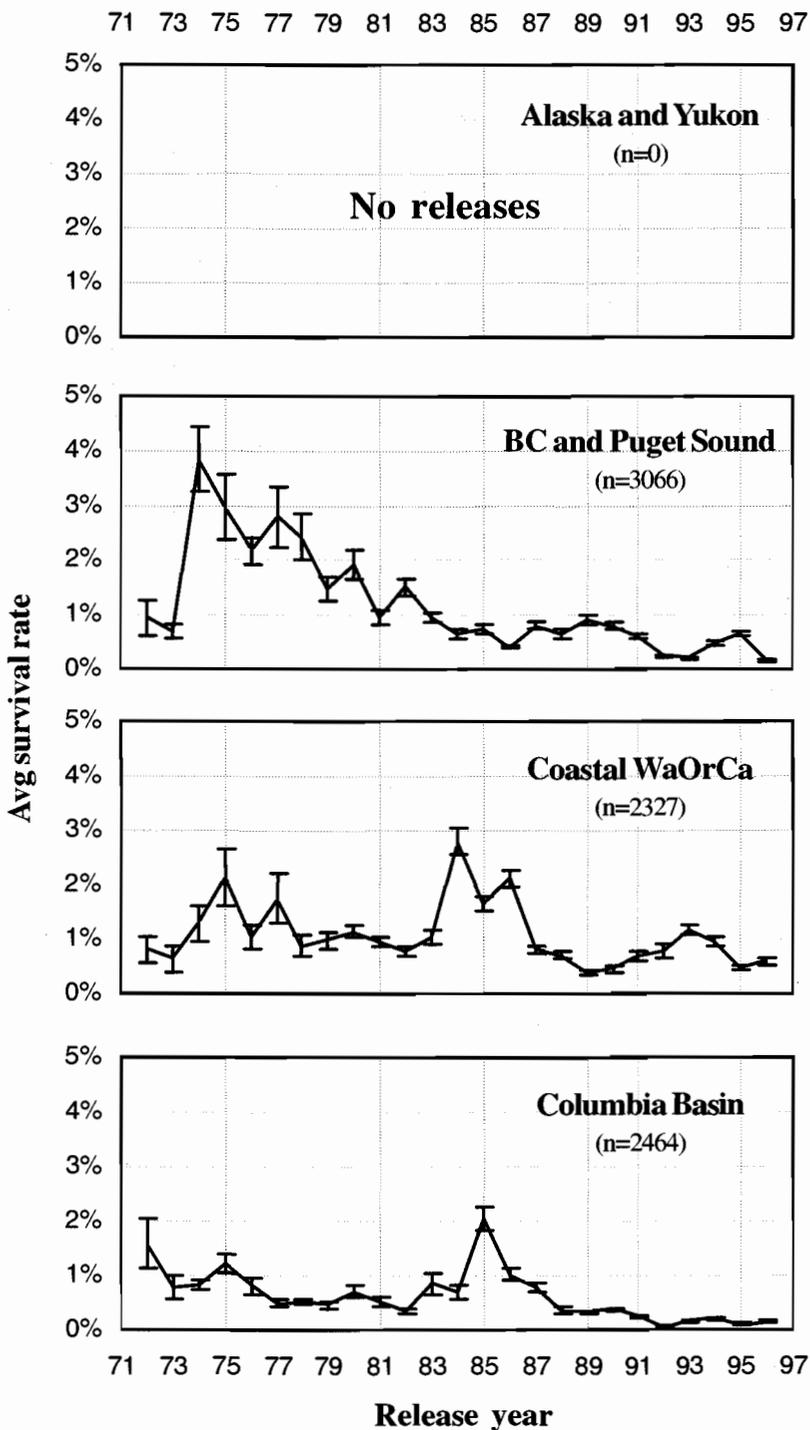


Figure 6.3. Fall chinook survival rates by release year in each geographical domain. The number of CWT groups released is shown within parenthesis and the error bars show the standard error of the mean.

All recoveries are treated the same, be they from ocean catches, freshwater catches, or hatchery escapement, which makes the survival rate a robust statistic under varying fishing intensity. Average survival was calculated as the arithmetic mean of survival for individual tag codes, grouped by hatchery location and release year, and the standard deviation of the mean is included in the charts as a measure of variability of the average survival.

The 189 hatcheries are grouped into four geographic domains on the basis of similar survival rate trends: (1) Alaska and Yukon; (2) British Columbia and Puget Sound; (3) Coastal Washington, Oregon and California; and (4) Columbia Basin. The 31 hatcheries in coastal Washington and coastal Oregon (Figure 6.1, Table 6.1) release coho and fall chinook into 22 different estuaries, and four key estuaries were analyzed in further detail: Grays Harbor, Willapa Bay, Yaquina Bay and Coos Bay. The wetted area of each estuary is 252 km², 347 km², 17 km² and 50 km², respectively (Simenstad 1984).

Apart from release and recovery data of hatchery-reared salmon, the CWT database contains a small amount of data from wild smolt tagging studies. When nearby hatcheries were releasing groups of the same species in the same year, these data allow a comparison of survival rates of hatchery and wild fish. The longest comparative time series are presented, with 85 wild groups of coho tagged in northern Washington and 34 wild groups of fall chinook tagged in northern California.

Results

All regions

The average survival rate of all 7279 coho CWT groups is 3.4%. In British Columbia and Puget Sound the survival rates have declined steadily from around 11% in the mid 1970s down to around 2% in the mid 1990s (Figure 6.2). During the same time period, the survival rates in Alaska have been increasing from around 1% to 6%, except for a sharp temporary decline in 1986–1988. The coho survival rate patterns in Columbia Basin are characterized by large fluctuations (between 1.3% and 5.6%) during the 1980s, followed by very low survival rates in the 1990s, around 0.5%.

Fall chinook are only released in regions south of Alaska, and the average survival rate of all 7857 CWT groups is 0.8%. The temporal patterns (Figure 6.3) are not unlike those found for coho, being a steady decline in British Columbia and Puget Sound, from around 3% in the mid 1970s down to around 0.5% in the mid 1990s. Another similarity is the consistent low survival rate in Columbia Basin during the later years, around 0.2% on average in the 1990s.

Coastal Washington and Oregon

The average survival rate of coho released from hatcheries in coastal Washington is 2.0%, somewhat higher than 1.2% in coastal Oregon (Figure 6.4). In Oregon, the highest coho survival rates are during the mid 1980s, but the fluctuations in Washington are less regular. Fall chinook survival rates average 0.6% in coastal Wash-

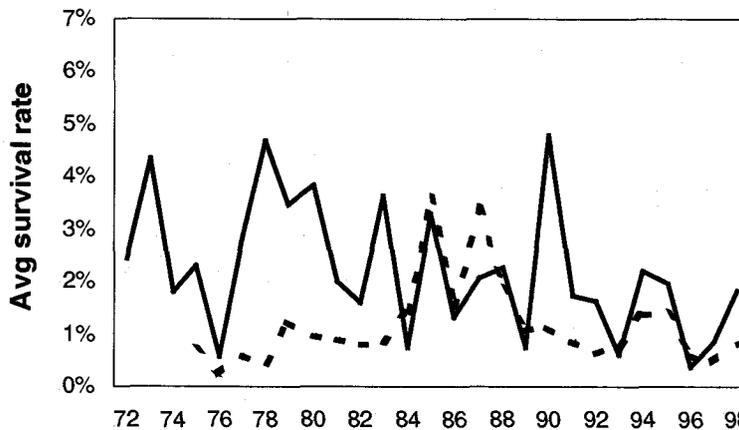


Figure 6.4. Coho survival rates by release year in coastal Washington (solid line, 561 CWT groups) and coastal Oregon (dotted line, 1430 CWT groups).

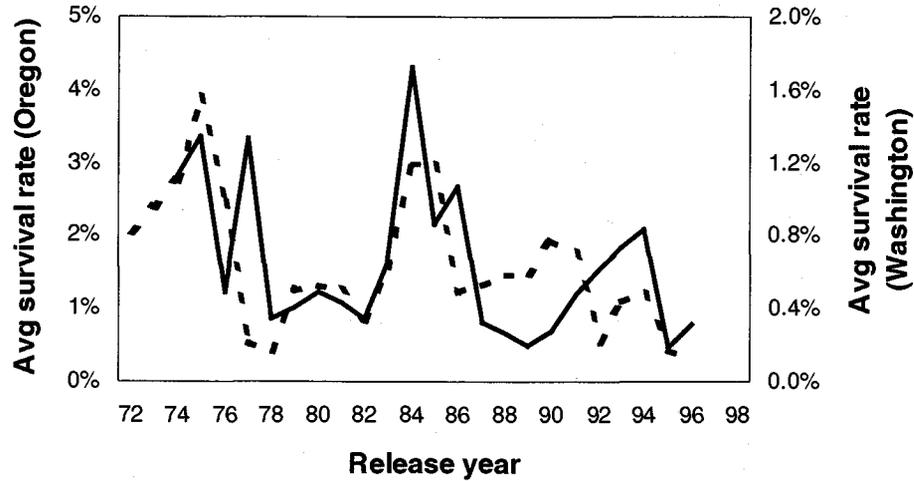


Figure 6.5. Fall chinook survival rates by release year in coastal Washington (solid line, 270 CWT groups) and coastal Oregon (dotted line, 976 CWT groups).

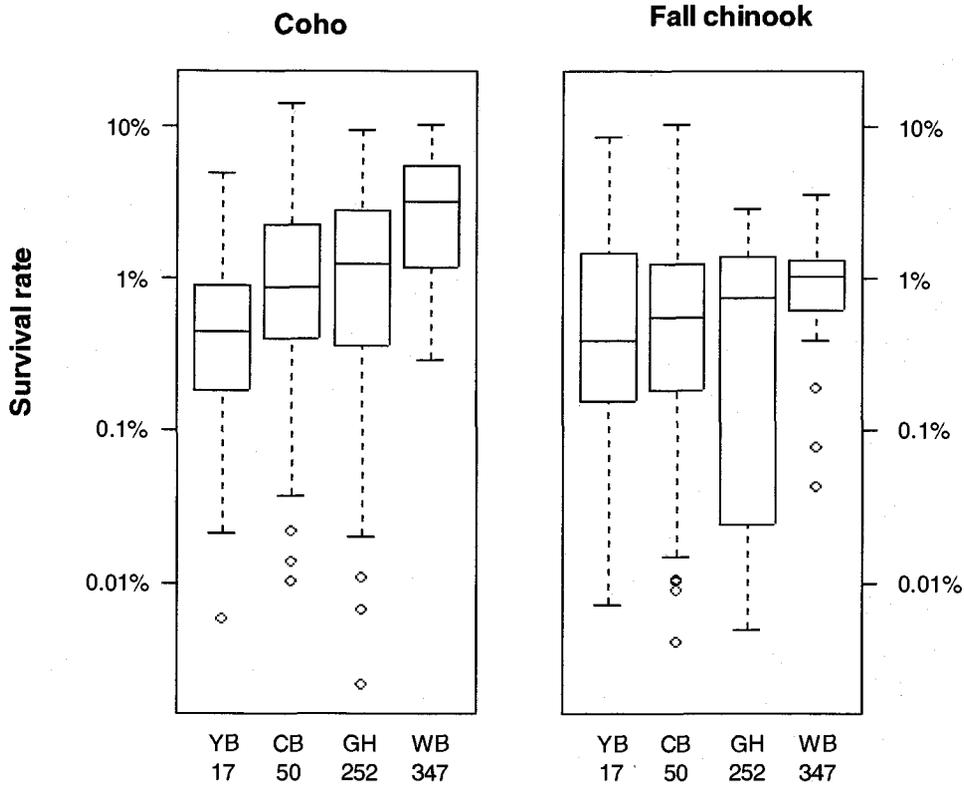


Figure 6.6. Boxplots of coho and fall chinook survival rates in Yaquina Bay (YB), Coos Bay (CB), Grays Harbor (GH), and Willamette Bay (WB). The survival rates are graphed on log-scale and the numerical labels show the size of each estuary in km².

ington, which is considerably lower than 1.5% in coastal Oregon (Figure 6.5), but in proportional terms the trends are quite similar. In both regions the highest survival rates are in the mid 1970s and mid 1980s.

The three hatcheries that have released most coho CWT groups are all in Oregon, (Yaquina Bay, Coos Bay/ Anadromous Inc., and Fall Creek), but the hatcheries with the highest coho survival rates are all in Washing-

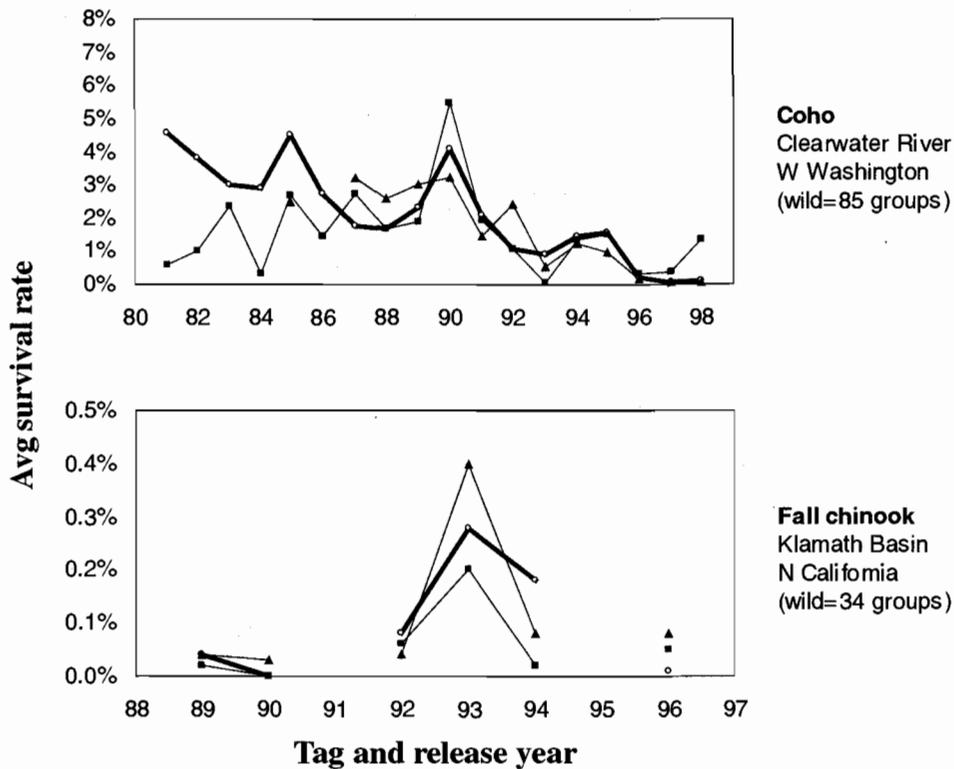


Figure 6.7. Survival rates of tagged wild (W) smolts compared with those released from nearby hatcheries (H). For the purposes of comparison, datapoints are only displayed in years when tagging was conducted both at hatcheries and in the wild.

ton: Naselle, Dungeness, and Makah (Table 6.1). For fall chinook, on the other hand, the hatcheries with the most releases (Cole Rivers, Elk River, and Trask) and the highest survival rates (Salmon River, Cole Rivers, and Elk River) are all in Oregon.

Estuary size

Looking at Grays Harbor, Willapa Bay, Yaquina Bay and Coos Bay with respect to estuary size, coho survival rates tend to be higher in the larger estuaries (Figure 6.6), but such a relationship is not apparent from the fall chinook data.

Wild and hatchery salmon

Survival rates of wild coho tagged in Clearwater River, western Washington, follow the same fluctuations as the survival rates of hatchery fish released from nearby hatcheries (Figure 6.7). The same is true for wild fall chinook tagged in Klamath Basin, northern California, although there are fewer years of data for the comparison.

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Applications

Publications:

Magnusson, A. 2002. Survival rates of coho (*Oncorhynchus kisutch*) and chinook salmon (*O. tshawytscha*) released from hatcheries on the U.S. and Canadian Pacific coast 1972-1998, with respect to climate and habitat effects. M.S. thesis, School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA.

Presentations:

Arni Magnusson. "Survival rates of coho and chinook salmon with respect to climate and habitat effects." M.S. defense, Jan 11, 2002, School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA.

Arni Magnusson. "Climate and habitat effects on smolt survival rates." Northwest Salmonid Recovery Conference, Oct 24, 2002, Mountaineers Club, Seattle, WA.

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 Steven Hare, International Pacific Halibut Commission

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Ray Hilborn, Professor, University of Washington
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Oyster Yield in Space and Time: Factors Influencing Performance of *Crassostrea gigas* in a Pacific Northwest Estuary Chapter 7

Jennifer R. Ruesink, Curtis Roegner, Brett Dumbauld, and David A. Armstrong

Abstract

Benthic production in estuaries has been demonstrated to vary with physical gradients and local biotic interactions. Two unanswered questions concern the pattern of within-estuary variation in energy sources, as well as how consistent these patterns are through time. We used historical and new studies of oysters (*Crassostrea gigas*) to determine spatiotemporal variation in benthic productivity in Willapa Bay, Washington. Because oysters are filter feeders, their growth rates reflect food availability from a variety of potential sources, including ocean advection, watershed inputs, and in situ production (macrophytes and benthic diatoms). To assay productivity, juvenile oysters were transplanted on settling plates attached along poles at five tidal elevations. Four sites were tested in late summer 2000 and nine in midsummer 2001. Growth was recorded after two months.

Two patterns in oyster growth were observed across sites. Along the south arm of Willapa Bay, highest growth of young oysters occurred at the mouth, whereas highest growth occurred upriver along the east arm of the bay. In situ measurements of fluorescence at two sites on the south arm indicate that some resources for filter feeders are more abundant near the estuary mouth. The pattern of highest growth near the estuary mouth is consistent with a similar 1967 study of juvenile growth and long time series of adult condition index. However, both of these historical data sets indicate declines in oyster productivity at several sites in the middle of Willapa Bay. The productive upriver site along the east arm may be fueled by inputs from the Willapa River, the dominant freshwater feature.

Two patterns in growth were observed across tidal elevations. In 2000, based only on sites in the southern arm, growth improved with immersion time, except that growth slowed on-bottom. This pattern was consistent in 2001, mirroring a 1994 study of adult oysters at one south site. Additionally, in situ measurements of fluorescence were low on-bottom during the day at this southern site. In contrast, growth in the east arm im-

proved with immersion time and was fastest on-bottom. Possibly, south oysters are food-limited when phytoplankton migrate off-bottom, whereas oysters in the east arm may be fueled by particulate organic matter that cannot migrate.

High rates of secondary production near the estuary mouth corroborate recent findings that phytoplankton biomass in Pacific Northwest estuaries is strongly influenced by oceanic inputs. Nevertheless, we found no simple gradient of benthic productivity along tidal elevation or estuary head/mouth axes. The temporal changes in productivity and nonlinearities in space that we observed have profound implications for defining anthropogenic change and for managing benthic estuarine resources.

Introduction

At the interface of salt and fresh water, estuaries have long been viewed as ecosystems of strong physical gradients, although a more modern view recognizes the effects of local biotic interactions and complex circulation on ecosystem structure and function (Ruckelshaus et al. 1993). Spatial variation in the quantity and quality of material in the water column is well known to affect benthic secondary production, particularly of filter feeders (Lenihan et al. 1996). These potential food sources have three origins: oceanic material that is advected into the estuary, material of primarily terrestrial origin that enters the estuary in fresh water, and material produced in situ, including estuarine microalgal species and macrophytes.

These three origins of primary production lead to quite different predictions about the spatial distribution of benthic secondary production throughout an estuary. They also suggest that both the amount and distribution of production could be affected by interannual differences in oceanic productivity, such as ENSOs and decadal oscillations, or in watershed inputs due to rainfall or land use change. Here we report on a recent study of spatial variation in growth of a conspicuous

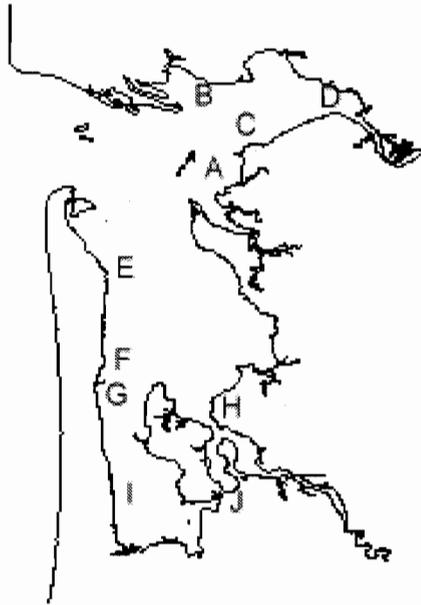


Figure 7.1. Willapa Bay, Washington, on the eastern Pacific coast just north of the Columbia River Mouth. The Willapa River enters from the northeast and Naselle River enters from the southeast. Letters show study sites. A=Bay Center, B=Toke Point, C=Stony Point, D=Range Point, E=Stackpole, F=Oysterville, G=Nahcotta, H=Sunshine Point, I=Shoalwater, J=Long Island.

benthic estuarine filter feeder (Pacific oyster, *Crassostrea gigas*) and relate our findings to historical data to explore how these patterns have changed over time.

Several environmental factors have been suggested to affect oyster growth, including salinity, temperature, and food supply (Kobayashi et al. 1997). We focused on resource availability because of documented fluctuations in phytoplankton within the estuary associated with coastal ocean events (upwelling and relaxation, Columbia River plume location; Roegner et al. in press). We expected oyster growth would decline at higher tidal elevations simply due to shorter feeding times. We also expected growth to improve with proximity to the estuary mouth, where for a century aquaculturists have transplanted oysters to fatten them. We used historical data on oyster growth and condition to address the anecdotal claim that "oysters don't grow as fast as they used to." To develop mechanistic explanations for observed spatial patterns in growth, we analyzed oyster tissues for evidence of different energy sources (stable

isotopes) and recorded water column fluorescence as a proxy for phytoplankton biomass. Any temporal changes or spatial nonlinearities have profound implications for defining anthropogenic impacts and managing benthic natural resources.

Methods

Study site

Willapa Bay (46°40'N, 124° 0'W) has two main orientations, one N/S axis of about 40 km and another short eastward arm towards the Willapa River (Figure 7.1). About 45% of the water in the bay is exchanged between mean lower low water and mean higher high water through a 10 km shallow entrance in the northwest corner (Hedgepeth and Obrebski 1981). Freshwater input to Willapa Bay is primarily from the Willapa River in the north, and two smaller rivers (Palix in the east, Naselle in the southeast) also contribute. Aquaculture in Willapa Bay produces about 15% of oysters in the U.S., although the yield from the bay has declined by more than half since the mid-1940s. This decline has been attributed to loss of suitable culture areas in the south part of the bay, possibly due to changes in water quality associated with upland timber extraction (Pacific County Regional Planning Council 1974 in Hedgepeth and Obrebski 1981) or exceeding the carrying capacity (Hedgepeth and Obrebski 1981).

Study design

In 2000, four sites within the bay were chosen for study based on similar widths of intertidal mudflat (Figure 7.1). Stackpole was the northernmost site, closest to the mouth of the bay. About 8 km south were two sites, one on the west side (Nahcotta) and one on the east side (Sunshine) of the bay. A fourth site (Shoalwater) was in the southwest. Four sites were added in 2001 along the east arm of Willapa Bay (up the Willapa River), and one was added in the extreme south.

In 2000, we determined oyster growth rates based on linear extension of shells from August 1 to October 13. Cultch (adult shells) with 10-20 juvenile oysters (initial length 3-30 mm), settled in a commercial hatchery the previous autumn, were used in the study. All individuals on each cultch were mapped and measured, so that growth and survival could be determined on an individual basis. At each site, oysters on cultch were trans-

planted on poles stuck in the sediment at mean lower low water (MLLW). Cultch were attached to PVC poles at intervals corresponding to full immersion (0% emersion), 20%, 40%, and 60% emersion. These immersion times occurred at 0 m, +0.6 m, +1.2 m, and +1.8 m MLLW tidal elevations, respectively. Within a site, five replicate poles were placed parallel to shore over a distance of about 50 m. Subsamples of surviving oysters (2 per cultch) were analyzed for dry meat biomass (60°C for 72 h) and stable isotopes ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$). In 2001, growth was based on the linear extension of shells of surviving oysters between June 20 and August 18. Oyster spat were settled onto 10 x 10 cm ceramic tiles about 6 weeks prior to the study and had reached shell lengths of 1-2 mm at its inception. A fifth tidal elevation (+2.4 m MLLW) corresponding to 80% emersion was added to the 2001 design.

Linear growth rate was calculated on a per plate basis as the average change in shell length of surviving juvenile oysters. Oyster growth rates throughout Willapa Bay were compared by analysis of covariance (ANCOVA) with site as a random factor and tidal elevation as covariate. Sample size was initially five poles per site, but only four poles remained at the end of the 2001 study at Nahcotta and Range Point and two at Long Island and Stony Point.

Water column properties

We recorded temperatures at all sites throughout each study period using temperature loggers that recorded every 20 or 40 minutes (iButton, Dallas Semiconductor). These time series allowed us to determine average water temperatures, fluctuations (primarily reflecting arrival and departure of cold ocean water), and the duration of dramatic temperature excursions during exposure to air, an indication of actual tidal elevation.

We recorded fluorescence in the water column during summer 2001 at Nahcotta and Stackpole (YSI Incorporated, Yellow Springs, OH 45387). For three-day periods in July and August 2001, we also recorded fluorescence and turbidity on-bottom, at the water surface, and half way in between. To record this way, we attached two loggers to a PVC "arm" jointed at the bottom so that one end could float up and down with the tide.

Historical Data

Condition index (CI) was measured for up to 30 adult oysters collected from four locations within Willapa Bay on a monthly basis from 1956-2000. CI is based on the ratio of meat biomass to shell internal volume. Specifically, $CI = D/5W$, where D is tissue dry weight (g) and W is the total wet weight not including the shell (mg), which corresponds to the amount of water inside the shell. These data are collected by the Nahcotta Shellfish Laboratory, Washington Department of Fish and

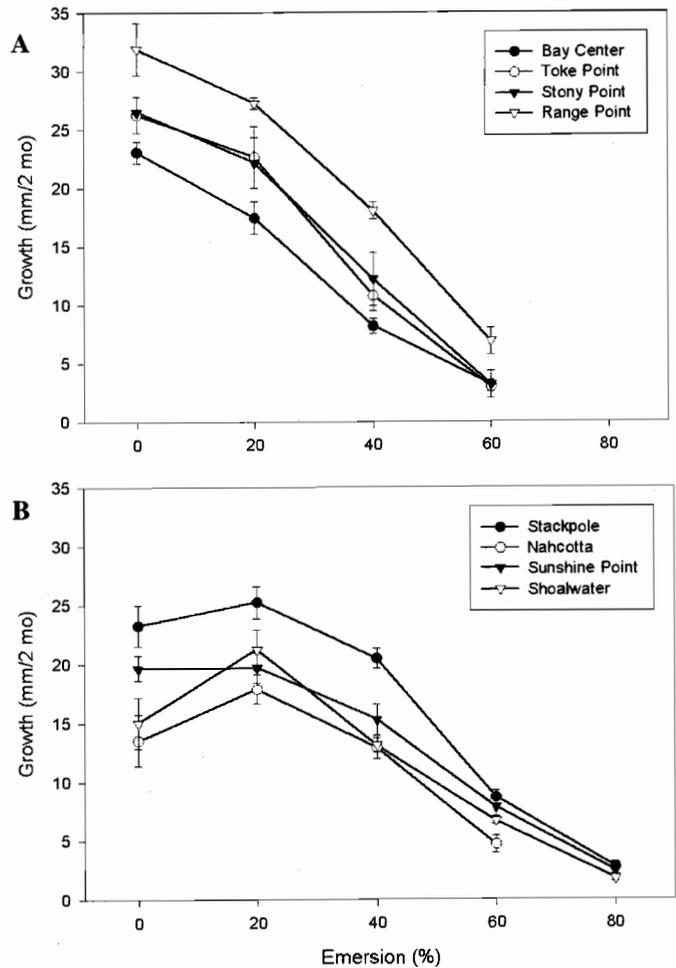


Figure 7.2. Growth of juvenile oysters across sites and tidal elevations in Willapa Bay. Different emersion times were achieved by hanging settling plates with oysters at different positions on PVC poles. Oysters at 0% emersion were on-bottom at MLLW; others were in the water column. Growth was measured in terms of linear shell extension from June-August 2001. A) Sites along the east arm of Willapa Bay; B) sites along the south arm. $N \leq 5$ plates per site and tidal elevation. Error bars show standard error. Missing data at 80% emersion represent complete mortality of oysters at that tidal elevation and site.

Wildlife, and have been reported previously in slightly different form (Ebbesmeyer and Strickland 1995).

Growth of adult oysters was measured at different intertidal elevations at Nahcotta in 1994. Adult oysters were placed in mesh bags in groups of five and attached to PVC posts at tidal elevations of + 0.8 m, + 1.1 m, + 1.4 m and + 1.7 m. All posts were replicated four times. Shell length was measured before and after the study (B. Dumbauld, unpubl. data).

Growth of oyster spat was recorded in 1967 by Sayce and Larson (1968) at five sites corresponding roughly to recent study sites. They placed cultch in the bay between July and August and in October recorded average length of spat that had settled and grown.

Results

Maximum growth rates of oysters in Willapa Bay exceeded 1 cm shell extension per month during both 2000 and 2001. Many of the oysters grown at 80% emersion (+2.4 m MLLW) did not survive, due to either desiccation or starvation.

Two patterns in oyster growth were observed across sites. Along the south arm of Willapa Bay, highest growth of young oysters occurred at the mouth, whereas highest growth occurred upriver along the east arm of the bay (Figure 7.2). In situ measurements of fluorescence at two sites on the south arm indicate that some resources for filter feeders are more abundant near the estuary mouth (C. Roegner, unpubl. data).

The pattern of highest growth near the estuary mouth is consistent with a similar 1967 study of juvenile growth (Figure 7.3) and long time series of adult condition index (Figure 7.4). In 1967, oysters that settled near the mouth grew nearly twice as fast as those settling in the south part of the bay, and the intermediate site, Sunshine Point, had relatively fast growing spat. Recently, however, growth rates at Sunshine have become more similar to those throughout the south part of the bay. Over more than 40 years, CI was consistently higher at Stackpole (near the mouth) than Nahcotta (about 8 km south). In addition, CI at Nahcotta declined significantly over

time. Interestingly, CI also declined at Stony Point, which is just 4 km from the mouth. Thus, both of these historical data sets indicate declines in oyster productivity at sites in the middle of Willapa Bay.

Two patterns in growth were observed across tidal elevations. In 2000, based only on sites in the southern arm, growth improved with immersion time, except that growth slowed on-bottom. This pattern was consistent in 2001 (Figure 7.2), mirroring the 1994 study of adult oysters at one south site (Nahcotta; B. Dumbauld, unpubl. data). Additionally, in situ measurements of fluorescence were low on-bottom during the day at this southern site.

Daytime levels of chlorophyll were estimated at 3.9 $\mu\text{g/L}$ at the water surface and halfway through the water column (SE = 0.36 and 0.19, respectively, $n = 6$ days), however they were much lower on-bottom ($-0.9 \mu\text{g/L} \pm 0.5$ SE). During the night, however, chlorophyll levels were high throughout the entire water column (High: $4.8 \mu\text{g/L} \pm 0.2$; Mid: $5.5 \mu\text{g/L} \pm 0.9$ SE; Low: $4.4 \mu\text{g/L} \pm 0.3$ SE). In contrast to slow on-bottom growth in the south arm of Willapa Bay, growth in the east arm improved with immersion time and was fastest on-bottom (Figure 7.2).

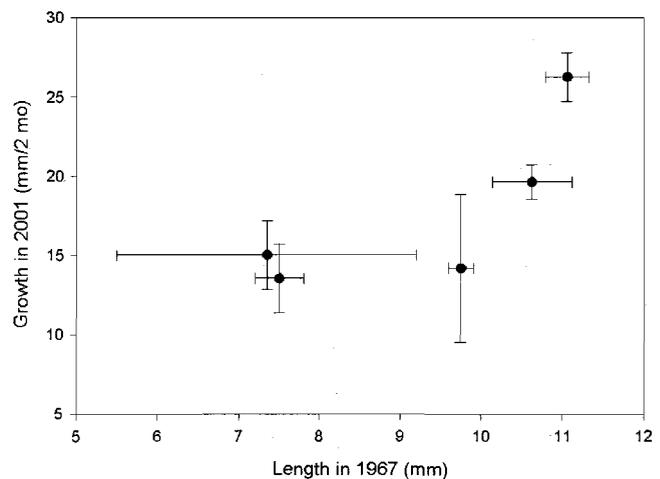


Figure 7.3. Comparison of juvenile oyster growth across sites in 1967 and 2001. In 1967, cultch was placed at different sites between June and August, and the lengths of oysters that settled were measured in October. Sample size represents cultch placed at a single site at different times. The 2000 study used pre-settled oysters and recorded growth (linear shell extension) from June-August for oysters grown on-bottom at MLLW. $N < 5$ plates per site. Error bars show standard error.

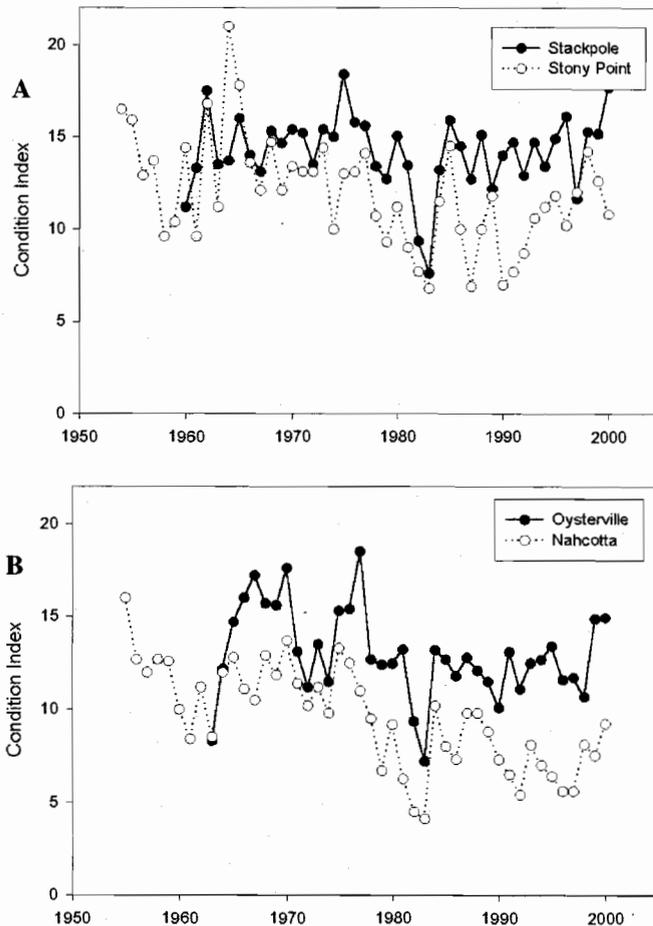


Figure 7.4. Condition index of oysters collected from four sites in Willapa Bay from the early 1950s until 2000. Condition index was available as multiple oyster samples per month throughout this time period; graph shows the annual maximum monthly mean value. A) Sites closer to the mouth; B) Sites farther from the mouth. Stackpole and Oysterville samples are dredged from commercial beds, whereas Stony Point and Nahcotta samples are collected by hand. Condition index has declined significantly at these latter sites but not the former. The large dip in condition index in the 1982-1983 is associated with an ENSO event.

Discussion

Dynamic exchanges of ocean and terrestrial inputs that characterize estuaries undoubtedly contribute to spatial and temporal variation in benthic secondary production. We found order of magnitude variation in growth of oysters from low to high intertidal elevations. Among sites, growth varied by >50%. Temporal variation was most obvious in the time series of condition index, which demonstrated that the best condition at any given site also varied interannually to a factor of two.

Because growth generally increased with immersion, feeding time (and therefore amount of available resources) is a likely contributor to observed variation. Furthermore, higher fluorescence near the estuary mouth than along the south arm suggests that food availability may contribute to differences in growth among sites. In particular, fluorescence and growth were both high at Stackpole (Figure 7.2; C. Roegner, unpubl. data). High rates of secondary production near the estuary mouth corroborate recent findings that phytoplankton biomass in Pacific Northwest estuaries is strongly influenced by oceanic inputs (Roegner et al. in press). However, watershed inputs may also play an important role in benthic productivity of Willapa Bay. Along the Willapa River, oysters grew most rapidly upriver where terrestrial effects should dominate.

Two spatial non-linearities emerged from our study. First, all sites south of Stackpole along the south arm had similar oyster growth rates, despite varying distances from the mouth of the bay. This observation is consistent with anecdotal reports of a “fattening line” in Willapa Bay, north of which oysters will fatten, and south of which they do not. As yet, it is unclear how abrupt this shift in benthic productivity may be, although ongoing intensive studies between Stackpole and Nahcotta should help resolve the issue. Second, oyster growth was linearly related to immersion time except for on-bottom oysters in the south arm, which grew 30-60% slower than the observed maximum. This slow on-bottom growth was consistent for juvenile and adult oysters (Figure 7.2; B. Dumbauld, unpubl. data). One factor that differs through the water column is fluorescence, which suggests phytoplankton densities are low on-bottom during the day. These low levels could be due to depletion (phytoplankton eaten by benthic filter feeders), low production (phytoplankton dividing slowly out of the light), or migration into the water column. The last explanation is most likely, because phytoplankton phototaxis must be difficult at night, consistent with the uniform distribution recorded during night. Possibly, south oysters are food-limited when phytoplankton migrate off-bottom, whereas oysters in the east arm may be fueled by particulate organic matter that cannot migrate. Other explanations for slow on-bottom growth include turbidity and restricted food in the boundary layer.

In addition to complicated spatial patterns of oyster growth, we also found evidence that sites within the bay show different historical patterns of benthic productivity. This suggestion is documented anecdotally by Chapman and Esveldt (1943, in Hedgpeth 1981). In 1936, "the growth rate slowed down markedly all over the Bay until oysters were taking three years to reach marketable size instead of one or two years, and in many areas, especially in the southern end, the oysters would not fatten to a marketable condition at all." None of the historical data sets available to us extend back before the 1950s, so we were unable to address the reported decline in productivity in 1936. However, historical data sets since that time indicate that productivity may be deteriorating in the middle portion of the bay. At Nahcotta, which now sits south of the fattening line, condition index has declined significantly since 1955, possibly dropping most dramatically in the late 1970s (Figure 7.4). The growth of juvenile oysters at Nahcotta was relatively low in 1967 and 2001, but growth at Sunshine Point appears more like south-end sites now than it did in 1967 (Figure 7.3). If so, these comparisons also indicate that this mid-bay site may have deteriorated in benthic secondary productivity.

Spatial nonlinearities and temporal changes in benthic secondary productivity in this estuary challenge ecologists and oceanographers to understand the contributions of circulation and a variety of sources of primary production. Mechanistic understanding should lead to determining local carrying capacities and predicting consequences of oceanic or watershed change. These tools are necessary for managers to make rational decisions concerning actions that could affect the productivity of the bay.

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Applications

Publications:
None.

Presentations:
Jennifer Ruesink, Curtis Rogner, Brett Dumbauld, and David Armstrong, "Assessing benthic-pelagic coupling through demography of oysters (*Crassostrea gigas*)."
PICES X Annual Meeting, October 9, 2001, Victoria, B.C., Canada.

Jennifer Ruesink, "Spatial variation in oyster (*Crassostrea gigas*) growth and recruitment: factors affecting yield in a west coast estuary." National Shellfisheries Association annual meeting, Sept. 20-21, Silverdale, Washington.

Jennifer Ruesink, "Spatial variation in performance of an introduced oyster (*Crassostrea gigas*) in a west coast estuary." Ecological Society of America annual meeting, Aug. 6-10, 2001, Madison, Wisconsin.

Jennifer Ruesink, "Oyster growth in 3-D: elevation, mudflat, and bay-wide effects." PNCERS Eat and Learn Seminar Series, February 21, 2001, University of Washington, Seattle, WA.

Workshops:
Jennifer Ruesink, Curtis Rogner, Brett Dumbauld and David Armstrong attended the PNCERS All-Hands Meeting, January 11-12, 2001, University of Washington, Seattle, Washington.

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The development and application of a bioenergetics model for juvenile *Cancer magister*: examining the relative contribution of different estuarine habitats to growth of juvenile Dungeness crabChapter 8

Kirstin K. Holsman, David A. Armstrong, David A. Beauchamp, and Jennifer R. Ruesink

Introduction

Cancer magister (Dungeness crab) range from the Pribilof Islands of Alaska, to Santa Barbara, California (Jensen and Armstrong 1987), and support one of the most important crustacean fisheries along the west coast of North America (Jamieson and Armstrong 1991). The value of the fishery and its cyclical nature have provided impetus for multiple studies of the biology and behavior of *C. magister* and the environmental influences important to its life history. Several studies have examined growth of *C. magister* since survival of juvenile crabs is higher for individuals that grow quickly and obtain a size refuge from predation at an earlier age (Reilly 1983; Fernandez 1999). Growth rates of juvenile *C. magister* generally increase along the latitudinal gradient, and are nearly twice as high in estuarine crab populations than in adjacent oceanic populations (Carrasco et al. 1985; Methot 1989; Gunderson et al. 1990). Crustacean growth is highly influenced by temperature and food availability (Hartnoll 1982), and observed differences in growth rates of *C. magister* are most likely due to warm water temperatures found in estuarine environments (Tasto 1983; Gunderson et al. 1990) combined with increased available prey biomass. Survival of juvenile *C. magister* is a bottleneck to the potential size of adult populations, and the enhanced growth and survival rates observed in estuarine populations may contribute significantly to the coastal fishery (Gunderson et al. 1990; Armstrong and Gunderson 1991).

Complex intertidal habitats characteristic of coastal estuaries provide critical refuge for settling young of the year (0+) crabs, as well as conditions ideal for growth (Stevens and Armstrong 1984; Armstrong et al. 1991; Dumbauld et al. 2000; Dumbauld et al. 1993; Fernandez et al. 1993). 0+ crabs settle into complex substrates, such as oyster shell or eelgrass beds, in spring after spending 3-4 months as planktonic larvae (Tasto 1983; Armstrong and Gunderson 1985). They continue to occupy these habitats through their next 4-5 molts, and migrate to subtidal channels in late summer upon reaching ~30mm carapace width (CW; Reilly 1983; Fernandez

1999). Most growth of juvenile *C. magister* occurs during the highly-productive warm summer months, thus crabs overwinter in subtidal estuarine areas and resume growth the following spring (Wainwright 1994).

The value of complex intertidal habitats to 0+ *C. magister* is well documented (Armstrong and Gunderson 1985; Gunderson et al. 1990; Jamieson and Armstrong 1991; Eggleston and Armstrong 1995) and artificial plots of oyster shell have been used as a tool to mitigate for the loss of crabs associated with dredging impacts. In 1992, the Army Corps of Engineers established intertidal plots of oyster shell in Grays Harbor, Washington, as it was believed that increased production of 0+ crabs could compensate for adult mortality (Dumbauld et al. 1993; Dumbauld et al. 2000). Enhanced juvenile survival in complex intertidal habitats is consistent with studies of *Callinectes sapidus* (blue crab), where growth and survival is higher in intertidal eelgrass beds than in adjacent mud or sand habitats (Heck and Thoman 1981; Heck and Wilson 1987; Wilson et al. 1990; Perkins-Visser et al 1996).

Although the importance of intertidal habitats to the growth and survival of 0+ crabs has been well demonstrated, the role of intertidal habitats to subsequent year classes remains unclear. Other brachyuran species, such as *Cancer productus* (Robles et al. 1989) and *Carcinus maenas* (Dare and Edwards 1981; McGaw and Naylor 1992), undertake extensive migrations at high tide from subtidal channels to intertidal foraging habitats, and intertidal foraging may also contribute significantly to the energy budget of $\geq 1+$ juvenile *C. magister* (35-130mm CW). Subtidal trawls conducted in Grays Harbor and Willapa Bay revealed higher densities of crabs at low tide in subtidal channels adjacent to extensive intertidal flats than in main channels (Rooper et al. in press). The high density of crabs in these channels (236-1,719 individuals ha^{-1} ; Rooper et al. in press), in conjunction with incidental catches of $\geq 1+$ juvenile crabs (60-130mm CW) in intertidal habitats at high tide (Gotshall 1978; Stevens et al. 1984; Dinnel 1986; Fernandez et al. 1993), suggest that a portion of the $\geq 1+$ juvenile crab popula-

tion may continue to utilize intertidal habitats throughout their estuarine life history.

Although the numerical abundance of a particular cohort of juvenile crabs within an estuary may decline from 0+ to subsequent juvenile year classes, the overall biomass of $\geq 1+$ juvenile crabs may increase (Gutermuth 1987). The abundance of $\geq 1+$ juvenile crabs in these estuaries, coupled with their high energy demand, suggest that a considerable amount of energy within the ecosystem flows through this life history stage. Although some studies have attempted to quantify energy flow through juvenile crab populations (Gutermuth 1987; Gutermuth and Armstrong 1989; Visser 1997), the comprehensive energetic requirements of $\geq 1+$ juvenile crabs remain unknown. Additionally, the particular importance of intertidal habitats in fulfilling these energetic demands has yet to be investigated.

The extensive intertidal flats of estuaries, such as Willapa Bay and Grays Harbor, may provide substantial available prey for juvenile *C. magister*, including crangonid shrimp, flatfish, bivalves, amphipods, and burrowing shrimp (Stevens et al. 1982), and could ostensibly contribute significantly to the energy requirements of $\geq 1+$ juvenile crabs. This is further evidenced by numerous studies that suggest predation by juvenile *C. magister* as a mechanism for limiting intertidal prey populations (Iribarne et al. 1995; Visser 1997; Fernandez 1999; Palacios et al. 2000).

The degree to which intertidal foraging contributes to crab growth may also be intensified by inter- and intraspecific interactions. Agonistic behavior has been shown to limit foraging efficiency in *C. sapidus* (Clark et al. 1999) and could similarly affect *C. magister* concentrated in subtidal channels at low tide.

The overall objective of this study is to gain a better understanding of the role of intertidal estuarine habitats in satisfying $\geq 1+$ juvenile crab energy requirements. In particular, we ask the following questions: (1) Is there enough prey energy in subtidal areas of Willapa Bay to support observed growth of $\geq 1+$ juvenile *C. magister*? (2) Is there enough potential prey energy in intertidal areas alone to support observed crab growth? (3) Given the potential prey energy of subtidal and intertidal areas of Willapa Bay, is the abundance of $\geq 1+$ *C. magister* limited by prey availability?

To investigate these questions: (1) we developed and parameterized a bioenergetics model for $\geq 1+$ juvenile *C. magister*; (2) performed a sensitivity analysis on the model parameters; and (3) applied the bioenergetics model to data available from Willapa Bay, Washington. The utility of bioenergetic models in ecological applications has been well established (Hewett 1989; Brant et al. 1992; Ney 1993), and have often provided similar consumption estimates for fish species (Rice and Cochran 1984; Beauchamp et al. 1989; Brodeur et al. 1992; Arrhenius and Hansson 1994; Hansson et al. 1996; Ciannelli et al. 1998). Bioenergetic models have already been developed to estimate consumption for other crab species (Klein-Breteler 1975; Guerin and Stickle 1992), and an estimation of the energetic demands of juvenile *C. magister* was developed based on respiration and production rates (Gutermuth 1987). However, to the best of our knowledge, an ontogenetically-based, environmentally sensitive bioenergetic model for crabs, similar to those applied to fish species, has yet to be developed.

Materials and Methods

Model parameters

The bioenergetics model is based on a method widely applied to fish species, where the energy consumed (C) must balance metabolism (R), egestion (F), excretion (U) and growth (G) (Hewett and Johnson, 1992):

$$C = R + F + U + G \quad (1)$$

Computations were based on specific rates (Joules per gram ash free dry body weight per day; $J g^{-1} day^{-1}$) and a daily time step. Energy was converted to biomass with caloric densities (calories per gram ash free dry weight; $cal g^{-1}$) and the calorie to Joule conversion factor ($4.1902 J cal^{-1}$). Estimated individual consumption rates ($J day^{-1}$) were extrapolated to predict the net energy requirement for the population of interest using initial population abundance adjusted for mortality over time.

Incremental molting and the loss of energy to shed exuvia complicates modeling growth in *C. magister*, and neglecting to account for this energy loss in the model can result in a significant underestimation of consumption. Therefore, exuvia was incorporated into the model using the following modified equation for consumption:

$$C = R + F + U + G + Ex \quad (2)$$

Table 8.1. Equations used to calculate consumption, respiration, egestion, and excretion rates of juvenile *Cancer magister*; W=ash free dry weight (g), T=temperature (°C). Parameter symbols are explained in Table 8.2 and Hewett and Johnson (1992).

1) Consumption (J g⁻¹d⁻¹)¹

$$C = (C_A * W^{CB} * P * f(T)) * \text{prey energy (J g}^{-1}\text{)}$$

where:

$$f(T) = K_A * K_B$$

$$K_A = (C_{K1} * L_1) / (1 + C_{K1} * (L_1 - 1))$$

$$L_1 = e^{(G1 * (T - CQ))}$$

$$G_1 = (1 / (C_{T0} - C_Q)) * \ln((0.98 * (1 - C_{K1})) / (C_{K1} * 0.02))$$

$$K_B = (C_{K4} * L_2) / (1 + C_{K4} * (L_2 - 1))$$

$$L_2 = e^{(G2 * (CTL - T))}$$

$$G_2 = (1 / (C_{TL} - C_{TM})) * \ln((0.98 * (1 - C_{K4})) / (C_{K4} * 0.02))$$

2) Respiration (J g⁻¹d⁻¹)²

$$R = (R_{rest} * ACT) * (0.02011 \text{ (J ul}^{-1}\text{O}_2\text{)}) + (SDA * (C - F))$$

where:

$$R_{rest}^2 = (R_a * T^2) + (R_b * \ln(W) * T) + (R_c * T) + R_d$$

3) Egestion and Excretion³

$$F = F_A * C$$

$$U = U_A * (C - F)$$

¹Thornton and Lessem 1979, ²Gutermuth & Armstrong 1989, ³Kitchell et al. 1983

where Ex is the energy lost to exoskeletons developed and shed during the simulation period and was predicted from molt frequency and growth estimates. This is explained in further detail below.

Consumption, respiration, egestion and excretion rates are described by separate algorithms from Thornton and Lessem (1978), Gutermuth and Armstrong (1989), Stewart et al. (1983), and Kitchell et al. (1977) (Tables 8.1 and 8.2). The model predicts physiological maximum consumption for a given body mass and temperature (Cmax·f(T)). Then the model calculates actual consumption (C) by solving iteratively for P, the proportion of maximum consumption that an individual requires to satisfy a specified or observed change in weight such that:

$$P \cdot C_{MAX} \cdot f(T) = C = G + R + F + U + E_x \quad (3)$$

The value of P ranges theoretically from 0 (no consumption) to 1 (maximum physiological consumption) but can also be as high as 2 when consumption is higher

than the average consumption rate for an individual (Hewett and Johnson 1992).

Consumption

Though studies of growth in *C. magister* are numerous, only one has examined the effect of body mass and temperature on growth and consumption rates of ≥1+ *C. magister* (Kondzela 1986). Kondzela (1986) recorded individual consumption rates, carapace width (mm), and molt frequency for 151 days over 5 different temperatures (0; 5; 10; 15; 20 °C). Crabs were fed the soft tissue of *Mytilus edulis ad libitum* on four different occasions. Total tissue consumed (grams of wet weight per crab per day) was recorded over a twenty-four hour period and the average carapace width of crabs during that time was also recorded. In order to derive Joules per gram of ash free dry weight of crab per day (J g⁻¹d⁻¹) from individual specific consumption rates, the following conversion was used; on average, the dry weight of mussel tissue equals 22.125% of wet tissue weight, 1 gram of dry mussel tissue is equivalent to 4.42 Kcal (Okumus and Stirling 1998), and 1 calorie is equal to 4.190 Joules. The average carapace width (CW; mm) of each crab was converted to grams of ash free dry weight (W) with the following algorithm (Gutermuth 1987):

$$W = (5.068 \cdot 10^{-5}) CW^{2.790} \quad (r^2 = 0.987) \quad (4)$$

Maximum consumption occurs between 15° and 20° C (Kondzela 1986), so consumption rates at these temperatures were used to derive the slope (C_B) and intercept (C_A) for the mass dependence function for maximum consumption (Cmax) such that:

$$C_{MAX} = C_A \cdot W^{CB} \cdot f(T) \quad (5)$$

where CA is 0.268 and CB is -0.220 (r² = 0.725, p = 0.00). Parameters for the temperature dependence function (f(T)) were visually estimated from a plot of the proportion of maximum consumption observed at each temperature. (Figure 8.1).

Respiration

Temperature- and size-specific respiration rates for ≥1+ *C. magister* were based on respiration rates from Gutermuth and Armstrong (1989), where:

$$\ln R = 0.012 \cdot T^2 - 0.029 \cdot T \cdot \ln W - 0.152 \cdot T - 6.21 \quad (r^2 = 0.67, P < 0.05) \quad (6)$$

for crabs (36-104 mm; CW) at 6, 10, 14, and 18°C. However, since the above regression results in extremely high respiration rates for small crabs at low tempera-

Table 8.2. Descriptions and values of the parameters used in the bioenergetics model of juvenile *Cancer magister*.

Symbol	Physiological Parameter Value	Value	Source
Consumption			
C	Specific feeding rate ($\text{g g}^{-1}\text{day}^{-1}$)		
P	Proportion of maximum feeding rate		
W	Crab weight (grams of ash free dry weight)		
C _A	Intercept for weight dependence of Consumption	0.263	1
C _B	Slope of weight dependence of Consumption	-0.22	1
C _Q	Lower temperature where dependence is C _{K1}	5	1
C _{TO}	Higher temperature where dependence is 0.98 of max	14.5	1
C _{TM}	Temperature > C _{TO} where dependence is still 0.98 of max	20.2	1
C _{TL}	Temperature where dependence is C _{K4}	21.2	1
C _{K1}	Temperature dependence at C _Q	0.42	1
C _{K4}	Temperature dependence at C _{TL}	0.83	1
Respiration			
R _{rest}	Specific rate of respiration ($\text{ul O}_2 \text{g}^{-1}\text{day}^{-1}$)		
R _a	Temperature dependence for quadratic respiration function	0.012	2
R _b	Temperature and weight dependence for quadratic respiration function	-0.029	2
R _c	Temperature dependence for quadratic respiration function	-0.152	2
R _d	Constant for quadratic respiration function	-6.21	2
ACT	Activity multiplier	3.2	5
SDA	Proportion of assimilated energy lost to specific dynamic action	0.2	5
Egestion			
F	Specific rate of egestion ($\text{J g}^{-1}\text{day}^{-1}$)	1	
F _A	Proportion of energy consumed lost to egestion	0.65	3
Excretion			
U	Specific excretion rate ($\text{J g}^{-1}\text{day}^{-1}$)		
U _A	Proportion of assimilated energy (C-F)	0.085	3
Predator energy density			
[energy]	energy density of predator in joules per gram of ash free dry weight	19382	4

(1) Kondzela 1986, (2) Gutermuth and Armstrong 1989, (3) Guerin & Stickle 1992, (4) Gutermuth 1987, (5) this study.

tures, it was only applied to temperatures greater than 10 °C. Thus, if temperature is less than 10 °C, T is set to a constant 10 (Figure 8.2). Joules per gram of ash free dry weight per day ($\text{J g}^{-1}\text{d}^{-1}$) day were obtained from the subsequent respiration rates (ml of O₂ per gram of ash free dry weight per day, $\text{ml g}^{-1}\text{d}^{-1}$) using the following conversion: 1 mg of O₂ is equal to 1.428 ml of O₂, and there are 4.8 calories per gram of O₂.

SDA, egestion, and excretion

Daily specific excretion rates (U_A) and specific dynamic action rates (SDA) were calculated as constant proportions of assimilated energy (consumption minus egestion); egestion (F_A) was calculated as a constant pro-

portion of consumed energy. Values for SDA generally range between 0.15 and 0.20 for fish species. Although SDA has not been determined for *C. magister*, it has been examined in other estuarine brachyuran species; a twofold and a 2.3-fold increase in oxygen uptake was observed in *C. sapidus* (McGraw and Reiber 2000) and *C. maenas* (Houlihan et al. 1990), respectively, during feeding events. Therefore, we assumed SDA was 0.20. Specific egestion and excretion rates were likewise unavailable for *C. magister* so parameters for *C. sapidus* were used (Guerin and Stickle 1992; Guerin and Stickle 1995). Parameter values and definitions are listed in Tables 8.1 and 8.2 respectively.

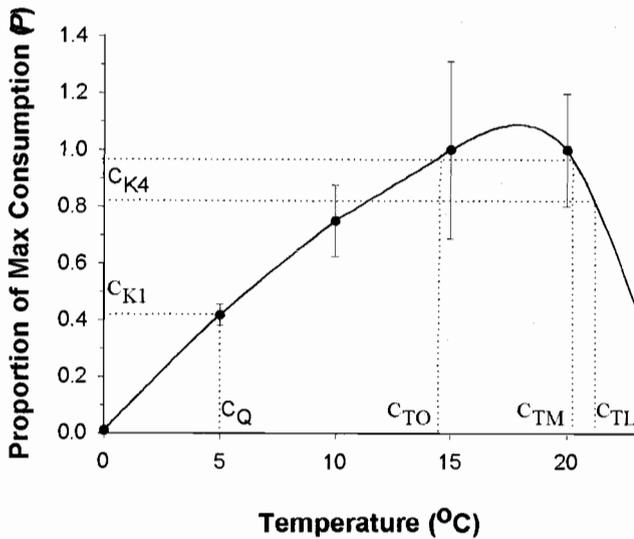


Figure 8.1. Mean (\pm standard deviation) proportion of maximum consumption (P) at each temperature for juvenile *Cancer magister*. Parameters C_{K1} , C_{K4} , C_{TO} , C_{TM} , and C_{TL} were visually estimated from this graph. Data from Kondzela (1986).

Exuvia and size at age

Since the energy lost to shed exoskeletons (Ex) is highly dependent on the duration of the simulation period and the initial weight of the crab, it was necessary to estimate Ex from size at age estimates for *C. magister*. Generally, studies of postlarval growth in crabs have focused on three aspects: the increase in carapace width (mm) at each molt (MI); the time elapsed between each molt (IP); and size at age (overall growth). Of the numerous studies of postlarval growth in *C. magister*, the most complete analysis was by Wainwright and Armstrong (1993), where size at age was predicted using the following equations:

$$MI = 1.3 + 0.23 \cdot X - 0.22 \cdot X' \quad (r^2 = , P =) \quad (7)$$

$$(IP \cdot T') = 190.57 \cdot e^{0.0175 \cdot X} \quad (r^2 = , P =) \quad (8)$$

where MI is molt increment (mm), IP is intermolt period (days), X is premolt carapace width (mm), X' is max (0, $X-105$), and T' is transformed temperature, defined as:

$$\left\{ \begin{array}{ll} 0, & \text{for } T < 1.13 \text{ }^\circ\text{C} \\ T' = T - 1.13 \text{ }^\circ\text{C} & \text{for } 1.13 < T < 13.55 \text{ }^\circ\text{C} \\ 12.42 \text{ }^\circ\text{C} & \text{for } 13.55 \text{ }^\circ\text{C} < T \end{array} \right\}$$

Based on the initial size of the crab, these equations were used to predict the frequency and magnitude of molting during the simulation period.

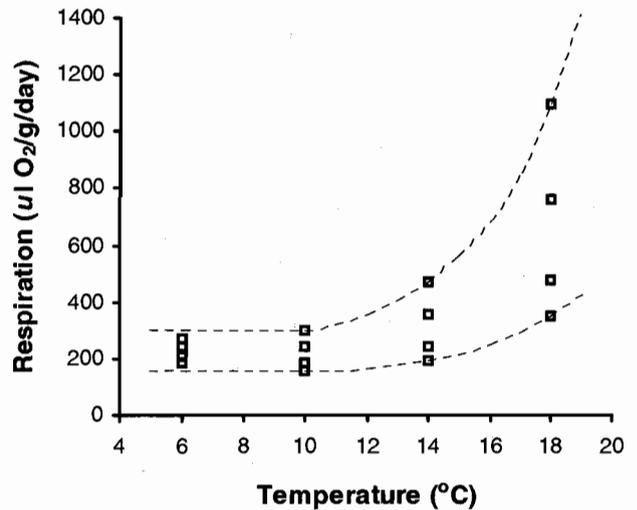


Figure 8.2. Respiration rates for juvenile *Cancer magister*. Respiration rates for 2, 4, 10, and 18 gram (ash free dry weight) crabs at different temperatures (open squares). Data are derived from the algorithm (Gutermuth and Armstrong 1989): $O_2 (ul) = (0.012 \cdot T^2) - (0.029 \cdot T \cdot \ln(W)) - (0.152 \cdot T) - (6.21)$ where T = temperature ($^\circ\text{C}$) and W = ash free dry weight (g). Respiration rates used in this study are expressed by the dashed line, rates below 10 deg were standardized such that $T=10$.

The regression for MI was used to calculate the carapace width of a crab prior to and following a molting event. Carapace widths (mm) were converted to grams of ash free dry weight (AFDW) using the width to weight regression (equation 4). The ratio of exuvia to whole crab weight is 0.289, and the energy density of the exoskeleton is 11,178.92 ($\text{J g}^{-1}\text{AFDW}$); therefore, the total energy lost to shed exuvia (E_x) during a simulation period in which more than one molting event occurred was:

$$E_x = \Sigma(Y_t) = \Sigma(163.73 \cdot X_t^{2.79}) \quad (9)$$

where Y_t is energy lost (J) to molting on day t , and X_t is the premolt carapace width (mm). Ex was then divided by the duration of the simulation period (days) in order to calculate the energy lost to shed exuvia on a daily time step. Y_t was not calculated for the first molting event since the energy of the exoskeleton lost during this molt was already incorporated in the initial whole body weight.

Sensitivity analysis

Following the method outlined by Ciannelli et al. (1998), sensitivity analysis of the model parameters was completed to examine the uncertainty of each parameter.

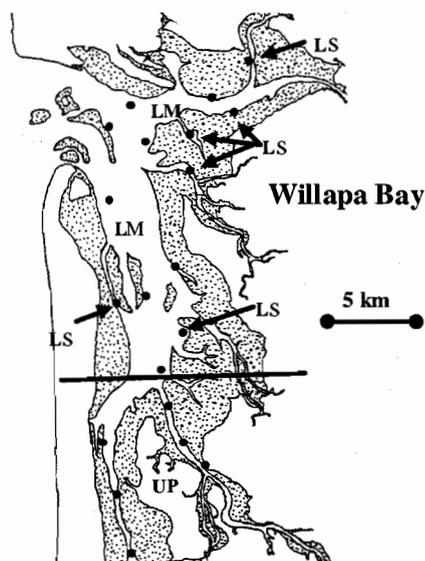


Figure 8.3. Trawl sites and strata definitions for Willapa Bay, Washington. Individual trawl sites used in 1985-1988 and 1998-2000 summer trawls, and strata definitions: lower main channel (LMC), lower side channel (LSC), and upper estuary (UP). Rooper et al. (in press).

Using individual parameter perturbation (IPP; Kitchell et al. 1977), each parameter was varied $\pm 10\%$ of the nominal value and the resulting model output was examined. All temperature parameters (C_{TO} , C_{TM} , R_{TM} , R_{TO} , R_{TL} , and T) were varied $\pm 1^\circ C$. The sensitivity of a parameter was calculated by comparing the final output with the baseline using the equation:

$$s(z) = \frac{(10 \times \Delta Z)}{Z} \quad (10)$$

where $s(z)$ is the sensitivity for a parameter (z), and ΔZ is the change in target output Z (Ciannelli et al. 1998). A sensitivity index equal to ± 1 means that a 10% (or $1^\circ C$ for temperature) variation in a parameter corresponds to a 10% variation in the output Z .

The result of IPP analysis is influenced primarily by two factors: the choice of the target output (Z), and whether or not P is refitted for each simulation. Since the consumption parameters cannot be examined thoroughly if P is refitted for each run, the sensitivity analysis was executed under three scenarios (Ciannelli et al. 1998): (1) P refitted in each simulation, where the target output was the final individual consumption (Rice et al. 1983); (2) P constant = 1, where the target output was final individual consumption (Ciannelli et al. 1998);

(3) P constant = 1, where the target output was final weight (growth; Kitchell et al. 1977).

Kitchell et al. (1977) defines the uncertainty of a parameter as the product of its sensitivity and the confidence in its value. Each parameter was assigned a subjective confidence ranking from 1-19 and this was plotted against the sensitivity of each parameter (Kitchell 1983). The result is a chart where parameters fall within areas of confidence and uncertainly, the latter defining parameters that will require further investigation.

Model application

The model is extremely useful for comparing consumption rates between populations in different areas since the algorithms predicting consumption and respiration are sensitive to ontogenetic and thermal variations in these parameters. This study examined the bioenergetic implications of crabs foraging in different subtidal and intertidal strata by simulating scenarios likely experienced by $\geq 1+$ juvenile crabs foraging in these areas.

Strata definition and population estimates

Estuary wide trawl surveys were conducted in Willapa Bay monthly during the summers of 1985-1989 and twice a summer from 1998 to 2000 (Figure 8.3). Individual trawls sites were grouped by geographic strata: lower main channel (LMC), lower side channel (LSC), and upper estuary (UP; Rooper et al. in press). Strata are defined by significant differences in mean water temperature, depth, and percentage of surrounding tide flat; the highest temperatures, shallowest depth, and highest proportion of surrounding tide flat occurs in LMC (Table 8.3).

Table 8.3. Average physical characteristics. Bottom temperature ($^\circ C$), salinity (ppt), area (ha), and depth (m) relative to mean low water for each strata: lower main channel (LMC), lower side channel (LSC), upper estuary (UP). Standard deviations are expressed in parentheses. Data is from summer trawls in Willapa Bay during 1998-2000.

Strata	Temp	Salinity	Area	Depth
LMC	15.83 (1.51)	25.52 (4.77)	6124	6.97 (2.11)
LSC	16.78 (0.94)	23.75 (5.18)	2835	4.14 (1.29)
UP	17.99 (1.38)	23.22 (4.33)	2241	5.05 (1.82)

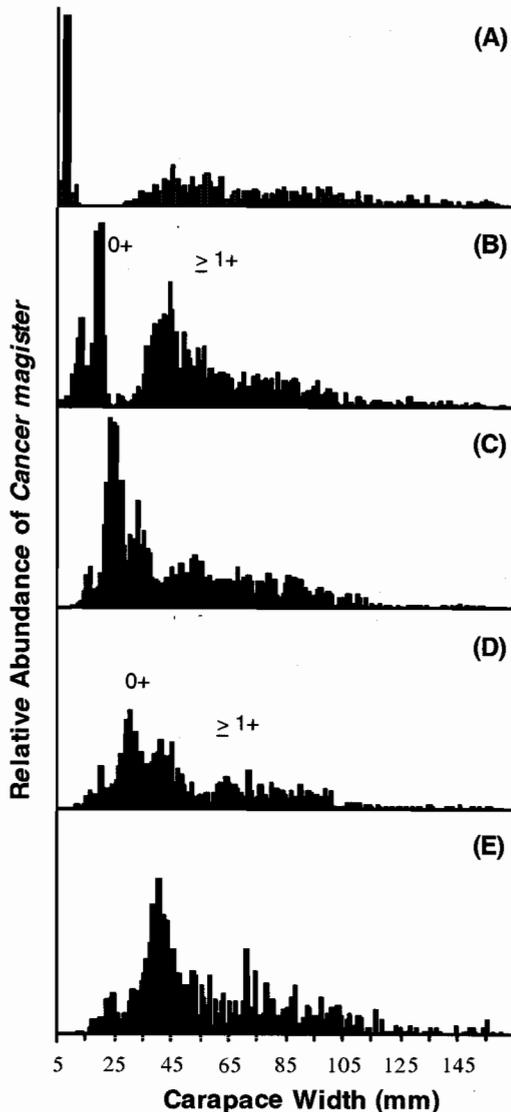


Figure 8.4. Example of size frequency histograms used to determine age classes. Relative frequency of juvenile *Cancer magister* from Willapa Bay, Washington, caught in monthly trawls from May (A)-Sept (E) in 1988. Visual estimation is used to derive carapace width (mm) ranges for each size class; young of the year (0+) and large juvenile crabs (≥1+).

Density and biomass estimates were derived for ≥1+ juvenile crabs caught in each haul, averaged across years, and summed by geographic strata. Average abundances estimated from June trawls were used as the beginning population estimates for each stratum, and abundances from August trawls were used for the ending population estimates.

Growth estimates and predator caloric density
 Size at age intervals were estimated for each strata from size frequency histograms of trawl data from each year (Figure 8.4). The average CW of 1+ and >1+ crabs from each month and strata were used to calculate growth rates in mm day⁻¹ and were converted to growth rates in g day⁻¹ using the width to weight relationship (equation 3). Age ≥1+ caloric density ([energy]) was set at 19.382 (kJ g⁻¹) throughout the entire simulation. Consumption estimates for each age class were then pooled to derive overall energy demands of ≥1+ *C. magister*.

Diel intertidal migrations

In order to examine the relative contribution of surrounding tide flats to the energy demands of ≥1+ crabs in each strata, model simulations were done for three scenarios: (1) crabs foraging 24 hours a day in subtidal channels only; (2) crabs foraging 12 hours a day in adjacent intertidal areas and 12 hours a day in subtidal channels; and (3) crabs foraging 12 hours a day in intertidal areas only. The resulting energetic demand of each scenario was compared to potential energy of prey organisms in both subtidal and intertidal habitats. Diet information was based on stomach analysis by Stevens et al. (1982); prey species distribution, production, biomass, and energy values were based on literature val-

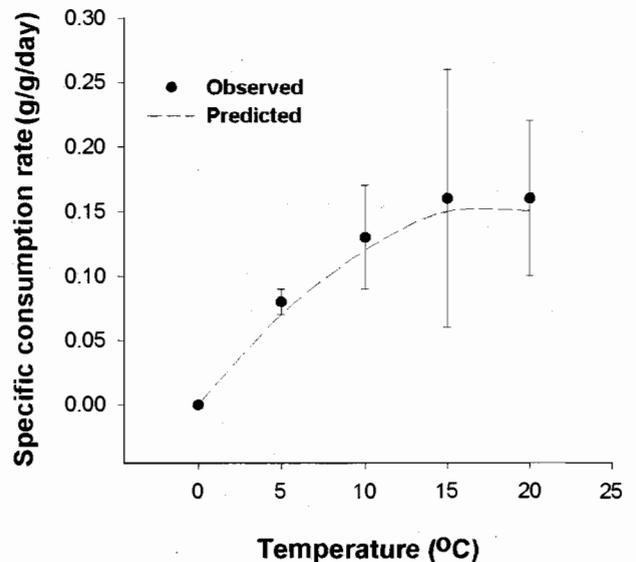


Figure 8.5. Specific consumption rates for juvenile *Cancer magister*. A comparison of the average consumption rates observed by Kondzela (1986) at different temperatures (circles), and the model estimate of maximum consumption (dotted line). Standard deviations of the mean are expressed by error bars.

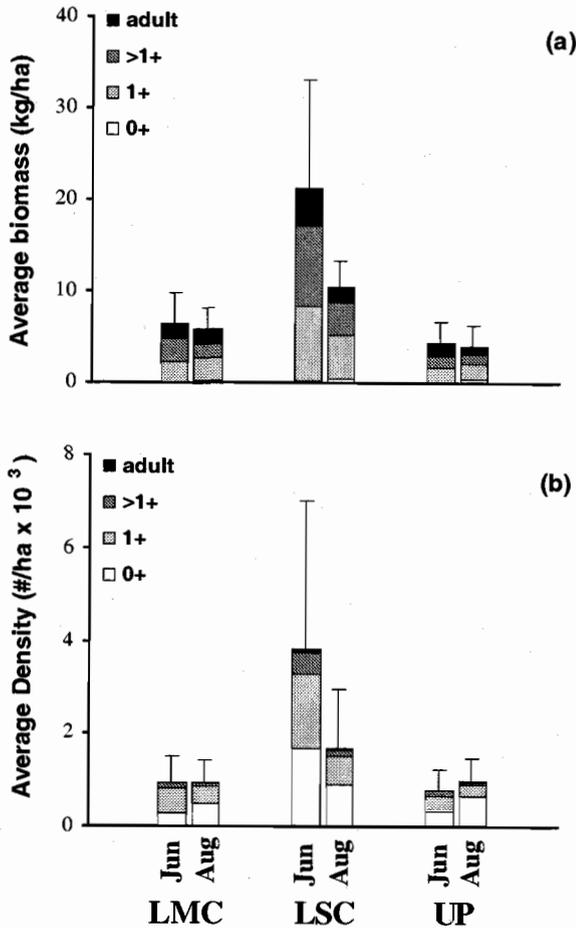


Figure 8.6. Average biomass and density of juvenile *Cancer magister* in Willapa Bay, Washington. (a) The average June and August biomass (kg ha^{-1}) of young of the year (0+), one year old (1+) and greater than one year old (>1+) crabs in each strata: lower main channel (LMC), lower side channel (LSC), and upper estuary (UP). (b) The average June and August density ($\#/\text{ha}$) of juvenile crabs in each strata. $\geq 1+$ juvenile crabs comprise the majority of the juvenile crab summer biomass, though 0+ crabs are in the highest abundance. Biomass and density of crabs is greatest in LSC and decreases from June to Aug.

ues for similar estuarine systems (Albright and Bouthillette 1982; Albright 1992; Visser 1997).

Preliminary Results

Results from model development and parameterization as well as initial average consumption estimates are detailed below. Results of sensitivity analysis, potential prey energy estimates for each strata, and diel intertidal migration model runs remain to be analyzed.

Bioenergetic model development

Initial estimates of consumption based on known growth rates resulted in consumption estimates systematically lower than those observed. Resting metabolism was therefore multiplied by an activity scalar (ACT) to derive consumption rates closer to those observed in Kondzela’s study (1986). ACT was on average equal to 3.2, and the subsequent predicted consumption rates fit the observed data accurately (Figure 8.5).

Initial population, biomass, and consumption estimates

The population and biomass of 1+ crabs in each strata during June and August is shown in Figure 8.6. Although LSC comprises only 25% of the overall subtidal area of Willapa Bay, on average it supports over 48% of the summer biomass of juvenile *C. magister* in the estuary. Initial estimates of the consumption rates of populations of 1+ crabs from each strata revealed significantly higher energy demands ($p = 0.003$) in LSC (Figure 8.7). There was no significant difference in the average energetic demand of populations of 1+ crabs in LMC and UP. The overall mean energetic demand of 1+ crabs in Willapa Bay from June to August was 11.57 ± 4.7 ($\times 10^6$ kJ).

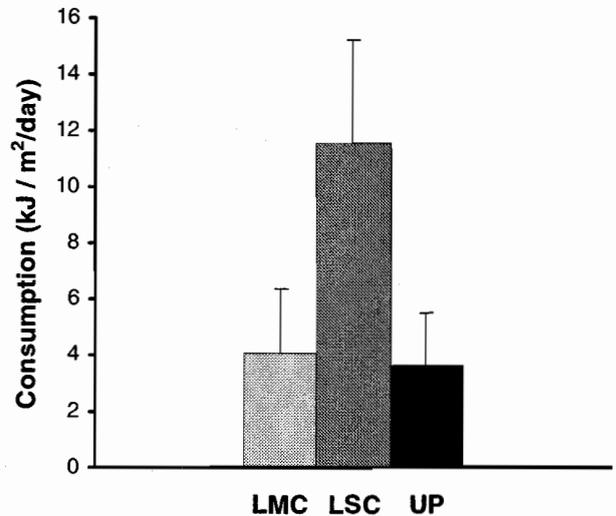


Figure 8.7. Average individual consumption rates ($\text{kJ}/\text{m}^2/\text{day}$) of 1+ *Cancer magister* from each strata: lower main channel (LMC), lower side channel (LSC), and upper estuary (UP). Individuals from LSC have significantly greater ($P = 0.003$) energetic demands than populations of crabs from other strata. Error bars express standard deviations of averages.

Further analysis

- 1) Complete thorough sensitivity analysis of model parameters in order to identify parameters which need further investigation;
- 2) Estimate the potential prey energy concentrated in subtidal channels of each strata as well as in adjacent intertidal habitats;
- 3) Compare the potential prey energy with the average consumption demands of $\geq 1+$ crabs from June and July in each strata.

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Applications

Publications:

None.

Presentations:

Kirstin Holsman, "The development and application of a spatially explicit bioenergetics model for Dungeness crab (*Cancer magister*)." Western Society of Naturalists 82nd Annual Meeting, November, 2001, Ventura, California, USA.

Kirstin Holsman, "A spatially explicit bioenergetics model for Dungeness Crab (*Cancer magister*)." 12th annual Graduate Student Symposium, November 2001, University of Washington, Seattle, USA.

Kirstin Holsman, David Beauchamp, and David Armstrong, "A Spatially Explicit Bioenergetic Model for *Cancer magister*." Poster presentation at PICES X Annual Meeting, October 10, 2001, Victoria, B.C., Canada.

Kirstin Holsman, David Armstrong, and David Beauchamp, " Modeling energy requirements which influence diel intertidal migrations by foraging Dungeness crab (*Cancer magister*)." Pacific Ecology Conference, February 17-19, 2001, Bamfield Marine Laboratory, B.C., Canada.

Workshops:
None.

Partnerships:
None.

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Estuarine Production of Juvenile Dungeness Crab (*Cancer magister*) and Contribution to the OR-WA Coastal Fishery Chapter 9

David A. Armstrong, Chris Rooper, and Donald R. Gunderson

Introduction

Fishery trends in coastal landings of Dungeness crab (*Cancer magister*) have long been regarded as an index of overall population dynamics which are well known for large amplitudes of 9-10 year cyclic periodicity (Peterson 1973; Botsford 1986a; McConnaughey et al. 1994; Higgins et al. 1997). Numerous analyses of time trends have focused on environmental forcing in the form of physical variables such as temperature, winds and current, or indices such as upwelling, operative during larval stages that might affect supply, survival, advection, and settlement in nearshore refugia (Wild et al. 1983; Botsford and Wickham 1975; Johnson et al. 1986; Hobbs et al. 1992; McConnaughey et al. 1992; see review by Botsford 2001). Since populations are so well synchronized along 1000s of kilometers of coast from N. California through British Columbia, Dungeness crab recruitment is viewed from a meta-population perspective as subject to very large-scale forcing regimes embodied in ENSO and non-ENSO contrasts (e.g., temperature, food, transport, predators) which, for the most part, affect egg/larval stages and are mirrored in fisheries data four years hence. Post-settlement density-dependent mechanisms such as cannibalism (Botsford and Wickham 1978; Botsford 1986b) have been considered and incorporated into models with exogenous environmental forcing to track long-term patterns in fishery data (Higgins et al. 1997). Across these and many other studies of life history and population dynamics, mechanistic and correlative models have focused on nearshore shelf processes to ascertain causes of fishery trends as explained by a mix of local and large-scale events (see reviews by Botsford et al. 1998; Botsford 2001). While the cyclic periodicity along 1000s of kilometers of coast is fairly synchronous, the amplitude of landings varies 4-8x at different geographic scales (see trends in McConnaughey et al. 1994 and greater detail in Higgins et al. 1997) with consequent economic implications that compel ongoing scrutiny of mechanistic causes underlying such fluctuations.

Although most Dungeness crab ontogeny occurs nearshore along the open coast (see reviews by Botsford

et al. 1989; Methot 1989), it has long been known that some portion of a given year class recruits directly to estuaries (Stevens and Armstrong 1984; Eggleston and Armstrong 1995; Eggleston et al. 1998), which results in regionally high density in systems such as San Francisco Bay, CA (Tasto 1983), small coastal Oregon estuaries (Rooper et al. 2002), and larger ones like Grays Harbor and Willapa Bay, WA (Stevens and Armstrong 1984, Gunderson et al. 1990; Wainwright et al. 1992). Coastal larvae hatch and occur in the plankton for about 3-4 months from December through March as a sequence of five zoeal stages, followed by a megalops stage in April to June (Lough 1976; Methot 1989), which settles both in estuaries and along the open coast. Estuarine cohorts of early benthic phase post-larvae grow much faster in the first summer than nearshore cohorts (Collier 1983; Gutermuth and Armstrong 1989), and reside in these systems over winter to a size of about 100-120 mm carapace width (CW) before emigrating to the nearshore by the end of the second summer at 1.5-2 years of age (Tasto 1983; Stevens and Armstrong 1984; Gunderson et al. 1990).

Based on attributes such as relative juvenile crab density, high abundance of prey (Stevens et al. 1982; Gunderson et al. 1990), faster rate of growth, and complex refugia (Fernandez et al. 1993; Palacios et al. 2000), estuaries of the northeastern Pacific from central California through Washington are often termed "nurseries" and assumed to be important to regional population production and fisheries. Anthropogenic activities are often viewed inimically as having a direct, significant, adverse impact on such populations and the subsequent fishery resources. Historical alteration of the San Francisco estuary with respect to many features (e.g., loss of tidelands and marshes, water quality, introductions of exotics; see review by Nichols et al. 1986), and concomitant collapse of the Central California crab fishery beginning in the early 1960s (to the mid-1990s) led to a comprehensive seven year ecosystem study of physical and biological variables and processes that might account for lowered abundance and provide basis of better management of the estuary in a nursery context (Wild and Tasto 1983). Given this view and evidence of

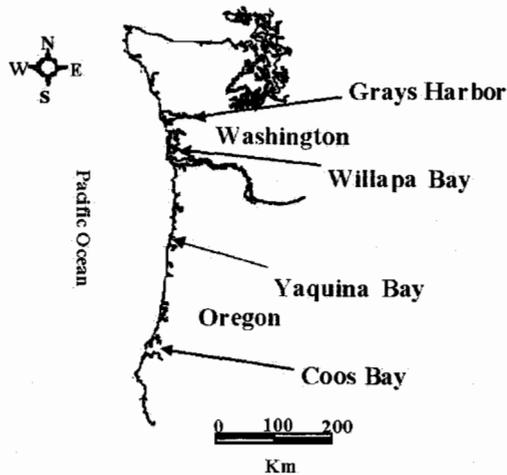


Figure 9.1. Map of the Oregon and Washington coast showing each of the four study areas.

a similar nursery function in Grays Harbor estuary, WA, plans by the Army Corps of Engineers (ACOE) to widen and deepen the navigation channel led to similar studies of juvenile crab ecology (Stevens and Armstrong 1984; Gunderson et al. 1990), means to attenuate potential loss of crab caused by dredging (McGraw et al. 1988; Dumbauld et al. 1993), development of an entrainment/mortality model to compute spatial extent of losses (Wainwright et al. 1992), and construction of intertidal shell mitigation habitat to enhance survival of juvenile crab (Dumbauld et al. 2000). Further estuarine perturbations that might affect juvenile crab populations vary from direct application of pesticides (see review by Feldman et al. 2000) to potential competitive and predatory interactions with exotic species such as green crab, *Carcinus maenas* (McDonald et al. 2001).

Yet despite such evidence of high crab density, and such pervasive presumptions about the nursery role of coastal estuaries, there has been little effort to portray estuarine production in the context of coastal fishery landings. Comparative studies of juvenile crab abundance in San Francisco Bay and adjacent Gulf of the Farallones led Orcutt et al. (1978) to estimate that about 50-80% of crab caught in the regional coastal fishery recruited directly to, or spent some portion of juvenile life in the estuary. Later, Tasto (1983) computed that 38-83% of 0+ juveniles in the late 1970s recruited directly to the estuary and took that as a significant future contribution to the coastal fishery. Based on early estimates of 0+ abundance in Grays Harbor, Stevens and Armstrong (1984) used mortality estimates of that time to compute

survival to the legal male fishery. Adding an additional value for Willapa Bay (as then unstudied with respect to juvenile crab population dynamics), they concluded that total estuarine production could account for most of the Washington coastal landings. Since that time, we have expanded assessment of estuarine crab ecology to Willapa Bay and two estuaries in Oregon (see Rooper et al. 2002). From this database and with other estimates of mortality, we compute in this paper the relative estuarine contribution of crab to the coastal fishery as another perspective of nursery function.

Materials and Methods

Study Area and field methods

Stratified random trawl surveys were used to compute juvenile crab density and abundance by age class within each estuary in two eras of data collection. Extensive nearshore and estuarine samples were taken in the 1980s as described by Gunderson et al. (1990) in Grays Harbor (GH; 1983-88; total subtidal area = 8,545 ha), Willapa Bay (WB; 1985-88; 11,200 ha) and in a portion of the adjacent nearshore (NS; 1983-88) about 7x larger than the combined estuarine areas. Three years of identical trawl surveys were done in 1998-2000 as part of the Pacific Northwest Coastal Ecosystems Regional Study (PNCERS; see Rooper et al. 2002) and included both GH and WB in Washington, and Coos Bay (CB; 1200 ha) and Yaquina Bay (YB; 490 ha) in Oregon (Figure 9.1; no coastal nearshore samples were taken off either state during this second phase). Four to five geographical strata were originally defined in the 1980s based on proximity to the mouth of the estuary which embodied attributes that vary seasonally and spatially such as degree of oceanic or riverine influence (temperature and salinity), sediment composition, nature and degree of epibenthic material that collects in channels (e.g., shell, macroalgae, terrestrial sticks and other vegetation, detrital eelgrass), and some differences in species composition (see Gunderson et al. 1990; Shi et al. 1997).

Similar strata were defined for CB and YB in Oregon beginning in 1998. However, the stratification was changed based on multivariate analyses (see Rooper et al. this volume) in an attempt to better standardize biotic and abiotic features common to subregions of each estuary, despite overall size. As a result, all crab density

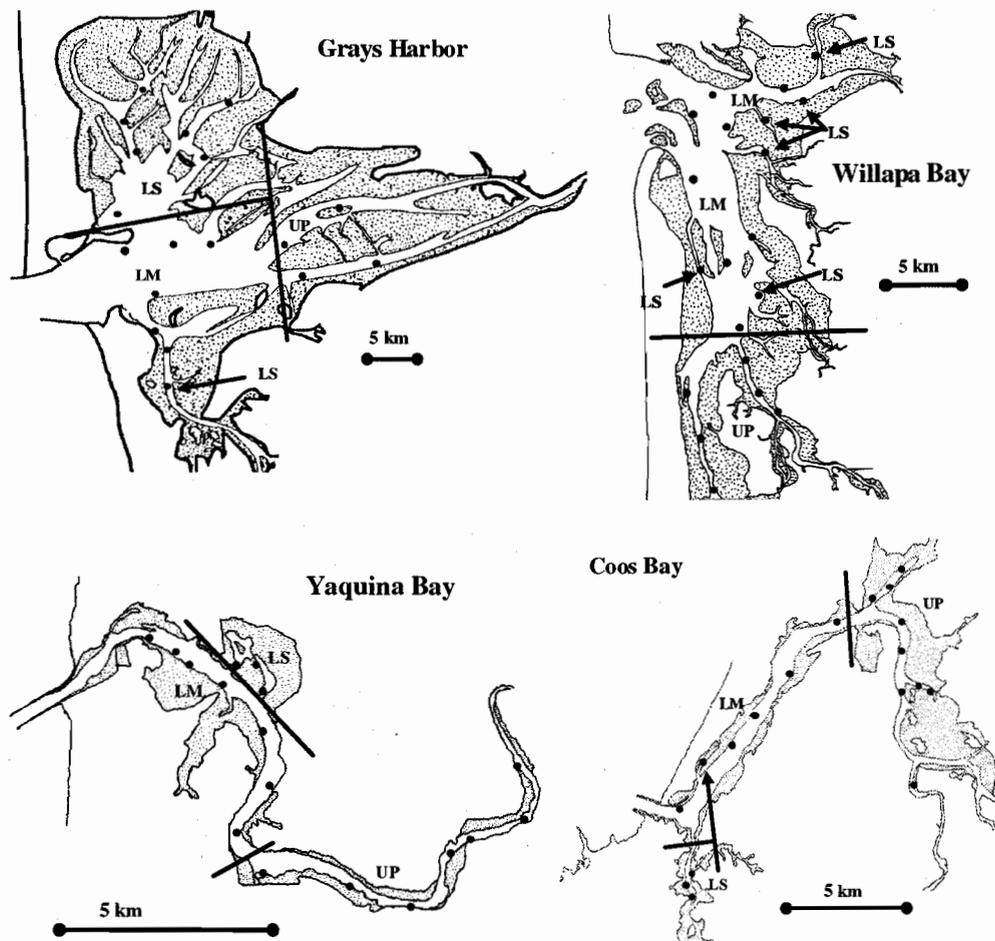


Figure 9.2. Map of each study estuary: Grays Harbor, Willapa Bay, Yaquina Bay, and Coos Bay. Dots represent trawl survey sites designated as lower main channel (LM), lower side channel (LS), and upper estuary (UP) sites.

and abundance data are now grouped in three habitat categories in each of the four estuaries (Figure 9.2): lower main channel (LMC; adjacent to the estuary mouth, colder summer temperature, higher salinity, deeper channels, very little adjacent intertidal zone, low epibenthic cover), lower side channel (LSC; higher temperatures, shallower depth, extensive adjacent intertidal, high epibenthic cover as shell and macroalgae), and upper estuary (UP; warmest summer temperatures, lower salinity, moderate intertidal, high epibenthic material as shell and allochthonous stick). Seventeen to twenty fixed stations were randomly selected from within 1 km² grids in each estuary. Each station was sampled at least monthly in the 1980s during seasonal spring recruitment and summer growth (May-September), but only in June and August during the more recent PNCERS era. Accordingly, all analyses in this paper are based on June and August density estimates across all four systems and all sample years.

Trawl samples were collected during daylight with a plumb-staff beam trawl developed by Gunderson and Ellis (1986) to target very small juvenile stages of benthic crustaceans and fishes by inclusion of a 4 mm stretch mesh in the codend and a double tickler chain preceding the net to dislodge buried animals. The gear has an effective fishing width of about 2.3 m and height of 0.6 m, and was towed at a minimum scope of 5:1 from a small boat (6.4 m) equipped with hydraulics to retrieve the net under slight forward motion and avoid loss of catch by backing down. Distance towed averaged 260 m in the 1980s when distance was estimated with visual range finders between anchored buoys deployed at start/stop of each trawl. Average distance towed in 1998-2000 was 140 m estimated with differential GPS on the vessel (Rooper 2002, Appendix 1). To the extent possible, trawls were done around low and high slack water and extreme currents of ebb/flood tides were avoided. All fish and invertebrates were iden-

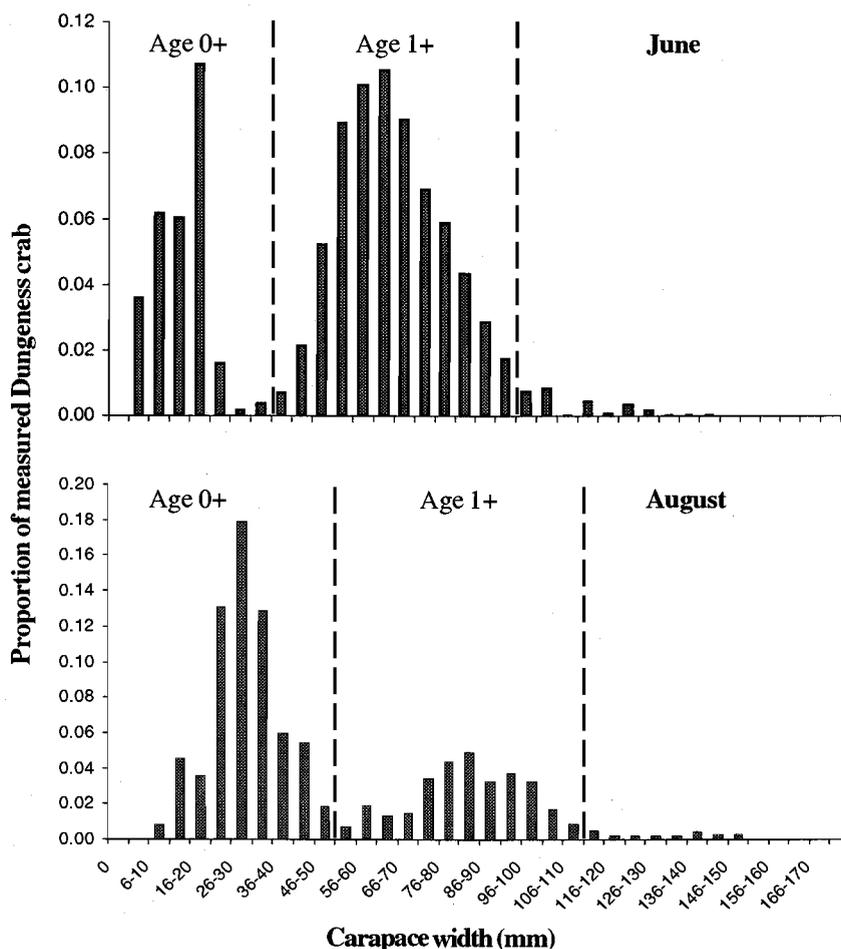


Figure 9.3. Length frequency plot of measured Dungeness crab captured in June and August surveys of the Coos Bay estuary. The plot shows the assumed breaks between the 0+ and 1+ age classes.

tified to species; crab were sexed and measured to nearest 0.1 mm CW. Habitat characteristics included depth of channels, index of adjacent intertidal area in 3.6 km² (1 NM²) grids, abundance of several prey items including crangonid shrimp (as kg/ha; Stevens et al. 1982) and potential predators such as staghorn sculpin (*Leptocottus armatus*; Armstrong et al. 1995), weight of epibenthic material caught by the trawl and sorted into shell (primarily three large species; oyster *Crassostrea gigas*, and two clams, *Tresus capax* and *Saxidomus giganteus*), detrital eelgrass (*Zostera marina*), macroalgae (*Ulva* spp., *Enteromorpha* spp.), and terrestrial vegetation (mainly sticks and large bark).

Juvenile density

Juvenile estuarine crab caught in the trawl surveys were grouped into age classes that, in most months,

were visually defined as reasonably clear modes depicting 0+, 1+, and >1+ (Figure 9.3). Density was calculated based on area swept for each tow, and is regarded as a relative estimate with no correction factor applied for gear efficiency. We choose 1+ juveniles as the best age-group estimate of estuarine crab production since 0+ recruitment is protracted during spring and summer and abundance highly variable, and older/larger

Table 9.1. Area (% of total) of each habitat type: lower main channel (LMC), lower side channel (LSC), and upper estuary (UP) in PNCERS study estuaries. Values are in hectares.

	LMC	LSC	UP
Coos Bay	761 (64%)	130 (11%)	306 (25%)
Yaquina Bay	247 (51%)	6 (1%)	236 (48%)
Willapa Bay	6,124 (55%)	2,835 (25%)	2,241 (20%)
Grays Harbor	2,775 (32%)	4,222 (49%)	1,548 (18%)

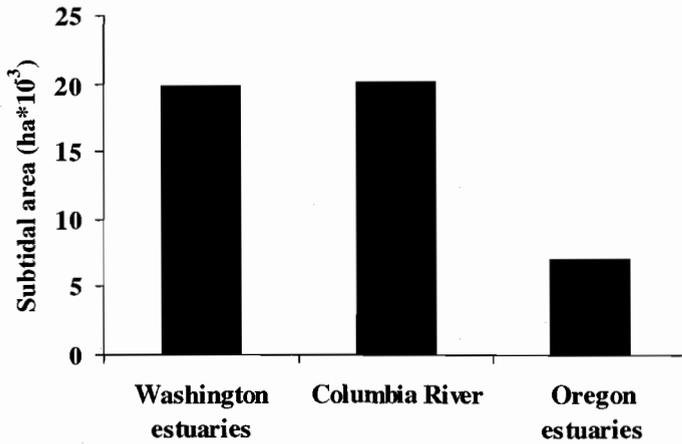


Figure 9.4. Area (ha) of subtidal estuaries in Oregon and Washington.

crab emigrate from the systems. Since there was no significant difference in 1+ density between months (ANOVA, $p > 0.05$), June and August station densities were grouped within each of the three strata (LMC, LSC, UP) to compute a mean summer density for a given year (Rooper et al. 2002). Abundance was then computed as simple multiplication of stratum density/ha by total subtidal ha for the strata in each estuary (Table 9.1). Resultant values were used for two primary estimations.

Estuarine contribution to coastal fisheries

In order to estimate eventual contribution of estuarine

1+ crab to future coastal fisheries, total estuarine subtidal area was expanded beyond the four systems measured directly to include the lower Columbia River and all Oregon estuaries, and then grouped in three geographic regions (Figure 9.4): 1) the two large Washington systems of GH + WB (19,745 ha); 2) the lower Columbia River estuary (20,042 ha) and; 3) all small Oregon coastal estuaries combined (7,042 ha; see Cortright et al. 1987, Monaco et al. 1992, Emmett et al. 2000 for maps and data on various OR and WA coastal estuaries, physical, and biological attributes). Overall mean summer 1+ estuarine density (weighted by stratum) was computed using the estuaries sampled in each year (e.g., in the case of 1983, only one estuary, GH, was sampled; in the case of 2000 all four

estuaries were sampled). The mean (778 crab/ha) and a high/low range (1,397, 406/ha) were used to compute annual 1+ abundance estimates in the three geographic groups above, given relative consistency of 1+ crab density between estuaries, and similar distributions measured in the lower Columbia River estuary (Emmett and Durkin 1985; McCabe et al. 1986). Mortality estimates (Wainwright et al. 1992) were used to compute surviving adults to a December fishery 3.5 yr later and that value reduced 50% to account for males only. Those values (effectively constants) were used to estimate the proportion of annual coastal crab catch based on estuarine juvenile production. Annual landings data were

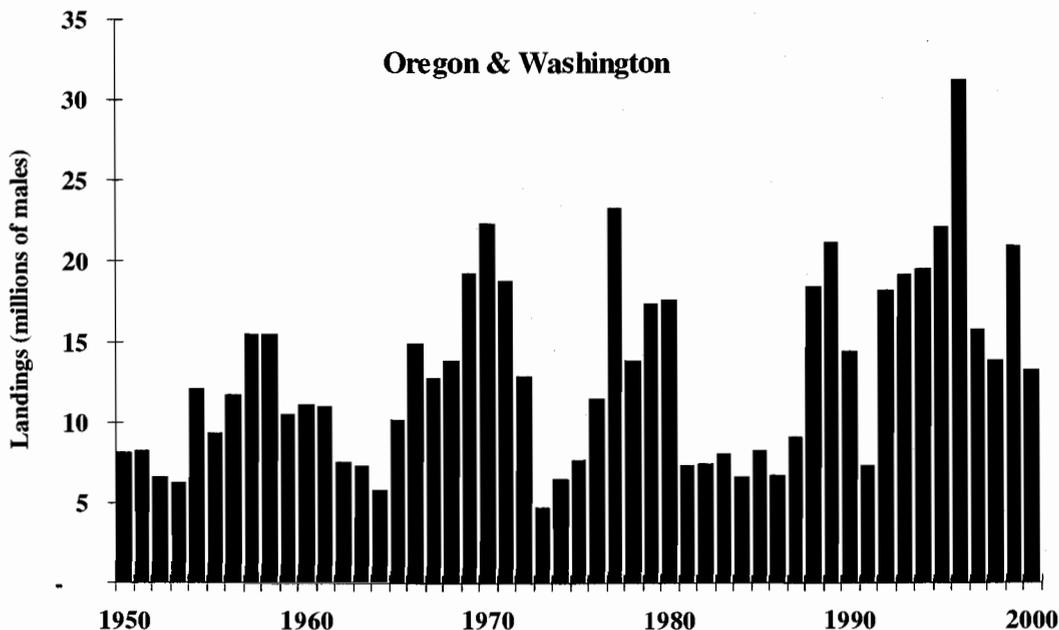


Figure 9.5. Time series of landings of Dungeness crab in Oregon and Washington combined from 1950-2000.

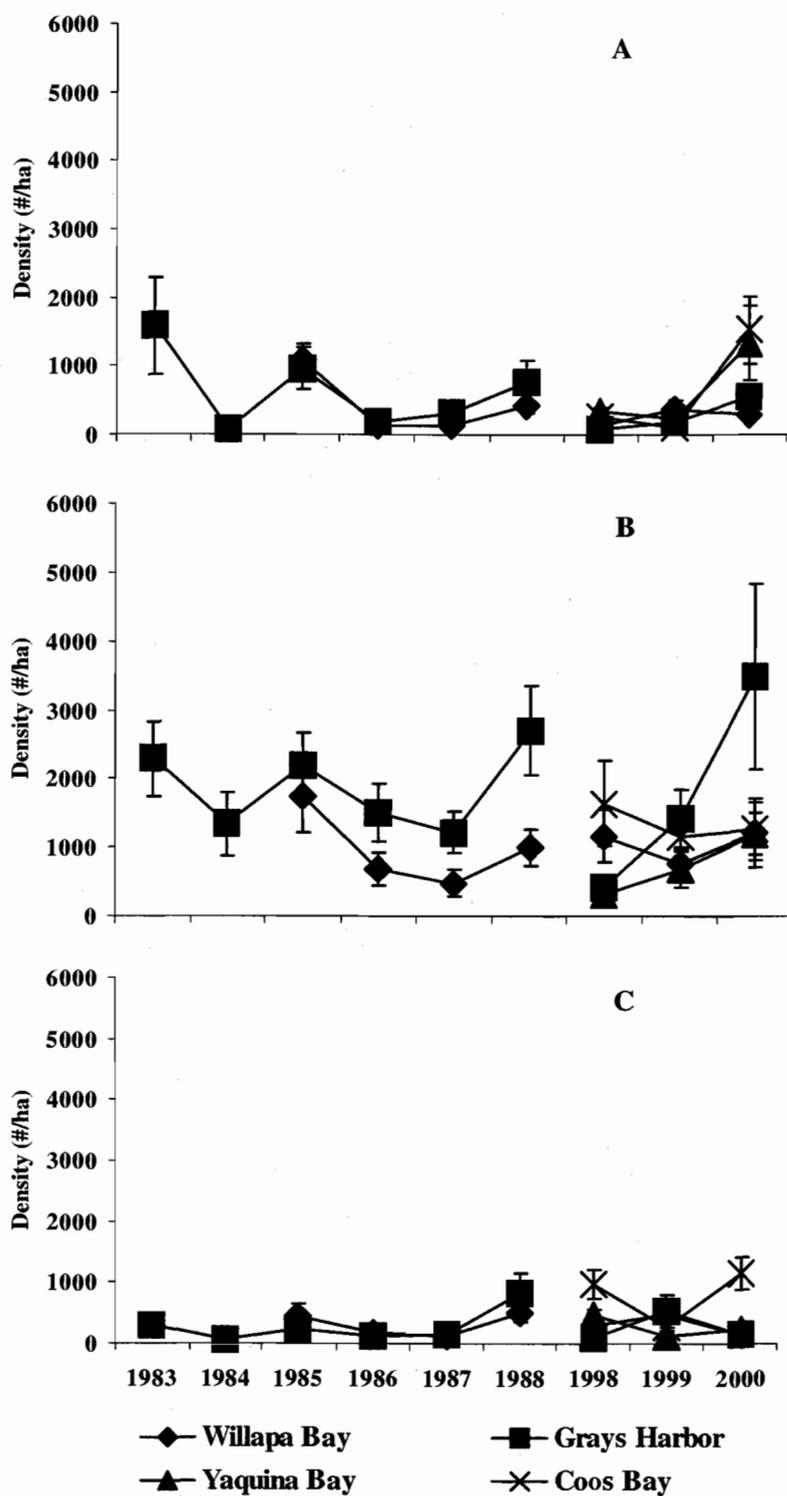


Figure 9.6. Average density of age 1+ crab in lower main channel (A), lower side channel (B), and upper estuarine (C) habitats of study estuaries in all years of trawl surveys. Standard error and shown for each data point.

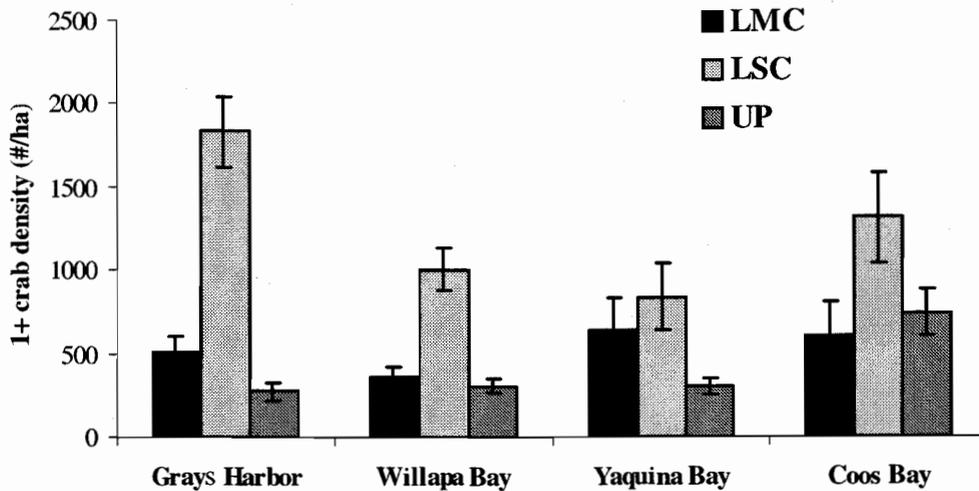


Figure 9.7. Average density of age 1+ crab observed in lower main channel (LMC), lower side channel (LSC), and upper estuary (UP) location for each of the PNCERS study estuaries.

obtained from the Pacific States Marine Fisheries Commission (PSMFC; their website and the PacFIN data files and annual reports, PSMFC 1998) and combined for Oregon and Washington since landings are not given by port nor by fishing area (Figure 9.5). Weight of male crab landed was divided by 1 kg/crab to compute number landed for comparison to estuarine production. Since the estuarine values were constant as applied to the variable years of catch data, the estuarine proportion was relatively high in low fishery years, and vice versa.

Relative production between habitats

Since summer density and resultant abundance were computed in each of three habitats, we estimated potential numeric and dollar value to the coastal fisheries such habitats provide. Again, annual density was averaged across years by strata, and abundance of 1+ crab computed. Mortality estimates were again applied for 2.5 year and the resultant population reduced by 50% to reflect legal males. An average legal male weight of 1 kg was used to compute dollar value per ha based on recent ex-vessel prices around US \$5.50/kg (\$2.50/lb).

Results

Juvenile density across habitats

Spatial patterns of 1+ distribution were consistent across all four estuaries and showed that summer density was significantly higher (Rooper et al. 2002) in lower side channels compared to both the lower main channels and upper estuary (Figure 9.6). In general, overall density was about 3x greater in LSC of all systems, and

lowest in the UP (Figure 9.7). For example, Grays Harbor, which was sampled over nine years, had long-term average densities of 1830, 500, and 275 1+ crab/ha in the LSC, LMC, and UP, respectively (Figure 9.7). Yaquina Bay, in comparison had three-year mean densities of 840, 640, and 300 crab/ha in those same habitats. Despite inherently smaller size of the Oregon estuaries (WB is about 20x larger than YB; Figure 9.2, Table 9.1), crab densities in each of the three major habitat groups were comparable to values estimated in the larger Washington systems (Figure 9.7).

There was significant inter-annual variation of average 1+ density (Rooper et al. 2002) in each estuary. During

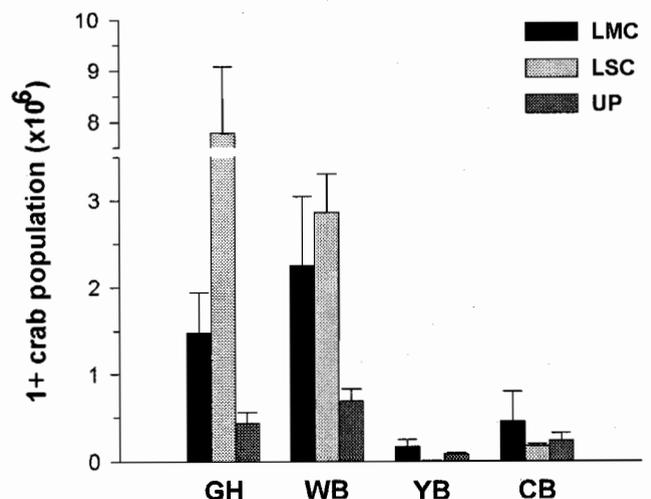


Figure 9.8. Average abundance of age 1+ crab across all years in lower main channel (LMC), lower side channel (LSC), and upper estuary (UP) locations for each of the PNCERS study estuaries.

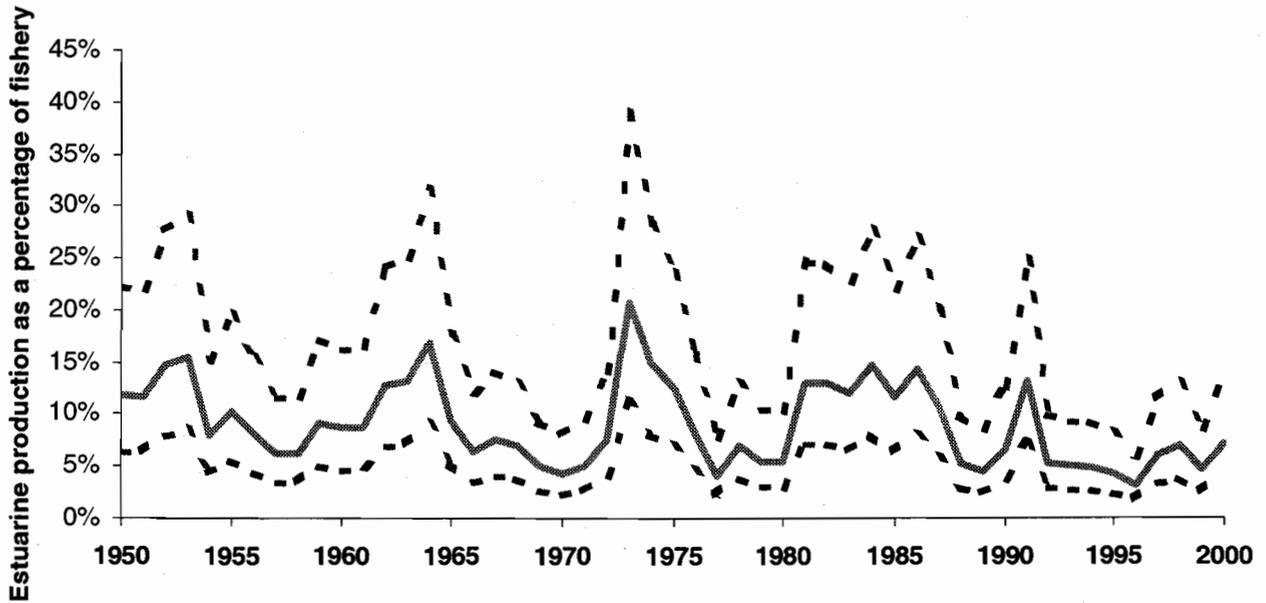


Figure 9.9. Percentage of offshore fishery produced in estuaries on average (with high and low ranges) based on 1:1 sex ratio, 2.2 pound size at age 3.5, combined OR-WA estuarine area and knife edged selection to the fishery.

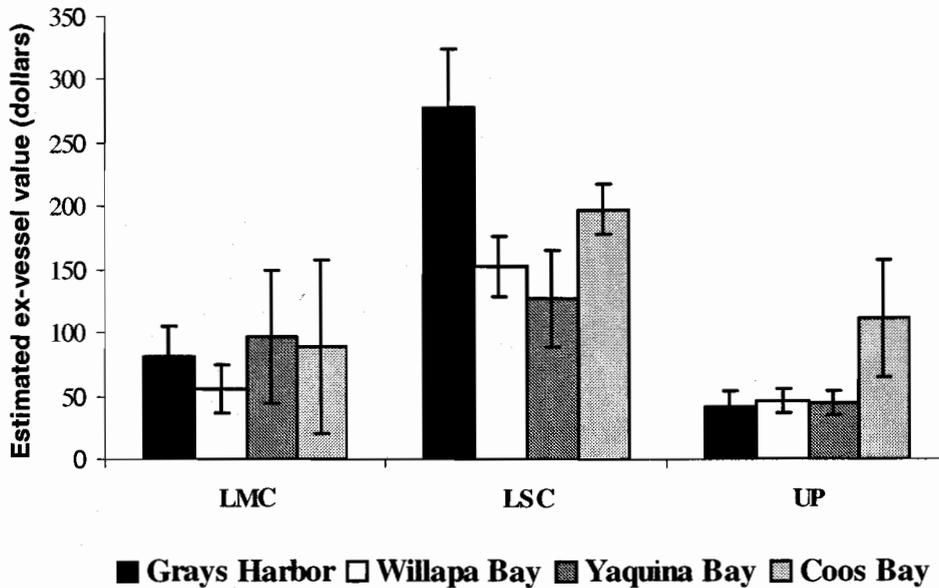


Figure 9.10. Average dollar value of crab per hectare produced in each habitat type: lower main channel (LMC), lower side channel (LSC), and upper estuary (UP) in study estuaries.

the 1980s sequence in GH for example, density in the LSC ranged from 1200/ha (1987) to 2700/ha (1988), and in the late 1990s from 420 to 3480/ha in 1998 and 2000, respectively (Figure 9.6). Average density across all habitats in WB ranged from 230/ha (1986) to 1100/ha (1985; Figure 9.6). Even during the three-year sampling program in the Oregon estuaries, average density within a habitat across years varied by a factor of about

2-4x (Figure 9.6). Viewed across all years and all estuaries, density estimates seem to indicate three relatively strong year classes (1+ survivors as index of the 0+ the year prior): 1984 and 1987 (high 1+ density in both GH and WB in 1985 and 1988, respectively; Figure 9.6), and 1999 (signal of high 1+ density in all four estuaries in 2000; Figure 9.6).

Juvenile abundance and fishery contribution

Although density was comparable across estuaries, abundance differed in accord with size of the system and relative amount of LSC habitat that supported highest densities of crab. Grays Harbor had the largest estimated population of 1+ averaged across all years (9.7×10^6), and 80% of those seasonal crab occurred in LSC habitat (49% of the total subtidal area; Table 9.1, Figure 9.8). In contrast, the average summer 1+ crab abundance in WB was 5.8×10^6 , and approximately 40% of these were in LSC habitat (only 25% of the total subtidal of that estuary; Figure 9.8). Although WB contains more subtidal area overall than GH (11,200 ha and 8545 ha, respectively), computed LSC area (location of greatest crab density) was higher in GH (Table 9.1). Estimated summer abundance of 1+ crab in the smaller Oregon estuaries averaged 235,000 and 850,000 for YB and CB, respectively (Figure 9.8). Survival these populations to age 4 indicated proportional contribution to male-only combined Washington and Oregon coastal fisheries of about 13% based on the overall mean density across all systems (Figure 9.9). Derived from the lowest and highest mean annual densities, the proportional contributions were estimated to be about 7% and 20%, respectively.

The three estuarine habitats vary substantial in potential economic role as nursery for this species from a fishery vantage computed as legal male value/ha. Production of 1+ in LSC equates to \$130 to almost \$300/ha as equivalent legal males, whereas LMC and the UP range from about \$50-\$100/ha (Figure 9.10). Based on overall average value/ha, and applied to total subtidal production areas of the three major geographic regions (Figure 9.4), combined Washington estuaries (GH + WB), the lower Columbia River estuary, and combined Oregon estuaries account for about \$2.2 MIL, \$2.2 MIL, and \$0.8 MIL, respectively.

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Applications

Publications:

Rooper, C.N., D.A. Armstrong, and D.R. Gunderson. Habitat use by Dungeness crab within nursery estuaries. *Proceedings of the International Symposium on Crabs in Cold Water Regions: Biology, Management and Economics*. Alaska Sea Grant College Report No. XX-XX. University of Alaska Fairbanks. (*in press*).

Feldman, K., D. Armstrong, B. Dumbauld, T. DeWitt, and D. Doty. 2000. Oysters, crabs, and burrowing shrimp: Review of an environmental conflict over aquatic resources and pesticide use in Washington State's (USA) coastal estuaries. *Estuaries* 23:141-176.

Palacios, R., D. Armstrong, and J. Orensanz. 2000. Fate and legacy of an invasion: extinct and extant populations of soft-shell clam (*Mya arenaria*) in Grays Harbor (Washington). *Aquatic Conservation: Marine Freshwater Ecosys.* 10:279-303.

Presentations:

David Armstrong, Chris Rooper, and Donald Gunderson, "Estuarine-Ocean Coupling and Link to Coastal Fisheries: Dungeness Crab and English Sole." PICES X Annual Meeting, October 9, 2001, Victoria, B.C., Canada.

Chris Rooper, David Armstrong, and Donald Gunderson, "Distribution and abundance over three years of English sole and Dungeness crab surveys." PNCERS Eat and Learn Seminar Series, January 24, 2001, University of Washington, Seattle, WA.

Chris Rooper, David Armstrong, and Donald Gunderson, "Habitat use by juvenile Dungeness crabs within nursery estuaries." Lowell-Wakefield Symposia, Crabs in Cold Water Regions: Biology, Economics and Management, January 17-20, 2001, Anchorage, AK.

Workshops:

David Armstrong, Donald Gunderson, Chris Rooper, Curtis Roegner, Kirstin Holsman, and Geoff Hosack attended the PNCERS All-Hands Meeting, January 11-

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Use of Estuarine Habitats by Juvenile English Sole (*Pleuronectes vetulus*) in Oregon and Washington..... Chapter 10

Chris Rooper, Donald R. Gunderson, and David A. Armstrong

Introduction

For many species of marine fishes and invertebrates, the habitat used as juveniles is believed to be important to survival through these stages. The amount and type of habitat available can influence predation rates (Fernandez et al. 1993; Lipcius et al. 1997), growth rates (Berghahn et al. 1995; Tupper and Boutilier 1995; Phelan et al. 2000) and distribution (Norcross et al. 1997; Howell et al. 1999; Abookire et al. 2000) of juveniles. The early juvenile stage is a time where recruitment patterns can be set or modified in marine fish species (Bailey and Spring 1992; Bradford 1992; Iles and Beverton 2000). Thus, the type and quality of habitat available to the juvenile stage of marine fishes may be especially important to the future contribution of a year class to the adult population.

For species of flatfish, the concentration of juveniles in nursery areas is believed to be especially important in stabilizing recruitment variation (Iles and Beverton 2000). For species that have egg and/or larval stages exhibiting strong correlation to environmental variables, wide fluctuations in larval supply can result in high variability in year class strength. When fish concentrate at some point during the early life history stages, wide fluctuations in larval supply may be ameliorated by density dependent affects. In flatfish species that concentrate in nursery areas, the amount and type of suitable habitat for survival is critical to determining the total number of flatfish that can be produced in any given year.

Numerous field and laboratory studies exploring juvenile flatfish habitat associations have been conducted. These studies have documented flatfish association with depth, sediment type, overlying litter, presence of predators, salinity, temperature, and combinations of multiple factors (Dorel et al. 1991; Kerstan 1991; Marchand 1991; Nash et al. 1991; Burke et al. 1991; Neuman and Able 1998; Wennhage and Gibson 1998; Howell et al. 1999; Steves et al. 1999; Walsh et al. 1999; Phelan et al. 2001; Stoner et al. 2001). In a number of studies, the habitat associations of juvenile flatfish have been found to change both seasonally (Abookire and Norcross 1998;

Marshall and Elliot 1998; Stoner et al. 2001), and with changes in fish size (Walsh et al. 1999; Phelan et al. 2001; Stoner et al. 2001). Many of these studies have focused on only one nursery area, or on only a limited selection of habitat variables.

This study focused on habitat associations of age 0+ English sole (*Pleuronectes vetulus*) within four nursery estuaries extending over 400 km of the Oregon and Washington coast. The data on English sole were collected over nine years of subtidal trawl surveys across four estuaries. The objectives were twofold; to identify common habitat types which could be used to categorize all four estuaries, and to determine if there were consistent patterns in spatial use of these habitats by age 0+ English sole. The analysis was conducted using a wide assortment of habitat variables designed to address important aspects of estuarine systems, and density observations for two size cohorts of age 0+ English sole that commonly occurred in each estuary.

Methods

This study was carried out at four estuaries on the Washington and Oregon coasts: Grays Harbor, Willapa Bay, Yaquina Bay, and Coos Bay (Figure 10.1). All four

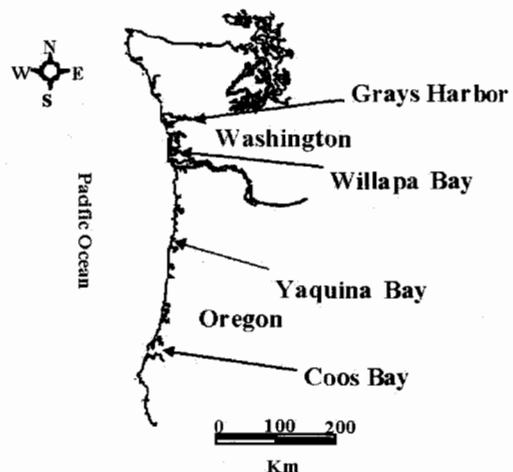


Figure 10.1. Coastline of Oregon and Washington showing each of the study areas: Grays Harbor, Willapa Bay, Yaquina Bay, and Coos Bay.

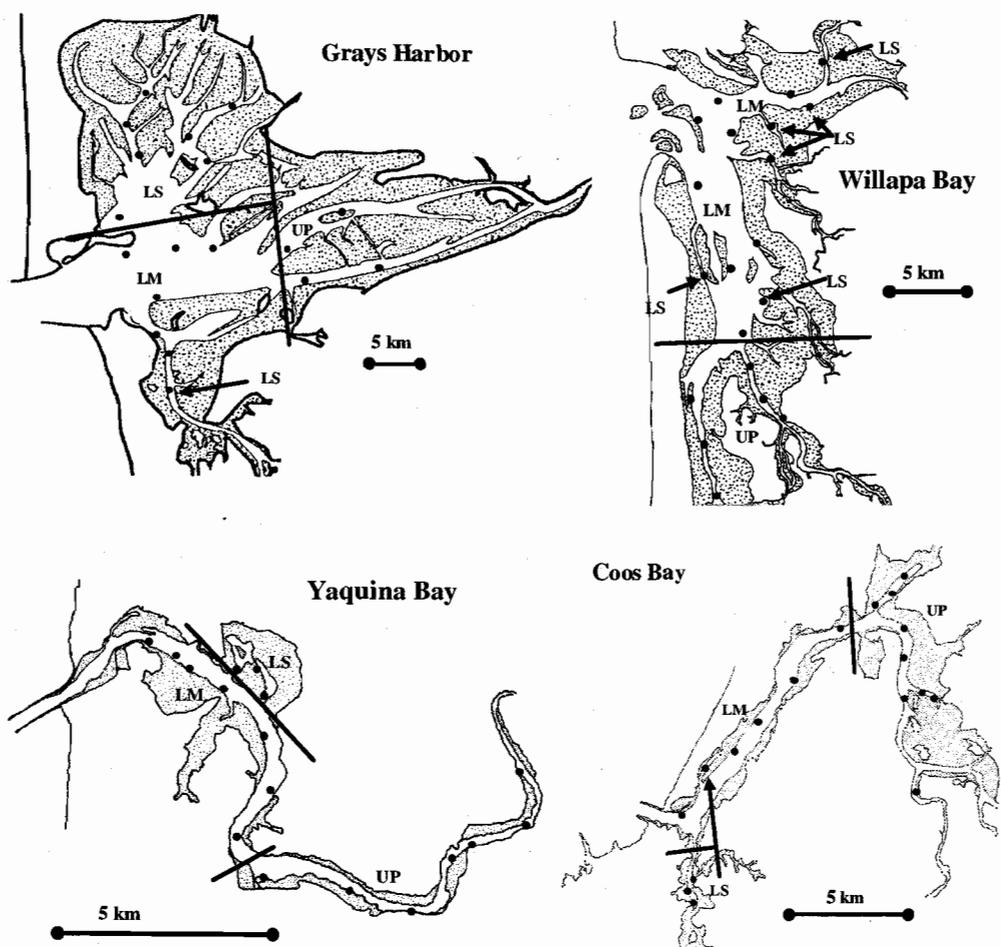


Figure 10.2. Map of the four study estuaries showing station locations.

estuaries were originally divided into 4-5 strata based on degree of oceanic influence (i.e. distance from estuary mouth). Trawl stations were chosen by random sampling within each strata with the caveat that no two stations were adjacent (Figure 10.2). Stations were allocated based on abundance of English sole and Dungeness crab (*Cancer magister*) within the stratum, with strata of higher abundance receiving more stations (Shi et al. 1994). Seventeen to 20 sites were chosen in each estuary. A constant location for each of the trawl survey sites was maintained throughout all years of the study. During the initial years of surveying (1983-1988) in Willapa Bay and Grays Harbor, sites were located using recognizable landmarks. During the final three years of the study (1998-2000), sites were located using a combination of these landmarks and global positioning system (GPS) readings. Thus, the exact site location varied somewhat from sampling period to sampling period roughly on a scale of 50 m.

Survey data collection

Trawl surveys of all four estuaries were conducted in both June and August from 1998-2000. During 1983-1988, trawl surveys were conducted at least monthly from May to September in Grays Harbor. For comparative purposes, only trawls from the June and August surveys from 1983-1988 data were used in the analysis with the 1998-2000 data. Benthic organisms including English sole were collected during daylight using a 3-m beam trawl described in Gunderson and Ellis (1986). The beam trawl had an effective opening width of 2.3-m and a height of 0.6-m. The net was towed at a speed of 0.8 to 0.9 m*s⁻¹ behind a 6.4-m research vessel with a minimum 5:1 scope of line out to depth. The distance towed averaged 140-m in 1998-2000, and 260-m in 1983-1988. Trawls were made against the prevailing current, and efforts were made to conduct trawling near the time of daylight low tides. Sampling was not conducted at high current velocities

during maximum ebb and flood to allow the greatest adherence of the beam trawl to the substrate. All fish and invertebrates captured were identified, and English sole caught during the surveys were measured for total length to the closest mm.

Transitions in life history of English sole occur as the fish grow in nursery estuaries. In estuaries, English sole undergo a feeding transition from feeding mainly on epibenthic prey (primarily harpacticoid copepods) to feeding on benthic prey (primarily polychaetes and juvenile bivalves) at lengths of 50-65 mm (Toole 1980). Predation pressure should also decrease with increased size of sole. In North Sea plaice (*Pleuronectes platessa*) an escape from predation by crangonid shrimp is usually attained at about 30-mm (Van der Veer et al. 1990). It was expected that the feeding transition, as well as the potential reduction of predation pressure as size increased would lead to different habitat requirements for different size classes of juvenile sole. Therefore, at each site densities of age 0+ English sole in the small (10-50 mm) and large (50-150 mm) size classes were calculated by dividing the catch in each size class by the area swept. The area swept was calculated using the net mouth opening width and the distance towed. Distance for each tow was measured from differential GPS readings in 1998-2000 (Rooper 2002, Appendix 1), and using a rangefinder and marker buoys from 1983-1988 (Shi et al. 1994).

It has been previously observed that significant variation in density of juvenile English sole occurs among estuaries, as well as on a seasonal and interannual basis (Rooper 2002). To standardize for this variation, I used the anomaly of English sole densities in each size class as the dependent variable in the analyses. The mean density for each estuary in each of the years and months where sampling occurred was calculated and removed from each individual density estimate. The values were then normalized by dividing by the standard deviation of the densities in each period so that

$$a_i = \frac{x_i - \bar{x}_{emy}}{sd_{emy}}$$

In this equation the subscript i refers to an individual density estimate from a trawl survey site within an estuary-month-year combination. Thus, emy refers to the estuary-month-year combination where a trawl survey occurred, and x and sd are the mean and standard de-

viation of all trawl surveys occurring in that estuary-month-year combination. By using the anomaly of the densities for each cohort I attempted to reduce the large scale variation in the dataset that was attributed to interannual, estuarine, and seasonal sources in order to concentrate solely on the component of variation related to within estuarine habitat types.

Habitat characteristics

In addition to documenting the fish and invertebrates captured during trawl surveys, additional samples and data were collected to further characterize each trawl site (Table 10.1). The substrate material (i.e., macroalgae, shell, woody debris, etc.) caught during each tow was weighed and/or its volume estimated. Additionally, the depth, bottom temperature, and bottom salinity were measured at the time of each trawl. In some cases this information was not recorded due to oversight or equipment failure. For missing depth values, the average depth calculated from other survey periods was used to fill gaps. For salinity and temperature, small gaps of missing stations were filled by the closest adjacent station sampled during the same time period. During the June 2000 surveys, a large number of stations had no temperature or salinity data due to equipment failure. The average temperature and salinity for each of these stations during the previous years June trawl surveys conducted were utilized.

A variety of known and suspected predators of juvenile sole that may influence the distribution of their prey inhabit estuaries, including crangonid shrimp (Van der Veer et al. 1990; Wennhage and Gibson 1998), and age 1+ Dungeness crab, *Cancer magister*, (Gotshall 1977; Stevens et al. 1982). Both of these predators were commonly captured during trawl surveys. The total density of age 1+ crab and the total biomass of crangonid shrimp were calculated for each trawl, and utilized in an index of predation pressure.

In 1998 a benthic grab was used to collect a sediment sample at most sites. In the laboratory grain size analysis was undertaken according to the methods in Rooper et al. (in press). The analysis gave the amount of sediment standard size classes according to the modified Wentworth scale (Cummins 1962). The average grain size at each site was determined based on the proportions of sediment in each size category and the mid-point of the grain size within each category. For ex-

Table 10.1. Habitat variables, classifications, and source of information used in principle component analyses to define habitat types in nursery estuaries.

Habitat variable	Classification	Source of information
Depth relative to mean low water (m)	<i>Static</i>	Nautical charts
Shell substrate (kg/ha)	<i>Static</i>	Trawl survey data
Woody debris substrate (kg/ha)	<i>Static</i>	Trawl survey data
Salinity (ppt)	<i>Ephemeral</i>	Trawl survey data
Temperature (°C)	<i>Ephemeral</i>	Trawl survey data
Sediment grainsize (um)	<i>Static</i>	Sediment collections, 1998
Macroalgal substrate (kg/ha)	<i>Ephemeral</i>	Trawl survey data
Distance from mouth of estuary	<i>Static</i>	Calculated from nautical charts
Percentage of surrounding tidal flat	<i>Static</i>	Calculated from nautical charts
Age 1+ Dungeness crab density (no/ha)	<i>Ephemeral</i>	Trawl survey data
Depth at trawl (m)	<i>Ephemeral</i>	Trawl survey data
Relative density of English sole	<i>Ephemeral</i>	Trawl survey data
Crangonid shrimp biomass (kg/ha)	<i>Ephemeral</i>	Trawl survey data

ample, the proportion of sediment sorted into a 1-mm sieve was assigned a grain size of 1.5-mm, as the grains were smaller than 2-mm yet larger than 1-mm. Sediment samples were not collected for five of the 73 trawl survey sites, so these sites were assigned the average grain size for the closest neighboring trawl survey site.

A number of other variables used to characterize each trawl survey site were taken from NOAA nautical charts. To assess the prevalence of intertidal area adjacent to each trawl survey site, the percentage of a 3.6 km² (one nautical mile) area around each trawl site that was composed of tide flat was estimated from nautical charts. The depth of each site relative to mean low water was also identified for each site. Finally, the distance of each site from the estuary mouth calculated as a percentage of the farthest up-estuary point sampled (in order to account for the large size difference among the four study estuaries) was calculated for each trawl survey location.

Data Analysis

Habitat characteristics for each site at which trawl surveys were conducted were classified as either ephemeral or static (Table 10.1). Ephemeral habitat characteristics were those that were likely to change between sampling dates, and thus needed to be treated separately from survey to survey. For example, the depth at which a trawl was conducted was considered to be ephemeral, since it varied with the tide stage and exact station location between sampling trips. Static habitat

characteristics were either stable or assumed to be fairly stable over the time of the study. The static variables included: depth of the site relative to mean low water, the average sediment grain size, the proportion of surrounding tidal flats, and the relative distance from the mouth of the estuary to each site. Additionally, the weight per ha of woody debris and average weight per ha of shell debris averaged across all trawls at each site from 1998-2000 was classified as a static variable, since these weights did not appear to vary substantially among years or seasons.

The static habitat variables were used to group sites across the estuaries in terms of a shared set of characters. Because of the correlation among the static variables (for example the amount of woody debris generally increased with distance from the mouth of the estuary), this was accomplished through principle component analysis. Prior to analysis, the static variable data for the 73 trawl survey sites was standardized, and the resulting covariance matrix was used in a principle component analysis to identify patterns in the data (SAS 1987). A classification scheme was developed based on these results in order to group trawl survey sites into categories that would apply across estuaries. The resulting classification scheme was used as a categorical variable in subsequent analyses of English sole density anomalies.

The ephemeral variables were also explored using principle components analysis to determine which of the

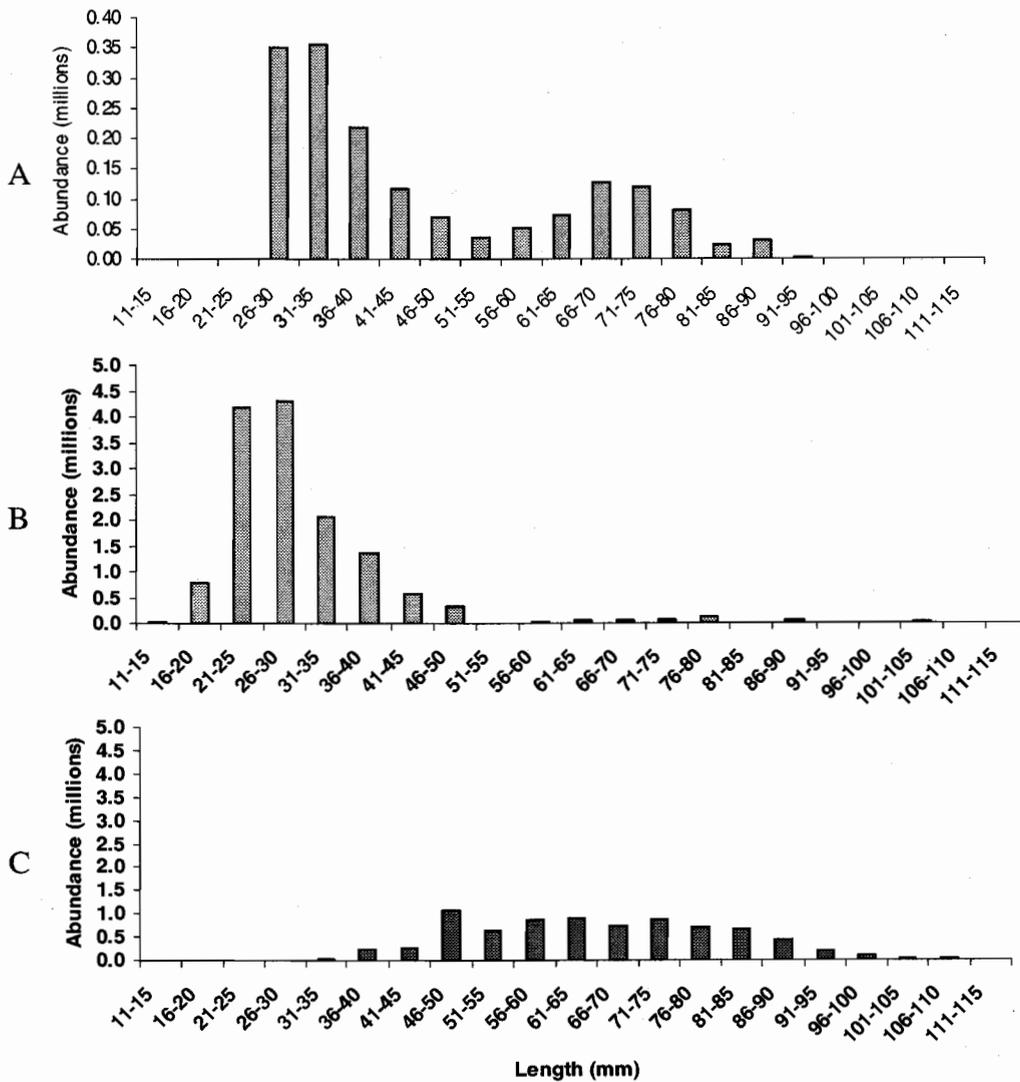


Figure 10.3. Length frequency plots for English sole captured in trawl surveys. Panel A depicts the bimodal length frequency of fish captured in the June 1998 survey of Coos Bay. Panels B and C are from Grays Harbor, 1998 from June (B) and August (C) surveys. The bottom two panels show the more typical length frequencies of fish captured in the June and August trawl surveys.

habitat characters exhibited the most variation over the estuaries. Principle components analysis was conducted on the six ephemeral variables over the 431 trawls that were conducted from 1998-2000. This analysis revealed variables that were both uncorrelated to each other, and varied substantially within the estuaries. These components were then used to guide further analyses of English sole densities, where it was hoped that this variability would help explain the variability in English sole density anomalies.

A final variable was added to the analysis to account for the overall density of English sole in each size class in each estuary-year-month combination. This variable

classified the density of each size class of sole within each estuary-year-month combination into one of three categories: high, average, or low. The categorization was accomplished by calculating the overall average density of each size class of English sole over all 800 trawls conducted in the nine years of the study. Then the estuary-year-month combinations that fell within two standard errors of the mean were categorized as average, two SEs above the mean as high and two SEs below the mean as low. The purpose of this relative density variable was to determine if there was an expansion of the range of English sole during years of high densities.

Table 10.2. Results of principle components analysis of static habitat variables at 73 estuarine sites.

Habitat variable	Correlation coefficients		
	Principle component #1	Principle component #2	Principle component #3
Depth relative to mean low water	-0.6051	-0.2065	0.5245
Shell substrate (kg/ha)	0.5582	-0.1687	-0.3798
Woody debris substrate (kg/ha)	0.8480	-0.1167	0.3546
Distance from the estuary mouth	0.4650	0.5710	0.6108
Average sediment grainsize	0.4696	-0.5881	-0.0410
Percentage of surrounding tidal flats	0.0996	0.7915	-0.3629
Cumulative variance explained	0.3072	0.5377	0.7130

Factorial analyses of variance was used to determine important variables affecting English sole density in the two size classes. Factorial analysis of density anomalies of the small size class of English sole were conducted only for the June survey data. In August surveys, there were very few English sole that were less than 50-mm total length, since settlement generally occurred in May of each year (Rooper 2002).

In all of the factorial analyses, an initial model was formulated including all main effects, as well as interaction terms. Insignificant ($p < 0.05$) terms in the analysis were removed sequentially until only significant terms remained. Pairwise comparisons for significant class variables were conducted using the least squares means approach (SAS 1987), with a Tukey adjustment for multiple comparisons (Zar 1974).

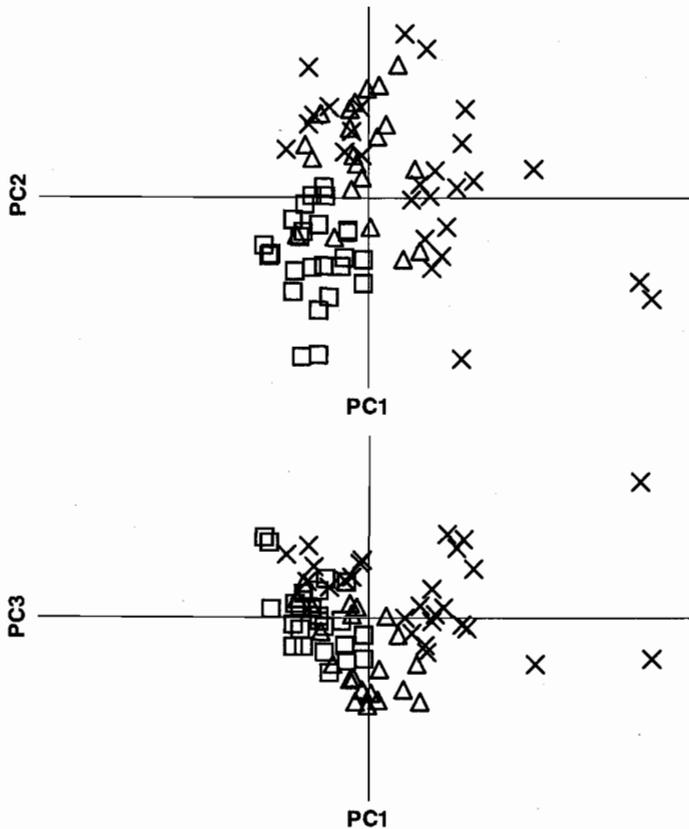
Results

Densities of small English sole at sites in June of 1998-2000 were between 0 and 11,300 per ha in Grays Harbor, 0 to 6,800 per ha in Willapa Bay, 0 to 6,000 in Yaquina Bay, and 0 to 5,400 per ha in Coos Bay. Densities of large cohort English sole in June and August 1998-2000 were observed over a wider range of values. During June and August trawl surveys, the density of large cohort ($50 < TL < 150$) English sole in Grays Harbor ranged from 0 to 5,200 per ha, in Willapa Bay densities ranged from 0 to 7,900, in Yaquina Bay densities were between 0 and 33,000 per ha, and in Coos Bay densities ranged from 0 to 3,900 per ha. Thus, there was considerable variability in density of both English sole size classes among sites in the estuaries.

In three of 12 sampling trips from 1998-2000 (Rooper 2002) there were significant cohorts of early settling (large size class) fish observed in the June surveys. This resulted in a bimodal length frequency distribution in June (Figure 10.3). The more typical length frequency histogram from June showed a smattering of large fish in the estuary, with a large number of late settling small fish (Figure 10.3). In August, the late settling fish had grown to a larger size, and the early settling fish may have moved out of the study area, resulting in a single mode of large fish (Figure 10.3).

Static variable analyses

The principle components analysis of static habitat variables resulted in each trawl survey site being classified into one of three categories: lower side channel, lower main channel, or upper estuary. The first three principle components explained over 70% of the variation in the static habitat variables (Table 10.2). The first principle component was weighted heavily on the average amount of woody debris found at each site, and the depth relative to mean low water. The second component was highly correlated with the percentage of surrounding tide flats in an area around each site, and the third component was most highly correlated with the distance from the mouth of the estuary. A scatterplot of PC1 against PC2 clearly separates the lower main channel sites from those in the rest of the estuary (Figure 10.4). The lower main channel sites all seem to fall within the area of negative values for both PC1 and PC2. The scatterplot of PC1 against PC3 separates out the lower side channel sites, with negative PC3 values, from the upper estuary sites, with predominantly positive PC3 values (Figure 10.4).



□ Lower main channel △ Lower side channel × Upper estuary

Figure 10.4. Scatter-plots depicting the significant principle components (PC1, PC2, and PC3) values for each trawl survey site. This principle components analysis was completed on the static habitat variables.

Lower side channel sites were typically shallower, had a slightly smaller average grainsize, and had larger areas of tide flats surrounding them than main channel sites (Table 10.3). Upper estuary sites were typically shallow with slightly less surrounding tide flats, exhibited higher amounts of both woody and shell debris and were farther from the mouth of the estuary (Table 10.3).

Ephemeral variable analyses

Of the six ephemeral variables assumed to change on a seasonal and interannual basis, three accounted for the majority of the variance in the habitat data set. Three principle components explained 67% of the variance in the ephemeral habitat variables (Table 10.4). The first principle component was highly correlated to bottom temperature and salinity measured at the time of trawling. These two variables were correlated to each other ($r = 0.52$), but because of its importance to growth rates in fishes and the consistency with which this data was collected, bottom temperature was chosen as the variable to be used in further analysis of English sole density anomalies. The second principle component was most strongly correlated to the depth at the time of trawling, and the third component was highly correlated to the two measures of predation, crangonid shrimp biomass and Dungeness crab density. Information on Crangon biomass was not adequately collected during the early period (1983-1988) of trawling, therefore age 1+ crab density was the only predation variable available over all years of the study. Because of their importance in the PCA, age 1+ crab density and bottom temperature were chosen as a covariates for analysis of small English sole density anomalies. For factorial analysis of large English sole, density anomalies and bottom temperature were utilized as covariates. In both of these analyses, depth was combined into 2-m bins in order to account for the variations in bottom depth that occurred over each trawl site. Thus, depth was used as a class variable in the analysis of both large and small English sole density anomalies.

temperature were utilized as covariates. In both of these analyses, depth was combined into 2-m bins in order to account for the variations in bottom depth that occurred over each trawl site. Thus, depth was used as a class variable in the analysis of both large and small English sole density anomalies.

Table 10.3. Average value (SE) of static habitat variables within each location category used to classify trawl survey sites.

Static habitat variable	Lower main channel	Lower side channel	Upper estuary
Depth relative to mean low water (m)	5.1 (0.14)	3.7 (0.17)	4.0 (0.17)
Shell substrate (kg/ha)	55 (14.2)	182 (17.9)	191 (43.6)
Woody debris substrate (kg/ha)	15 (2.3)	32 (4.7)	155 (22.8)
Distance from the estuary mouth	0.33 (0.02)	0.46 (0.02)	0.80 (0.02)
Average sediment grainsize (um)	263 (8.3)	223 (5.7)	275 (10.0)
Percentage of surrounding tidal flats	20.6 (1.8)	53.1 (2.6)	39.8 (2.5)

Table 10.4. Results of principle components analysis of the ephemeral habitat variables.

Variable	Correlation coefficients		
	Principle component #1	Principle component #2	Principle component #3
Depth (m)	0.3232	-0.7295	0.1389
Bottom temperature (°C)	-0.7484	0.2726	-0.3019
Bottom salinity (ppt)	0.8863	0.0761	-0.0937
Crangonid shrimp biomass (kg/ha)	-0.4976	-0.4102	0.6182
Age 1+ D. crab density (no/ha)	0.0424	0.4747	0.6352
Macroalgae (kg/ha)	0.3103	0.4770	0.2994
Cumulative variance explained	0.2993	0.5049	0.6706

Table 10.5. Results of factorial analysis of variance of small and large age 0+ English sole density anomalies. Significant (p<0.05) variables are shown, as well as the squared correlation coefficient, * denotes p<0.01.

Cohort of English sole	Significant factors	n	R ²
Small (TL < 50 mm)	Location*	400	0.17
	Bottom temperature*		
	Depth		
	Relative density of small English sole		
Large (50 mm < TL <150 mm)	Location*	800	0.05

Factorial Analyses

For analyses of the small size class of English sole density anomalies the factors used were estuary location and three ephemeral variables: bottom temperature, depth, and an index of predation (age 1+ crab density). The relative density of small fish in each estuary-year-month combination was also used in the analyses.

Factorial analysis of small (TL < 50-mm) English sole June density anomalies resulted in one significant (p < 0.05) continuous effect, bottom temperature, as well as three class effects: estuary location, depth, and relative estuarine density of English sole (Table 10.5). English sole density anomalies decreased with increasing bottom temperature, although variability in density anomalies was high. English sole density anomalies also decreased with increasing depth in the smaller size class (Figure 10.5), with positive anomalies occurring only at the shallowest depths (1 to 3-m). Significantly higher density anomalies were observed at lower side channel locations than at all other locations within the study estuaries (Figure 10.6), while at the

upper estuary sites, density anomalies were significantly lower than at all other locations. The relative density term was significant with higher density anomalies at all locations in years of relatively high densities, however, the density-location interaction term was not significant, indicating that no disproportionate expansion among locations was occurring at higher densities of small English sole. The index of relative predation pres-

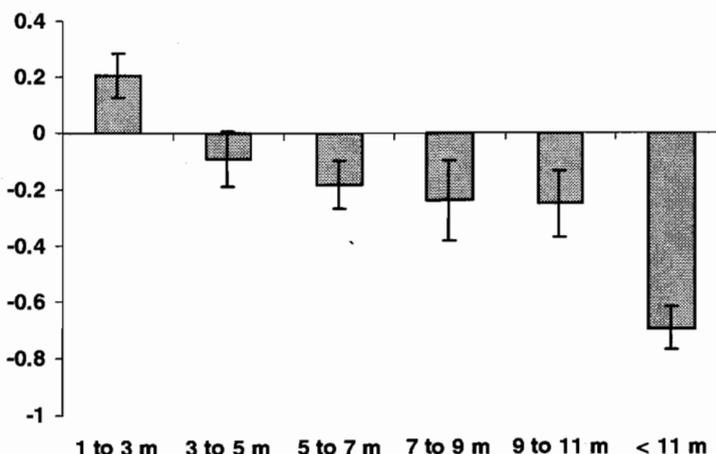


Figure 10.5. Density anomalies of small English sole at depths of trawling from 1983-1988 and 1998-2000 surveys. The depths were compiled into two meter bins for the analysis.

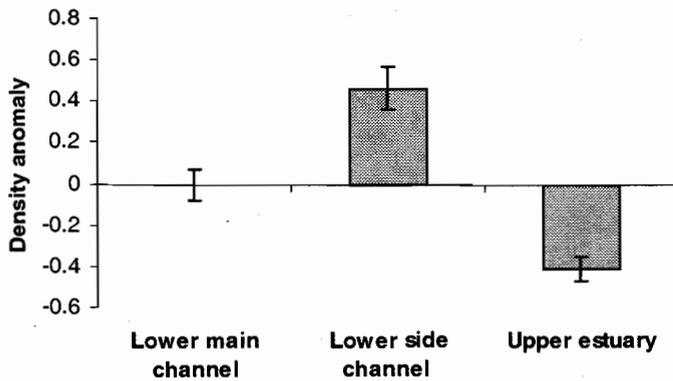


Figure 10.6. Average density anomalies of small English sole (total length <50mm) at locations within the study areas.

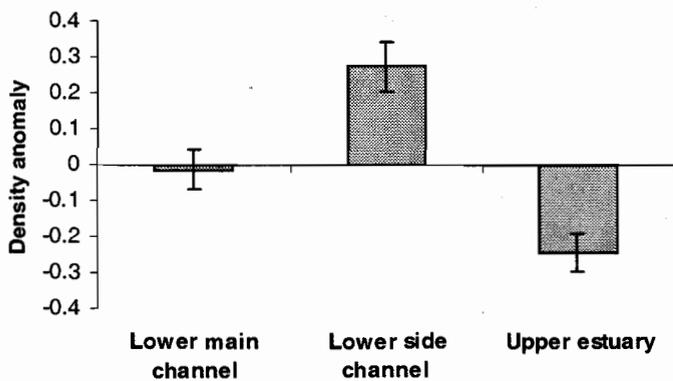


Figure 10.7. Average density anomalies of large English sole (50mm<Total length<150mm) at locations with estuaries.

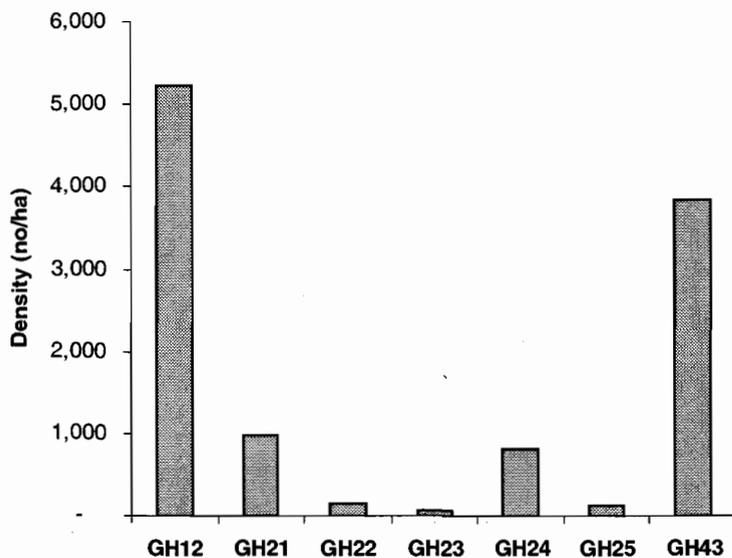


Figure 10.8. Density of large cohort English sole in Grays Harbor during the June 2000 trawl survey. The depicted stations constitute the lower side channel location sites for Grays Harbor.

sure measured by age 1+ crab density at each site was also not significant in the analysis. Approximately 17% of the total variation in density anomalies for small English sole was explained in the statistical analysis, thus a large proportion of the variation in English sole density anomalies was not explained by the habitat variables examined.

For analyses of the large size class of English sole density anomalies, the estuary location variable based on the cluster analyses of the static habitat variables, bottom temperature and depth were included as factors. The two ephemeral variables, bottom temperature and depth, were included based on the results of the PCA of the total set of ephemeral variables. The relative density variable was also utilized in the analysis.

Factorial analyses of the large size class (50 < TL < 150) English sole density anomalies resulted in only one significant effect (Table 10.5). The anomalies of English sole density at different locations in the estuaries were significantly higher in lower side channel sites than in either lower main channel or upper estuary sites (Figure 10.7). This pattern was much the same as with the small cohort English sole, but the differences in density anomalies were not as large. Although the factorial analysis model for large sole was statistically significant, it explained only about 5% of the variation in the data set. There was substantial variation in the density anomalies for large English sole that was not explained by the habitat variables we examined. Much of this variation was caused by large density differences occurring among sites within the same location. For example, many times the density of one or two lower side channel sites was very large, while the adjacent lower side channel sites were of average magnitude (Figure 10.8).

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Applications

Publications:

- Rooper, C.N. 2002. English sole transport during pelagic stages on the Pacific Northwest coast and habitat use by juvenile flatfish in Oregon and Washington estuaries. Ph.D. Dissertation, University of Washington, Seattle. 260 pp.

Presentations:

- Chris Rooper, Donald Gunderson, and Barbara Hickey, "English sole egg and larval transport on the Oregon-Washington shelf from 1997-2000." American Society of Limnology and Oceanography, Ocean Sciences 2002, February 11-15, 2002, Honolulu, Hawaii.

- Chris Rooper, Donald Gunderson, and Barbara Hickey, "English sole egg and larval transport on the Oregon/Washington shelf 1997-2000." Poster presentation at 12th Western Groundfish Conference, February 11-15, 2002, Ocean Shores, Washington.

- Chris Rooper, Donald Gunderson, and Barbara Hickey, "English sole egg and larval transport on the Oregon/Washington shelf 1997-2000." Poster presentation at PICES X Annual Meeting, October 10, 2001, Victoria, B.C., Canada.

- David Armstrong, Chris Rooper, and Donald Gunderson, "Estuarine-Ocean Coupling and Link to Coastal Fisheries: Dungeness Crab and English Sole." PICES X Annual Meeting, October 9, 2001, Victoria, B.C., Canada.

- Chris Rooper, Donald Gunderson, David Armstrong, and Barbara Hickey, "Young-of-the-year English sole transport and habitat use in coastal Oregon and Washing-

ton." Special seminar, Juneau Center for the School of Fisheries and Aquatic Sciences, University of Alaska Fairbanks, August 6, 2001, Juneau, Alaska.

Chris Rooper, David Armstrong, and Donald Gunderson, "Distribution and abundance over three years of English sole and Dungeness crab surveys." PNCERS Eat and Learn Seminar Series, January 24, 2001, University of Washington, Seattle, WA.

Workshops:

David Armstrong, Donald Gunderson, Chris Rooper, Curtis Roegner, Kirstin Holsman, and Geoff Hosack

attended the PNCERS All-Hands Meeting, January 11-12, 2001, University of Washington, Seattle, WA.

Partnerships:

None.

Personnel

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Resident Attitudes Regarding the Coastal Environment and Resource Management Chapter 11

Christopher Farley and Rebecca Johnson

Introduction

Natural resource management often involves difficult trade-offs between economic and environmental considerations. As part of the Coastal Resident Survey conducted in the spring of 2000, coastal residents were asked to compare their preferences for resource management on a 1 to 5 scale, with a one being "highest priority given to protecting environmental conditions" and a five being "highest priority given to economic considerations." Responses were grouped into three categories (1-2 Favors Environmental Protection, 3 Balance between Economy and Environment, 4-5 Favors Economic Considerations). Cross tabs were made comparing major demographic characteristics with the question asking respondents to rate their management preferences for economic or environmental considerations. Demographic and other characteristics that were examined are gender, age, employment status, occupation, income, length of residence in the community, and most trusted source of environmental information.

In addition to the quantitative questions addressing environmental attitudes, survey respondents were also asked for open-ended comments about their opinions on environmental management, current regulations, or other concerns. A content analysis using ATLAS.ti® qualitative analysis software is being conducted on these

open-ended comments written at the end of the survey in order to identify primary themes, and look for a common set of "facts" that coastal residents use when thinking about natural resource issues.

In the future, these comments will be compared to newspaper articles written in the local coastal newspapers in the three months prior to the mailing of the Coastal Resident Survey. Coastal residents identified these local newspapers as a primary source of environmental information in the coastal resident survey (PNCERS 2000 Annual Report, p. 125), and this comparison of qualitative data will allow us to determine whether resident opinions are shaped or reflected accurately by the local news media.

Study Results

Current results are tentative pending completion of the Washington surveys data entry and analysis of the coastal newspapers.

Quantitative Results

Women's' attitude distribution was skewed significantly more towards environmental concerns compared to men in the study (Figure 11.1). Differences between the bay communities were also clearly evident, with the more

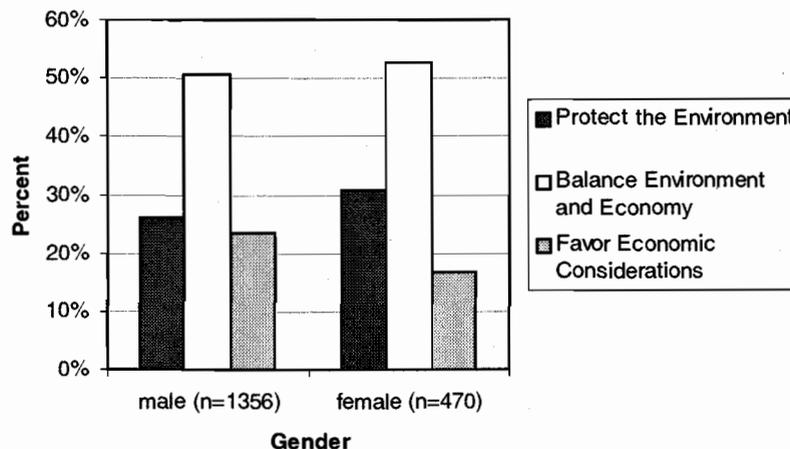
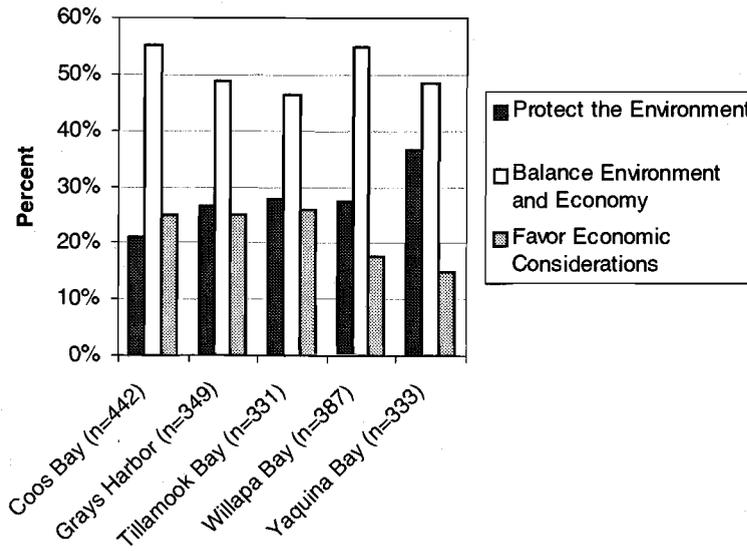
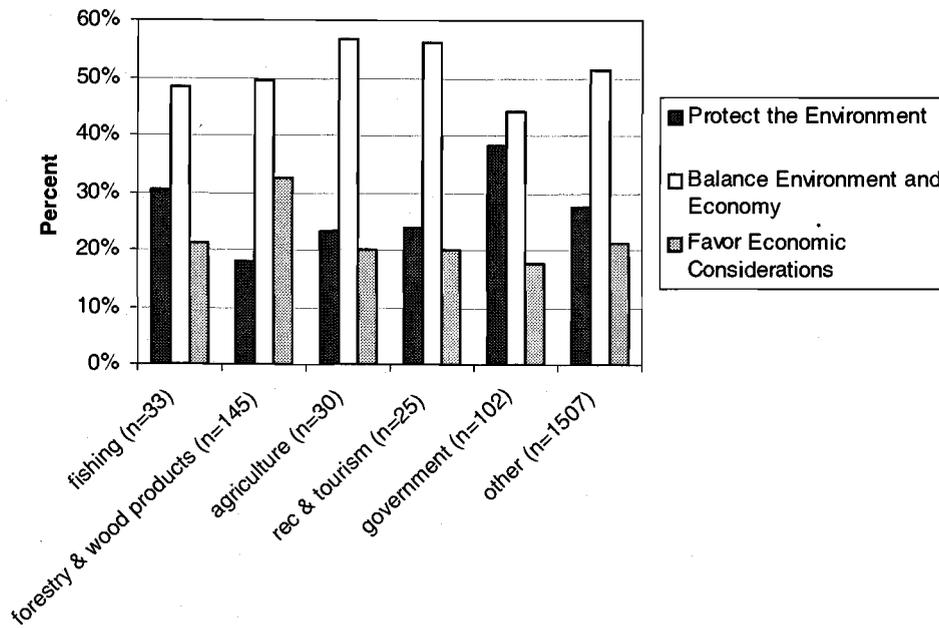


Figure 11.1. Gender differences regarding preferences for management trade-offs between environmental protection and economic considerations (Chi Square value=0.008).



Coastal Community

Figure 11.2. Differences between study bays regarding preferences for management trade-offs between environmental protection and economic considerations.



Occupation

Figure 11.3. Differences between resource related occupations regarding preferences for management trade-offs between environmental protection and economic considerations.

industrial areas (Coos Bay and Grays Harbor) skewed more towards the economy than the fishing/aquaculture and tourism dependent areas (Yaquina Bay and Willapa Bay; Figure 11.2). This difference was also reflected in differences between occupations (Figure 11.3). Finally, long-term residents (those who have lived

in community for over 20 years) were much more likely to favor the economy than those who moved to the area more recently (Figure 11.4). Small statistically significant differences were also found for differences between age groups.

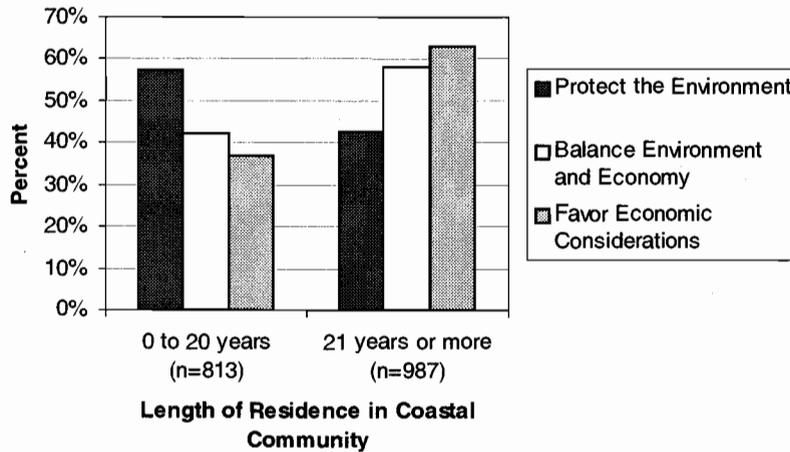


Figure 11.4. Differences between long and short term residents in coastal communities regarding preferences for management trade-offs between environmental protection and economic considerations (Chi Square value<0.001).

Qualitative Results

Currently only the comments from the three Oregon bays have been analyzed. One item of interest is the sheer volume of comments written by the coastal residents. 507 of the 1340 (37.8%) Oregon respondents added additional comments at the end of the survey. These comments amounted to over 115 typed pages of resident opinions. Residents from Coos Bay were much less likely to add comments (21.7% of residents) than residents of the Yaquina or Tillamook study areas (45.2% and 50.6% respectively).

The most commonly cited opinions and facts identified in the comments of Oregon coastal residents are:

- Increased populations of predators (Marine mammals and Terns) are a major cause of salmon decline.
- The STEP volunteer program is highly effective and should be supported.
- Dissatisfaction with bureaucratic control and government waste.
- Polarized views regarding current regulations (either too strong, or not strong enough), especially regarding fishing regulations.
- A perception that environmental problems are studied too much, with too little action taken to correct things.
- Appreciation for agencies and universities soliciting local input into resource decision-making and analysis.

- Rivers and estuaries are being choked off by silt and gravel, leading to flooding and poor fish passage.
- Ocean conditions are a major cause of salmon decline.

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Applications

Publications:

Bell, K., R. Johnson, D. Huppert, and C. Farley. 2001. Coastal Resident Survey Basic Summary of Responses: Coos Bay, Coos County, Oregon.

Bell, K., R. Johnson, D. Huppert, and C. Farley. 2001. Coastal Resident Survey Basic Summary of Responses: Yaquina Bay, Lincoln County, Oregon.

Bell, K., R. Johnson, D. Huppert, and C. Farley. 2001. Coastal Resident Survey Basic Summary of Responses: Tillamook Bay, Tillamook County, Oregon.

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Presentations:

Chris Farley and Rebecca Johnson, "Coastal Residents' Attitudes Regarding Estuarine Environments and Resource Management." Poster presentation at PICES X Annual Meeting, October 10, 2001, Victoria, B.C., Canada.

Workshops:

Christopher Farley and Rebecca Johnson attended the PNCERS All-Hands Meeting, January 11-12, 2001, University of Washington, Seattle, WA.

Personnel

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Willingness to Pay for Coho Salmon Enhancement Programs Chapter 12

Daniel Huppert, Jessica Leahy, Kathleen Bell, and Rebecca Johnson

Introduction

As a part of the PNCERS Coastal Resident Survey, we sought to determine the degree to which local residents would be willing to support increased local efforts to restore Coho salmon (*O. kisutch*) runs. We have particularly focused on the information collected about the residents' response to a question about a hypothetical Coho salmon enhancement program. That question asked whether individuals would vote "yes" or "no" on a local ballot measure calling for funding of a local salmon enhancement program through local taxes. The program was described as providing improved management of fishing activities and efforts to protect and restore local salmon spawning and rearing habitats. In the economics literature this is termed a "contingent valuation method" experiment, because each individual is asked to reveal whether they value the program offered enough to support a tax bill that is varied across respondents from \$5/year to \$500/year, contingent on the description of the program and the individual's perception of its importance and relevance. Analysis of such contingent valuation questions yield willingness to pay (WTP) values for goods and services that are not typically traded in markets. Significant effort was devoted to exploring different theoretical and statistical models for estimating WTP values for Coho salmon enhancement programs from the survey data. Results from a conventional linear logit analysis and a nonparametric approach, called the Turnbull lower bound estimator, are presented in this annual report chapter.

Methods

The contingent valuation method was used in the PNCERS Coastal Resident Survey, which was sent to 1,000 residents that lived within 30 miles of each PNCERS areas: Grays Harbor, Willapa Bay, Tillamook Bay, Yaquina Bay, and Coos Bay. A modified Total Design Method was used to increase response rate (Dillman, 1978). The response rate for each community ranged from 49-62%.

Background information about historical salmon runs was provided before the dichotomous-choice question, which was presented in the form of a ballot measure or referendum that provided funds for the implementation of a local Coho salmon enhancement program. The baseline condition was defined as the 1996-1998 average annual coho salmon run. Expected enhancement was presented in terms of run size and allowable catch in 2004. Two different levels of enhancement, high and low, were randomly assigned to respondents. When asked to vote, respondents were told that the program would cost their household an additional amount in taxes. The annual dollar amount varied from \$5 to \$500, and was randomly assigned to the survey questionnaires.

We used two different analysis methods to calculate WTP for salmon enhancement programs: the conventional linear logit regression and the nonparametric Turnbull lower bound estimator. A methodological issue regarding the statistical estimation concerned the assumption that the variation in response among individuals reflects random variation among individual value functions that can be captured by a random error following the logistic distribution. The logistic distribution has a single-peaked probability density distribution that assumes responses should smoothly approach all "No"s as the tax cost increases beyond \$500/year and smoothly approaches all "Yes"s as the cost approaches zero. An alternative, nonparametric method of estimating the cumulative probability function and probability density functions for WTP was invented by Turnbull (1976) and introduced to the environmental economics literature by Haab and McConnell (1997). This approach essentially uses the observed fraction of "No" responses at each level of tax cost to construct a cumulative probability distribution across tax costs, imposing the assumptions that the probability of "No" responses to the contingent valuation question must never decrease as the bid increases from zero to \$500, the probability of a "No" response for a zero bid is zero, and if there are still "yes" responses at the highest bid offered, the probability of getting a "No" response at higher, untested bids equals 100%. This approach makes no assumption about the shape of the probability density function.

Results

The conventional approach to analysis of such data, using the linear logit function, generated estimated values as described in Table 12.1. The values ranged from \$-33.72 to \$78.62 average annual WTP per household

Table 12.1. Mean WTP for local coho salmon enhancement programs based upon linear logit models. Each estimate is from the full sample of responses to the referendum question. Units are dollars per household per year.

	Overall	Low Income High Income	
		(< \$30,000)	(≥ \$30,000)
Grays Harbor	\$62.86	\$57.98	\$82.48
Willapa Bay	\$74.91	\$56.16	\$86.68
Tillamook Bay	-\$32.95	\$19.55	\$63.89
Yaquina Bay	\$78.62	\$65.37	\$101.51
Coos Bay	-\$33.72	\$11.40	\$13.61

per year. We found the estimated negative values per household estimated for Coos Bay and Tillamook Bay somewhat suspect because they fall outside the range of values actually observed. The negative estimated values from the simple linear logit model suggested that the assumed logit distribution was empirically untrue. A slightly more complex version of the linear logit model, which estimated how household income level (high/low) affected responses to the “yes”/“no” question, yielded WTP estimates from \$11.40 to \$101.51 per household per year.

With the empirical probability distributions calculated using the nonparametric Turnbull lower bound estimator, we found relatively high estimated average WTP values displayed in Table 12.2. These values ranged from \$107.39 to \$163.83 average WTP per household

Table 12.2. Mean WTP for coho salmon enhancement programs based upon nonparametric Turnbull lower-bound estimator. Each estimate is from the full sample of responses to the referendum question. Units are dollars per household per year.

	Overall	Low Income High Income	
		(< \$30,000)	(≥ \$30,000)
Grays Harbor	\$153.77	\$114.88	\$194.16
Willapa Bay	\$143.09	\$98.32	\$172.38
Tillamook Bay	\$163.83	\$84.52	\$203.89
Yaquina Bay	\$127.26	\$72.52	\$168.45
Coos Bay	\$107.39	\$72.15	\$196.61

per year. The empirical probability distribution developed using this approach had high probabilities at the zero and \$500 levels. This was consistent with the notion that there are many polarized individuals who will not support Coho enhancement at any price or who are willing to pay a very high price. Of course, there were also many people whose values were in between those two extreme positions. When income was included as a covariate, the range in WTP values became \$72.15 to \$203.89 depending on the PNCERS area and high or low-income category.

Discussion and Conclusion

Analysis of responses from the Coastal Resident Survey revealed substantial willingness to pay for local Coho salmon enhancement efforts. Significant citizen willingness to spend tax dollars in order to enhance local Coho salmon populations is an example of the pressures to better manage coastal estuarine systems. Average amounts of willingness to pay per household were as high as \$204 per year, depending upon location, covariate, and estimation method used. The comparison of the conventional linear logit model and Turnbull lower bound estimator results showed that the nonparametric estimate procedure eliminates the negative estimated WTP, and generated uniformly higher estimates of WTP. Breakdowns of the estimated WTP by demographic characteristics suggested that higher WTP was associated with higher household incomes. Future analysis will focus on additional demographic characteristics and the possibility of combining observations from PNCERS areas to find WTP estimates at the state level for Oregon and Washington.

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Applications

Publications:

Huppert, D., K. Bell, and R. Johnson. (*in review*) Willingness to Pay for Coho Salmon Enhancement in Coastal Communities. Proceedings of the North American Fisheries Economics Forum.

Bell, K., D. Huppert, and R. Johnson. (*in review*) Willingness to Pay for Local Coho Salmon Enhancement in Coastal Communities. Marine Resource Economics Journal.

Huppert, D., J. Leahy, K. Bell, and R. Johnson. (*in prep.*) A Distribution-Free Estimate of WTP for Salmon Enhancement.

Bell, K., R. Johnson, D. Huppert, and C. Farley. 2001. Coastal Resident Survey Basic Summary of Responses: Coos Bay, Coos County, Oregon.

Bell, K., R. Johnson, D. Huppert, and C. Farley. 2001. Coastal Resident Survey Basic Summary of Responses: Yaquina Bay, Lincoln County, Oregon.

Bell, K., R. Johnson, D. Huppert, and C. Farley. 2001. Coastal Resident Survey Basic Summary of Responses: Tillamook Bay, Tillamook County, Oregon.

Bell, K., R. Johnson, D. Huppert, and C. Farley. 2001. Coastal Resident Survey Basic Summary of Responses: Willapa Bay, Pacific County, Washington.

Bell, K., R. Johnson, D. Huppert, and C. Farley. 2001. Coastal Resident Survey Basic Summary of Responses: Grays Harbor, Grays Harbor County, Washington.

Presentations:

Daniel Huppert, Kathleen Bell, and Jessica Leahy, "Potential Local Economic Support for Coho Enhancement Programs." Poster presentation at PICES X Annual Meeting, October 10, 2001, Victoria, B.C., Canada.

Daniel Huppert. "Willingness to Pay for Coho Salmon Enhancement in Coastal Communities." Presented at North American Fisheries Economics Forum, April 1-4, 2001, New Orleans, LA.

Daniel Huppert, "Willingness to Pay for Coho Salmon Enhancement in Coastal Communities." Department of Economics Seminar Series, February 28, 2001, University of Washington, Seattle, WA.

Daniel Huppert, "Summary of Findings from the PNCERS Coastal Resident Survey." PNCERS Eat and Learn Seminar Series, January 17, 2001, University of Washington, Seattle, WA.

Workshops:

Daniel Huppert, Rebecca Johnson, and Kathleen Bell attended the PNCERS All-Hands Meeting, January 11-12, 2001, University of Washington, Seattle, WA.

Partnerships:

None.

Personnel

Daniel Huppert, Associate Professor, University of Washington.

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Challenges and Strategies for Better Use of Scientific Information in the Management of Coastal Estuaries..... Chapter 13

Thomas Leschine, Kathleen Bell, Bridget Ferriss, and Sarah MacWilliams

Introduction

The theme of the studies described in this section is the practice of environmental management as it affects the PNCERS estuaries. Our perspective is informed by principles of ecosystem management. Key actors in ecosystem management are managers, researchers, and the public¹. Institutional arrangements provide a context in which these groups interact and perceive, study, and manage environmental problems (Figure 13.1). The role of the individual studies in informing our view of ecosystem management is indicated in the figure.

Studies were conducted on institutional, social and managerial aspects of environmental management in one or more of the five case study estuaries of Washington and Oregon. A summary of five such studies is presented in Table 13.1.

Methods

In order to develop survey and interview questions, we conducted informational or exploratory interviews with local managers and researchers. We also reviewed his-

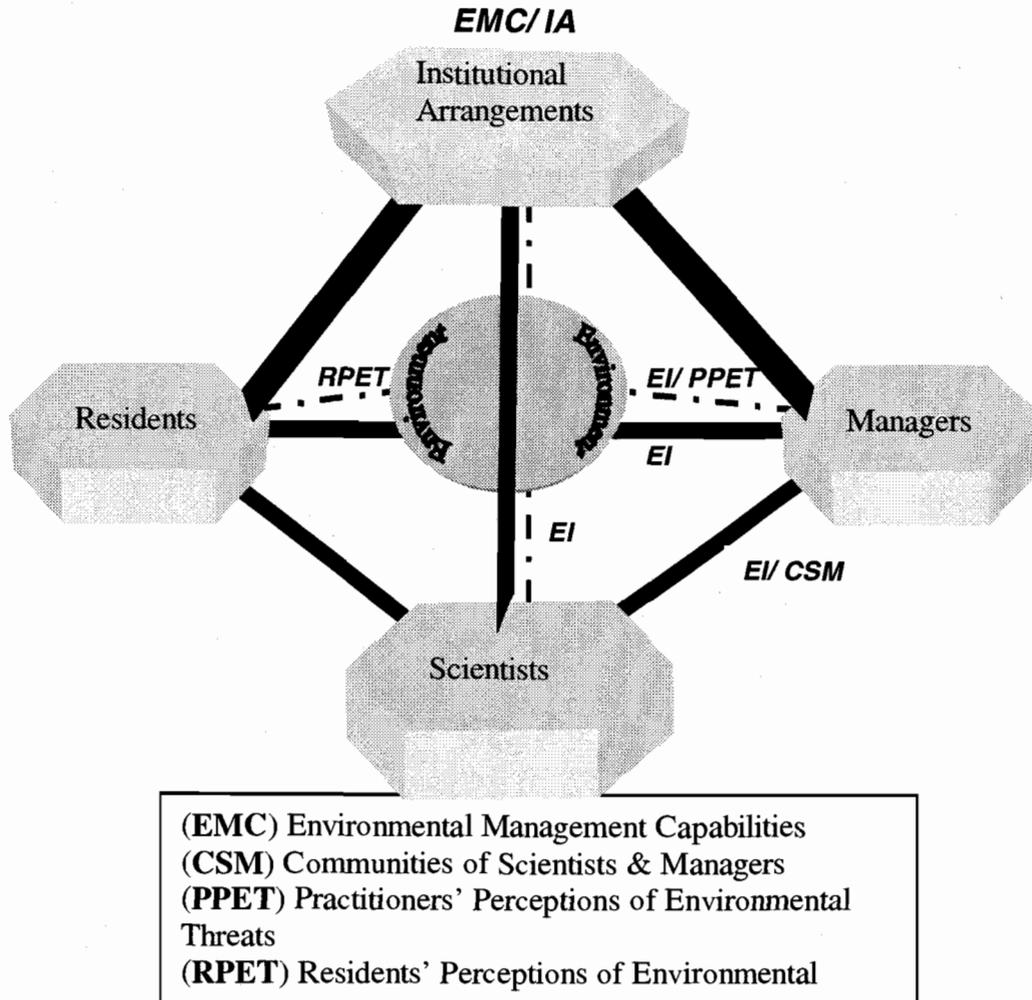


Figure 13.1. PNCERS social research projects as they pertain to key actors in ecosystem management.

¹Related residents' surveys are described in the companion report by Leahy et al.

Table 13.1. Research studies conducted from 1998 to 2002 on the institutional, social, and managerial aspects of environmental management in the five case study estuaries. (Residents' perceptions of threats are discussed in the companion report by Leahy et al.)

Code	Study Focus (principle investigators)	Date Conducted	Estuaries in Study	Primary method
EMC	Ecosystem Management Capabilities (Bennett)	1998/1999	Grays Harbor	Interviews, Systems Analysis, Case Study
CSM	Communication Between Scientists and Managers (Pico)	2000	Grays, Willapa, Yaquina, Tillamook, Coos	Survey
PPET	Coastal Practitioners' Perceptions of Environmental Threats (Bell, Leschine and Ferriss)	2001	Grays, Willapa, Yaquina, Tillamook, Coos	Survey
IA	Institutional Arrangements for Environmental Management (MacWilliams and Huppert)	2001/2002	Grays, Willapa, Yaquina, Tillamook, Coos	Interviews, Case Studies
EI	Environmental Indicators (Ferriss)	2001/2002	Grays, Willapa, Yaquina, Tillamook, Coos	Survey and Interviews

torical and planning documents describing management processes in each bay. Based on the information provided, several facets of research were developed as outlined in the table above, and as indicated by our review of the ecosystem management literature.

Andy Bennett's systems analysis of the environmental management processes of two Grays Harbor, Washington area environmental planning institutions (Line 1, Table 13.1) was conducted by comparing them with a model of an ideal ecosystem management institution based upon Laszlo's (1996) four propositions of natural systems. The Grays Harbor Estuary Management Plan (GHEMP) Task Force and the Chehalis Basin Partnership (CBP) were analyzed using six evaluation criteria of ecosystem management processes (Table 13.2): 1) stakeholder representation; 2) geographic scale; 3) temporal scale; 4) adaptive goals, strategies, techniques, and participants; 5) monitoring; and, 6) vertical and horizontal integration. Data sources for this analysis included planning documents produced by the GHEMP Task Force and the CBP, historical papers on the early stages of the GHEMP process, and interviews with participants from both institutions.

Michelle Pico employed the Dillman (1978) Total Design Method for the scientist and manager survey questionnaire (Line 2, Table 13.1). Two hundred thirty-one surveys of the 303 distributed to scientists and managers familiar with the five-estuary study region were returned, for a response rate of 76%. Managers and researchers were encouraged to self-define their roles

according to criteria provided. Scientists were defined as having conducted research studies in the 5-bay region and/or associated hinterlands in the last 5 years, and includes those from academe, agencies, and non-profit/private entities. Members of the resource managers and planners subpopulation work within the 5-bay region of study and are directly involved with or have an influence on the decision-making process that affects coastal and marine resource management. Michelle Pico sought answers to three main questions through the survey instrument: 1) how do the survey populations compare to 'established culture' theories; 2) is there information transfer inefficiency in the system; and 3) how can information transfer be improved in this region?

The coastal practitioners' survey (Line 3, Table 13.1), developed by Kathleen Bell, Thomas Leschine, and Bridget Ferriss, was conducted online in June and July of 2001 using the format and implementation of the Tailored Design Method (Dillman 2000). The survey targeted 242 coastal practitioners knowledgeable with or responsible for at least one of the five case study estuaries. The survey participants are considered an elite sample following Burgess' definition (1988:114). One-hundred forty-six practitioners completed the survey questions addressing the perceptions of coastal managers towards environmental threats in specified estuaries of the PNCERS study, resulting in a response rate of approximately 60% for that section. Additionally, 153 of the practitioners responded to a section of questions, developed by Bridget Ferriss, addressing their

Table 13.2. Comparison between an ideal ecosystem management institution, the GHEMP, and the CBP in terms of six evaluation criteria.

Evaluation Criteria	Ideal Ecosystem Management Institution	GHEMP	CBP
1. stakeholder representation	Values of all interested stakeholders are represented in the decision making process.	More public participation needed. Role of Citizens Advisory Committee is limited.	More public participation needed. Consensus decision making process is successful.
2. geographic scale	Geographic scope is sufficiently large to encompass the majority of human-nature and nature-nature interactions affecting the system being managed.	Limited to minimize the size of the Task Force and therefore cannot address issues on an ecosystem basis.	Defined by boundaries of the watersheds draining into Grays Harbor. Sufficient to achieve resource management goals.
3. temporal scale	The time frame addressed is adequately long to include several generations of the principle species being managed, including humans.	No sunset clause; however, personnel turnover in state and federal management agencies has resulted in lack of awareness of the GHEMP, limiting its effectiveness.	Time frame not addressed as of time of study.
4. adaptive goals, strategies and techniques	The goals, strategies, techniques and participants are adapted over time based on the results of closely monitored management experiments.	Review of entire GHEMP required every 5 years and guidelines for adopting amendments are provided. Lacks concrete goals. Desired flexibility has not materialized due to opposition to amended plans resulting in failure of adoption. Participants feel they lack authority to change the core document and there may be insufficient buy in from local communities.	Has demonstrated adaptability with changes in legislation. Participants are willing and able to take initiative in defining the role of the partnership.
5. monitoring	Both the ecological and socioeconomic systems are carefully monitored.	Task Force emphasizes monitoring changes in higher level decision making, but does not emphasize monitoring environmental conditions.	Demonstrated ability to monitor changes in state and federal policy. Members not directly responsible for environmental monitoring. Conducting two levels of environmental inventories which will provide an environmental baseline.
6. vertical and horizontal integration	The local, regional and higher levels of government and management are closely coupled.	Brings together local, state and federal government representatives in an effort to produce coordinated policy towards development issues in Grays Harbor. Debate as to role of GHEMP in providing guidelines versus regulations. Lacks vertical integration since responds to changes in higher level government but makes no effort to exert influence in higher level government policy.	Exhibits vertical integration since members actively lobby at state level on issues relevant to the CBP. Although decided not to include federal government representatives in the partnership, there are alternate means of integrating CBP policy with federal policies. There is general agreement among partners as to the role of the watershed plan they are developing.

perceptions of environmental indicators as management tools including their utility and limitations, resulting in a response rate of approximately 63%, respectively (Line 5, Table 13.1).

Bridget Ferriss and Sarah MacWilliams conducted elite interviews (Burgess, 1988:114) in the summer and winter of 2001/2002 for both the research on practitioners' perceptions of environmental indicators and the research on institutional arrangements in estuary management (Lines 4 and 5, respectively, Table 13.1). For the indicator research, interviews were conducted with twenty-seven practitioners using a structured format, as defined by Fontana and Frey (1994). The practitioners were selected based on their knowledge and familiarity with the management of one or more of the case study estuaries. Principal questions addressed the perceptions of coastal practitioners toward the use of environmental indicators as management tools. Specifically, the uses, limitations, and utility of indicators were explored, in selected estuaries of Washington and Oregon.

Sarah MacWilliams' research on institutional arrangements (Line 4, Table 13.1) is based upon five questions concerning arrangements for dredging and water quality management: 1) which stakeholders are involved; 2) What role(s) is (are) played by each stakeholder group; 3) how do stakeholders interact (e.g., collaborate, consult, reach consensus, conflict, litigate, etc.); 4) how do participating stakeholders define and rate the success of the management process they are involved in; and, 5) why did the institutional arrangements found in each estuary evolve in their present form? This research was conducted within the framework of a causal, explanatory theory-based, multiple-embedded case study (Yin 1994). Data sources included eighteen elite, topical/evaluation, semi-structured interviews using a standardized open-ended interview approach in all five estuaries (Patton 1990), in addition to planning documents, an unpublished PNCERS report (Jennings and Jennings 2000), and institutional web sites. Interviewees, including representatives of federal, state, and local government agencies, the aquaculture and dairy industries, NGOs, and private citizens, were identified through document data sources, the internet, and local contacts. Sarah MacWilliams is presently preparing the institutional arrangement data for analysis using ATLAS.ti © qualitative data analysis software. Coded interview data will be analyzed using criteria from the institutional analysis

and development framework (IAD), as well as from the literature on collaborative ecosystem management (see Ostrom 1999; Imperial 1999; Wondolleck and Yaffee 2000).

Results

Results of the five studies listed in Table 13.1 are summarized.

Environmental Management Capabilities

This study led to a comparative evaluation of two local environmental management organizations whose activities affect Grays Harbor, Washington (Table 13.2). Criteria for the comparison were generated from a review of the ecosystem management literature and principles of systems analysis, summarized in an ecosystem management "ideal" that served as a benchmark (Bennett 2000; Table 13.2).

Even though the Chehalis Basin Partnership and Grays Harbor Estuary Management Plan apply to geographically overlapping areas, there is relatively little interaction between the two entities. They reflect two very different approaches to environmental problem solving, the latter being process oriented and focused on permit facilitation, the former more proactive and focused on seeking environmental restoration opportunities. Though neither is representative of the ecosystem management ideal, the entrepreneurial "reinvented government" approach of the newer CBP results in more emphasis on environmental monitoring and greater likelihood that feedback from the environment will lead to adjustments in approach. By contrast, the Task Force in charge of the GHEMP focuses its monitoring on higher-level governmental organizations and appropriate responses. Taken together, the differences between the two seem indicative of the great variability that exists in regional and local environmental management institutions within the PNCERS study area.

Communication between Researchers and Managers

Responses to survey questions in four areas selected to exemplify potential "cultural" differences between researchers and managers working in the PNCERS study area showed that such differences did indeed exist (Pico 2000; see also PNCERS 2000 Annual Report Chapter

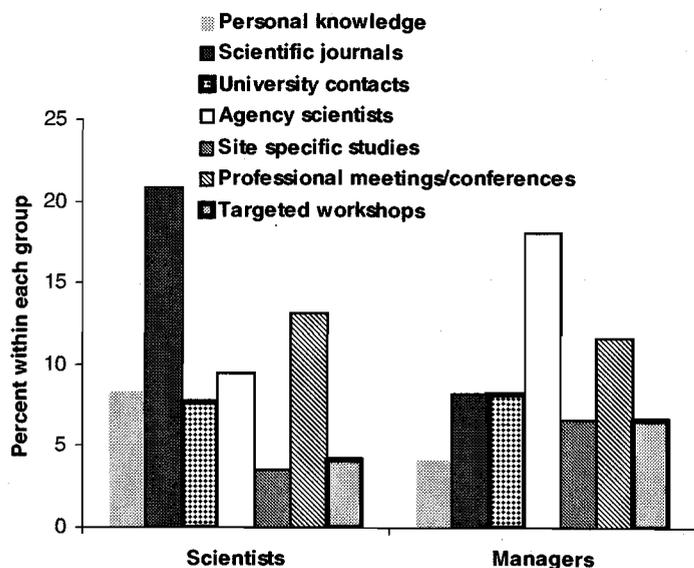


Figure 13.2. Results from the coastal practitioners' survey comparing the sources of scientific information used by scientists and managers.

A comparison of Figures 13.2 and 13.3 reveals both similarities and differences in the patterns of information dissemination and search utilized by managers and scientists. Unlike managers, scientists rely on professional journals for information they both seek and wish to disseminate to others. Managers rely most on agency scientific and technical staff for information they seek, with professional meetings and conferences also an important information source. The importance scientists also attach to professional meetings and conferences as vehicles for information dissemination makes these particularly important for information exchange between the two groups, including dissemination of management-relevant information resulting from PNCERS research. Archives and databases are the most frequently named information dissemination mechanisms by both groups however.

15). Moreover, respondents from both groups viewed these differences as potentially inhibiting communication between the groups.

Respondents offered a number of suggestions for improving communication between researchers and managers (Figure 13.4). Topical workshops and "integrated scientist/manager teams" were the top two choices of

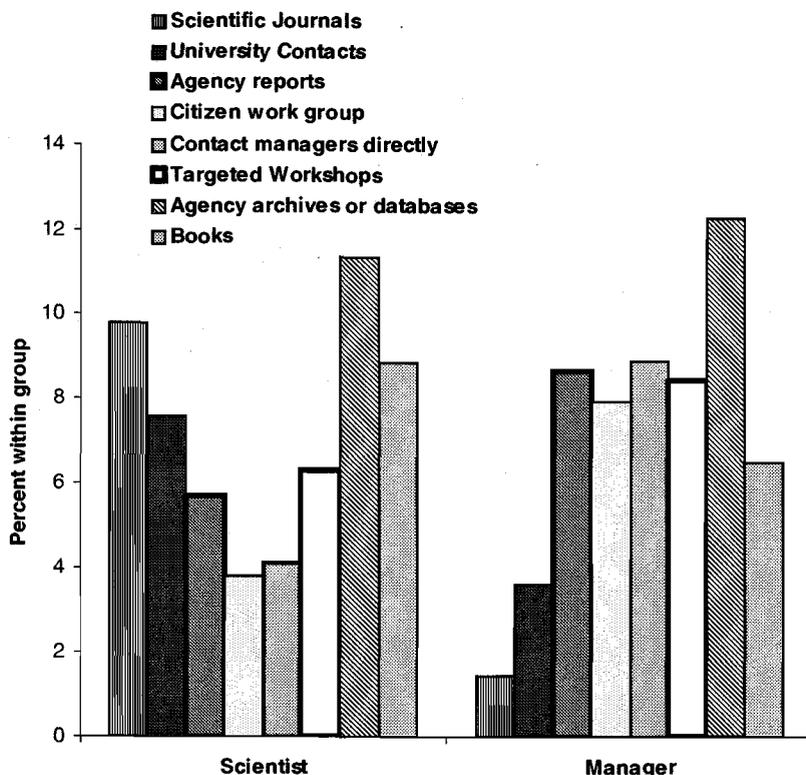


Figure 13.3. Results from the coastal practitioners' survey comparing the methods and tools used to disseminate information by scientists and managers.

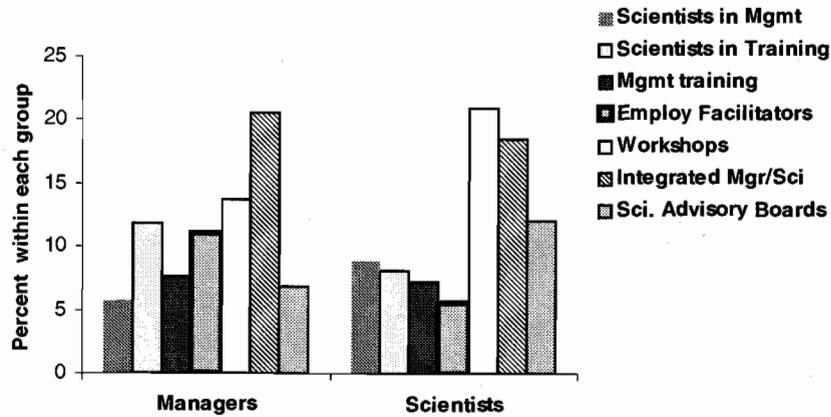


Figure 13.4. Results from the coastal practitioners' survey comparing the opinions of scientists and managers with respect to bridging the communication gap between the two groups.

both groups, with science advisory boards and programs to place "scientists in training" in agencies also receiving relatively high ratings. More direct and sustained involvement of researchers with managers working on problems of the PNCERS study region is a way to improve the use of scientific information in management beyond the duration of PNCERS itself.

Practitioners' Perceptions of Environmental Threats

Bay-to-bay differences dominate practitioners' perceptions of the most severe environmental threats faced by each (Figures 13.5-13.9). Not surprisingly, as a comparison of Tables 13.3 and 13.4 shows, practitioners' perceptions show sharper discrimination of what does and does not constitute a serious threat than do the perceptions of residents (further described in this report by Leahy et al.). If responses are summed across the bays and then analyzed according to the managers vs. researchers dichotomy utilized in the communications studies described above, no statistically significant differences emerge.

The relative geographic isolation of the five principal estuaries of the PNCERS study area may account for the fact that what is experienced and perceived to be a serious threat in one estuary is not necessarily so perceived in the others (e.g., spartina invasion in Willapa Bay, shoreline development and erosion in Grays Harbor, farm runoff in Tillamook Bay, and oil spills in Coos Bay, the site closest to the 1999 *New Carissa* oil spill). Beyond the environmental problems that dominate practitioners' con-

cerns on an estuary-specific basis, there are problems of somewhat lesser concern that are more uniformly perceived across estuaries. For example, upland logging is named among the top three threats in all five estuaries, and decline in fish or oyster-rearing habitat appears among the top three threats for all bays except Yaquina. The bivariate correlation statistics displayed in Table 13.3 provide a very useful comparative assessment of the relative importance practitioners familiar with each estuary attach to various environmental threats.

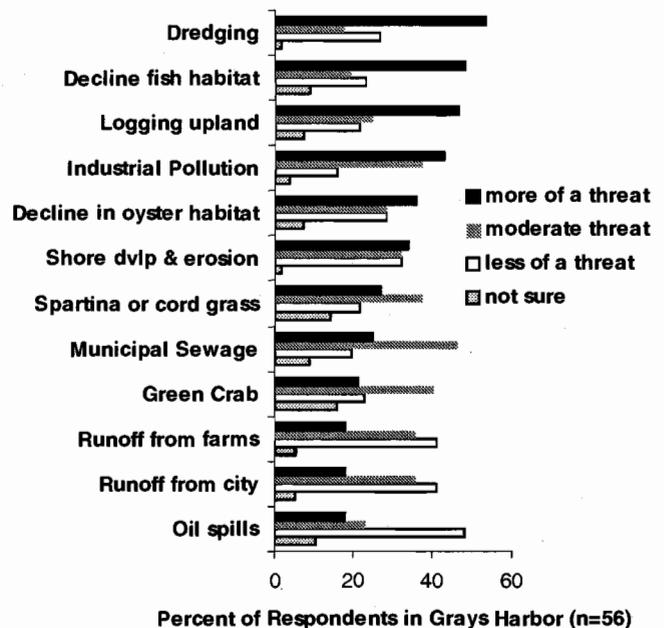


Figure 13.5. Results from the online survey of coastal practitioners regarding their perceptions of environmental threats in Gray Harbor.

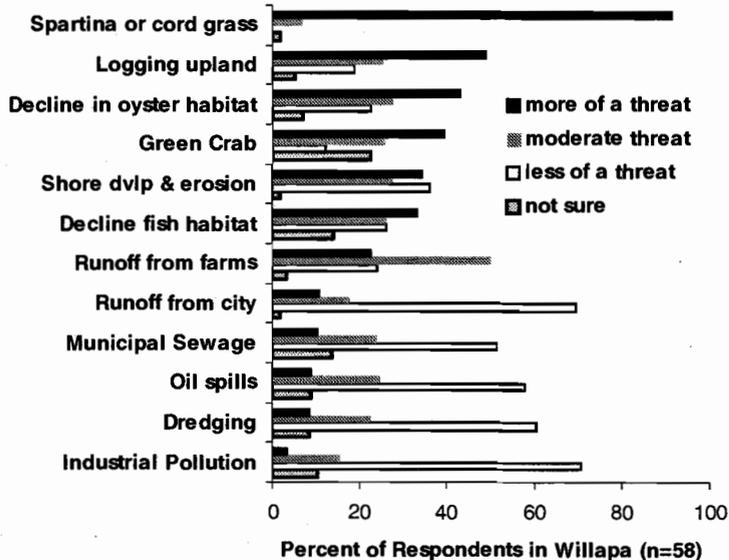


Figure 13.6. Results from the online survey of coastal practitioners regarding their perceptions of environmental threats in Willapa Bay.

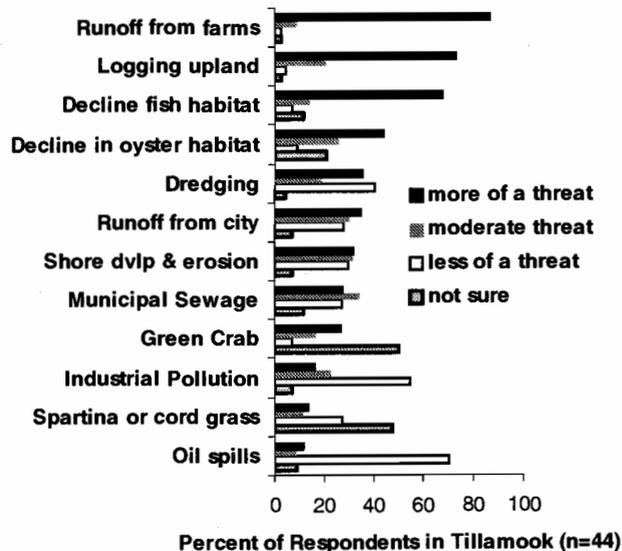


Figure 13.7. Results from the online survey of coastal practitioners regarding their perceptions of environmental threats in Tillamook Bay.

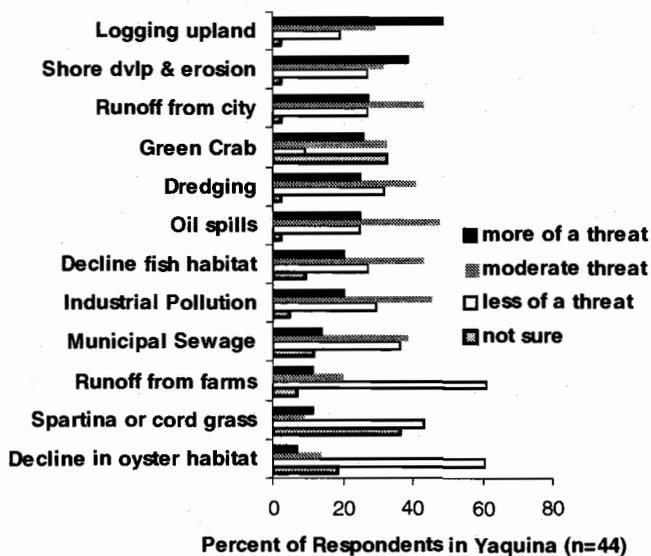


Figure 13.8. Results from the online survey of coastal practitioners regarding their perceptions of environmental threats in Yaquina Bay.

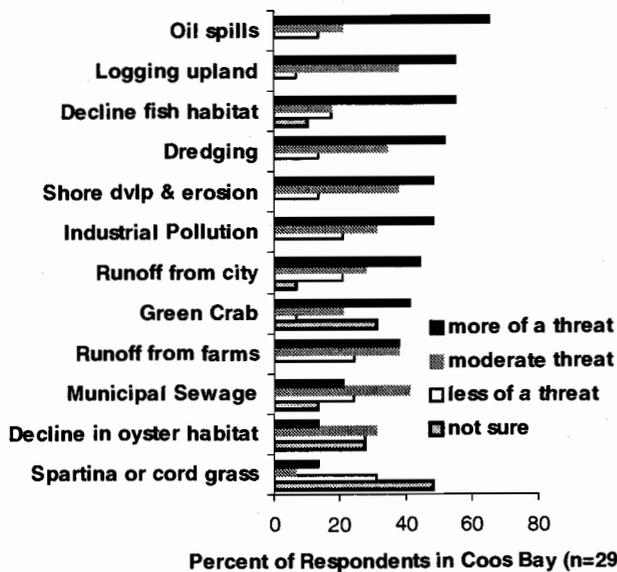


Figure 13.9. Results from the online survey of coastal practitioners regarding their perceptions of environmental threats to Coos Bay.

Institutional Arrangements

Although Sarah MacWilliams has not completed the institutional arrangement data analysis, it is possible to note some preliminary concepts emerging from the data (Table 13.5). These results stem from common themes observed in interviewees' responses to several sets of questions. Some questions addressed the interviewees' own familiarity with and time spent in a given estuary. This factor appears correlated with the degree to which various stakeholder groups employ a collaborative man-

agement approach. In estuaries in which the majority of stakeholders have been a part of the same community for many years, they often have an established working relationship or personal history with one another which fosters a more collaborative style of management between them. A second line of questioning pertained to how goals are set for institutional arrangements involving multiple stakeholders, or individual stakeholders groups. Based on common interviewee responses, it appears that clear goals are often set for

Table 13.3. Results from the online coastal practitioners survey. A summary of Kendall's tau b bivariate correlation tests comparing perceptions of environmental threats relative to each estuary.

THREAT		Correlation Coefficient (N)				
		GRAYS	WILLAPA	TILLAMOOK	YAQUINA	COOS
Industrial pollution	N=218	.292** (54)	-.380** (52)	-.135* (41)	NS (42)	.208** (29)
Municipal Sewage	N=204	.167* (51)	-.238** (50)	NS (39)	NS (39)	NS (25)
Shore dvlp & erosion	N=302	.424** (126)	-.221** (58)	-.161** (44)	-.128* (45)	NS (29)
Oil spills	N=214	NS (50)	-.180** (52)	-.213** (40)	.178** (43)	.347** (29)
Spartina or cord grass	N=171	NS (48)	.619** (57)	-.208** (23)	-.343** (28)	-.200** (15)
Green Crab	N=163	-.201** (48)	NS (45)	NS (21)	NS (29)	NS (20)
Dredging	N=220	.169** (55)	-.295** (53)	NS (40)	NS (43)	.172** (29)
Runoff from city	N=218	NS (53)	-.294** (55)	.128* (40)	NS (43)	.168** (27)
Decline in oyster habitat	N=196	NS (52)	.133* (54)	.210** (34)	-.338** (35)	NS (21)
Decline fish habitat	N=204	NS (51)	-.128* (49)	.272** (38)	-.209** (40)	NS (26)
Runoff from farms	N=220	NS (51)	NS (56)	.495** (43)	-.317** (41)	NS (29)
Logging upland	N=219	NS (52)	NS (55)	.195** (43)	NS (40)	NS (29)

**Correlation is significant at the 0.01 level (2-tailed).

*Correlation is significant at the 0.05 level (2-tailed).

Table 13.4. Results from the residents survey. A summary of Kendall's tau b bivariate correlation tests comparing perceptions of environmental threats relative to each estuary.

THREATS		Correlation Coefficients (N)				
		GRAYS	WILLAPA	TILLAMOOK	YAQUINA	COOS
Industrial Pollution	N=1670	.072** (353)	-.059** (352)	NS (307)	.110** (318)	-.134** (340)
Municipal Sewage	N=1621	NS (340)	-.056* (341)	NS (298)	.106** (312)	-.094** (330)
Shore dvlp & erosion	N=1694	NS (348)	NS (367)	.043* (320)	.112** (321)	-.171** (338)
Oil spills	N=1697	NS (353)	NS (355)	-.053* (312)	.089** (325)	NS (352)
Spartina or cord grass	N=1320	NS (282)	.354** (377)	-.110** (213)	-.101** (203)	-.212** (245)
Green Crab	N=1331	NS (294)	.158** (351)	-.073** (216)	NS (211)	-.092** (259)
Dredging	N=1545	.083** (322)	.060** (329)	-.110** (292)	.069** (281)	-.103** (321)
Runoff from city	N=1642	NS (341)	NS (364)	NS (305)	.078** (301)	-.103** (331)
Decline in oyster habitat	N=1455	NS (307)	.054* (330)	NS (265)	NS (250)	-.083** (303)
Decline fish habitat	N=1594	NS (335)	NS (353)	NS (297)	NS (292)	-.066** (317)
Runoff from farms	N=1639	NS (326)	NS (357)	.110** (316)	NS (303)	-.147** (337)
Logging upland	N=1652	NS (343)	NS (367)	NS (302)	.104** (300)	-.117** (340)

**Correlation is significant at the 0.01 level (2-tailed).

*Correlation is significant at the 0.05 level (2-tailed).

individual stakeholder groups rather than collectively for stakeholders working on related management issues. Similarly, interviewees expressed dissatisfaction with estuary management projects that are run jointly by all involved staff with no single authority. Hence, while they would like collectively established goals, stakeholders would prefer to have established agency or project leaders in charge of management projects. Many interviewees cited this lack of central authority and collective goals as problematic in current estuary management institutional arrangements.

We are currently developing a combined list of long-term and short-term design principles that describe successful institutional arrangements based upon the institutional analysis and collaboration literature. We will then determine whether it is feasible to apply those principles as criteria for success to institutional arrangements in our case study estuaries.

Environmental Indicators

An online survey and elite interviews of coastal practitioners were used to determine the perceived utility of

Table 13.5. Preliminary observations from institutional arrangement case study data.

Importance Factors in Institutional Arrangements for Estuary Management	Preliminary Observations
Familiarity of Institutional Participants with Community	-- Stakeholders who have lived in a community for a long duration tend to be involved in arrangements that are more collaborative -- Stakeholders prefer to work with people who are knowledgeable about their particular estuary rather than estuarine systems in general
Leadership	-- Stakeholders prefer to have established central leaders for individual agencies and working groups rather than having all projects run jointly by staff
Goal Selection Process	-- Stakeholders prefer the establishment of collective goals across their groups rather than individual stakeholder group goals

Table 13.6. Methods and questions used to determine the perceived utility, current uses, and the perceived limitations of environmental indicators.

QUESTIONS		ANSWERS
<i>Perceived Utility</i>		
Survey	-- Are indicators needed in your area of work?	open question
Interview	-- Are environmental indicators a worthwhile tool?	open question
<i>Current Use</i>		
Survey	-- Are indicators (ecological, physical, or social) being used in the area that you manage and/or research? -- If indicators are used in the area you manage and/or research, how would you classify their primary purpose?	Yes; No; Not Sure Monitoring; Research; Communicating with other Managers and Researchers; Communicating with the Public; Measures of Management Success; Tools for Management Decisions; None of the Above
Interview	-- How are indicators used in your job?	open question
<i>Perceived Limitations</i>		
Survey	-- What is the primary factor that limits the use of indicators in the area you manage and/or research?	Unfamiliarity with Indicators; Lack of Resources; Not Required/Suggested in Mandate; Not Useful; Have been Tried and Found Unsuccessful; No Initiative for their Development and Use; No Perceived Need at this Time; Lack of Data/Indicators for Area
Interview	-- What are the disadvantages to using indicators?	open question

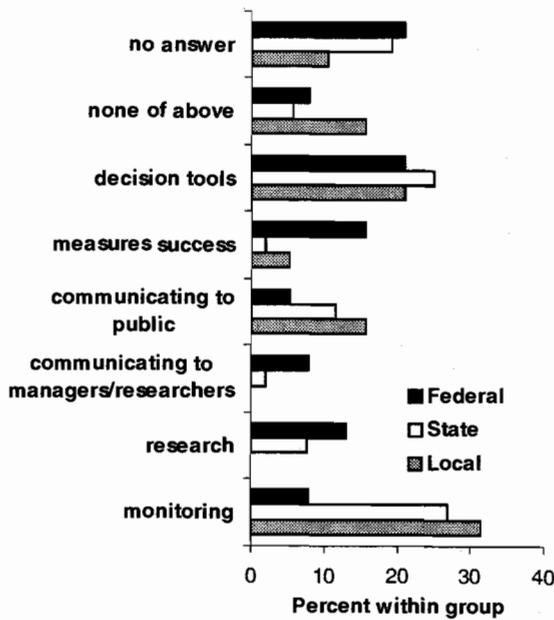


Figure 13.10. Results from the online survey of coastal practitioners regarding the primary purpose of indicators in their area of work.

indicators as environmental management tools, their current uses, and the perceived limitations to their use (Table 13.6). In general, indicators are not being used to their full potential in PNCERS estuaries.

Utility

Of the 144 survey respondents, 53% selected “yes” indicators are needed but 40% skipped the question, a surprisingly large number. Interviews produced similar responses. When asked if environmental indicators are a worthwhile tool there was again a strong positive response (59%) but quite a few who were unsure (22%) and 11% did not provide an answer.

Use

Of the 152 survey respondents, 63% said yes while 39% were again not sure. The survey and interviews also asked how indicators were being used in the practitioner’s area of work. Monitoring (survey, 22%; interviews, 19%) and aids to decision making (survey, 24%; interviews, 11%) were two of the most common. The interviewees also listed “focus attention” as a primary use (14%). Interestingly, 19% of the survey respondents skipped this question even though there was a “none of the above” choice listed (6% selected this option). The suggestion is that those who are familiar

with indicators believe they are useful but a large number of coastal practitioners are unfamiliar with them.

Differences across groups emerge in the primary uses of indicators, when the responses are sorted by job function and institution of employment. When compared to other job functions, a significant number of researchers listed “research” as their primary indicator use ($\chi^2=7.955, p<0.01$) while Educators and Outreach workers selected measures of success more frequently than the others ($\chi^2=6.822, p<0.01$). On the other hand, Federal employees (compared to State and Local government employees) selected monitoring significantly less ($\chi^2=5.240, p<0.05$), State employees selected measures of success less than Federal and Local government employees ($\chi^2=4.378, p<0.05$), and Administrators selected monitoring ($\chi^2=4.330, p<0.05$) less than those in other job functions (Figure 13.10).

Factors Limiting Indicator Use

When asked what the primary limiting factor to indicator use is, 45% of survey respondents chose “lack of resources.” This response was followed in frequency by those who skipped the question (22%) and the “lack of data” selection (19%). Unfamiliarity with indicators was next in rank with 10% of the responses. Further analysis of the respondents who selected unfamiliarity with indicators as a limiting factor showed uneven distribution across job function and level of government. When sorted by job function, a significant number of those in Planning and Community Development, versus all other jobs, chose unfamiliarity with indicators as the primary limiting factor ($\chi^2=0.210, p=0.01$). When sorted by organization of employment (Federal, State, or Local government employee), a significant portion of Local government employees chose the same unfamiliarity response ($\chi^2=16.379, p<<0.01$).

A prominent concern among interviewees was the reliability and validity of environmental indicators. Their most frequent responses concerning the limiting factors of indicators were: choosing the wrong indicator (15%), the requirement of a good understanding of the ecosystem (10%), and that people can focus on indicators too much (9%). Other issues were dangers of misuse and misinterpretation; unreliability; not knowing how to properly apply indicators; and that they can be relied upon too heavily.

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Applications

Publications:

- Ferriss, B.E. and T. Leschine. (*submitted*) The Use of Environmental Indicators as Management Tools in Pacific Northwest Estuaries (U.S.A.). Aquatic Ecosystem Health and Management.

Presentations:

Bridget Ferriss and Thomas Leschine, "The Use of Environmental Indicators as Management Tools in Pacific Northwest Estuaries (U.S.A.)" Presentation at the 6th International Conference of the Aquatic Ecosystem Health and Management Society (AEHMS), November 4-7, 2001, Amsterdam, The Netherlands.

Thomas Leschine, "Challenges and Strategies for Better Use of Scientific Information in the Management of Coastal Estuaries" Presentation at PICES X Annual Meeting, October 9, 2001, Victoria, British Columbia, Canada.

Bridget Ferriss and Thomas Leschine, "The Role of Indicators in the Management of PNCERS Estuaries." Poster Presentation at PICES X Annual Meeting, October 10, 2001, Victoria, British Columbia, Canada.

Sarah MacWilliams and Daniel Huppert, "Styles of Collaborative Resource Management in Pacific Northwest Coastal Estuaries." Poster presentation at PICES X Annual Meeting, October 10, 2001, Victoria, British Columbia, Canada.

Workshops:

None.

Partnerships:

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