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PNCERS

Pacific Northwest Coastal Ecosystems Regional Study

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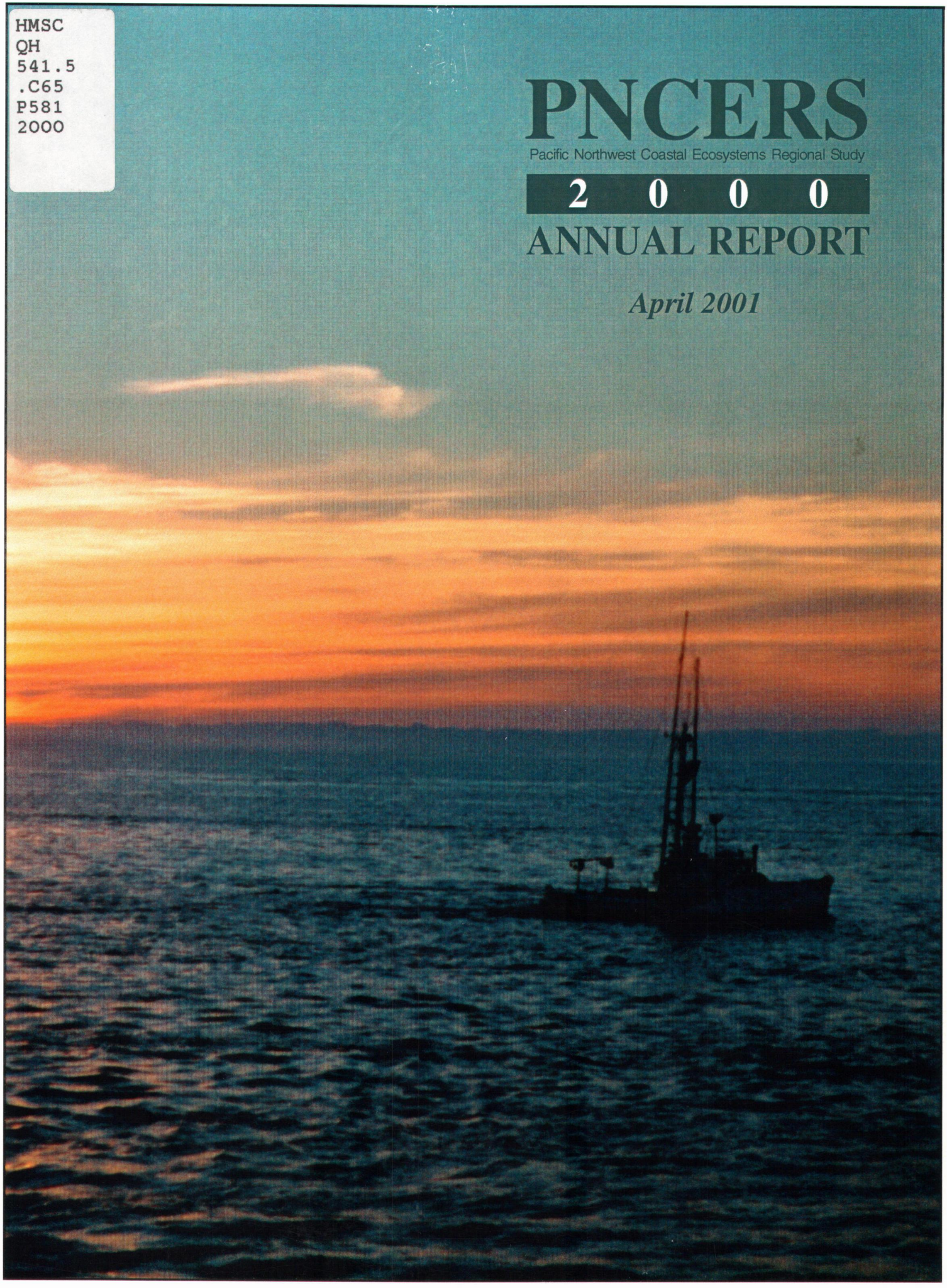
ANNUAL REPORT

April 2001



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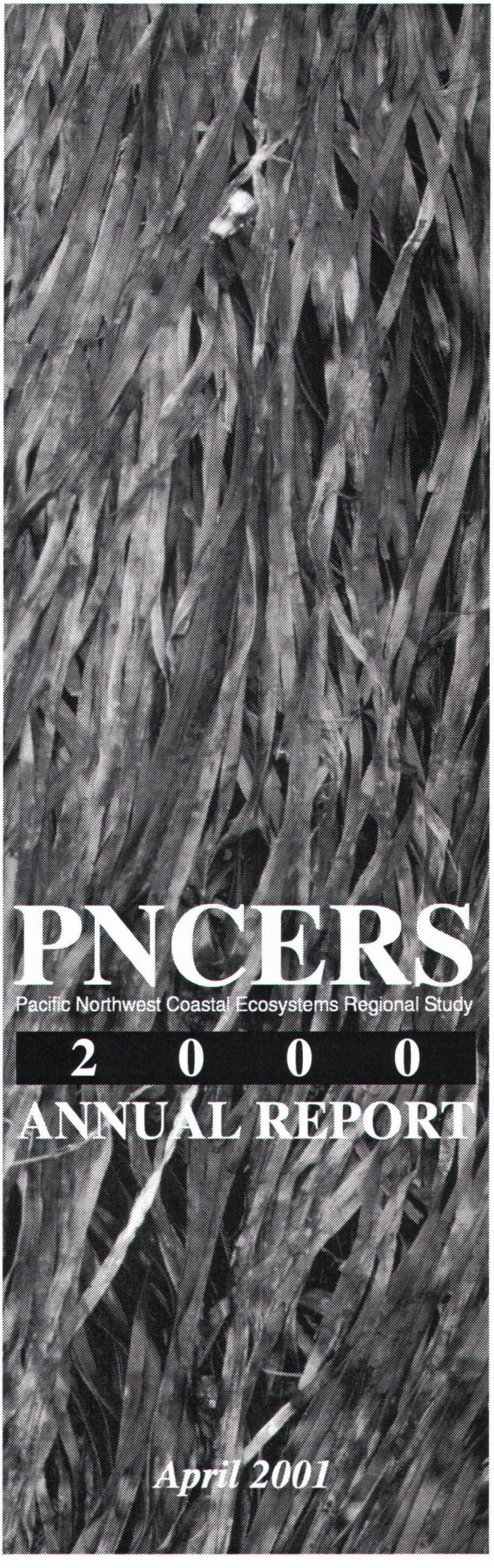

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Title Page: Eelgrass on Washington coast, 1988. Photo by Sara Breslow.

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Figure 3.6. Time series of biophysical parameters measured at estuarine instrument moorings (from Washington Department of Ecology/EPA). (a) Salinity recorded at Bay Center. (b) Temperature recorded at Toke Point (brown) and Bay Center (red). (c) Fluorescence recorded at Bay Center. (d) Water level recorded at Toke Point. The origin of the water masses is labeled above.

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Figure 3.7. An excerpt of Figure 3.6 highlighting the transport of a coastal phytoplankton bloom into Willapa Bay by tidal currents during the relaxation period (from Washington Department of Ecology/EPA). Fluorescence, salinity, and high tide signals are synchronous. Note also the salinity gradient reversals as the Columbia River plume returns to the estuary.

egon. Across all five counties, services, retail trade, and government provided the most employment opportunities. Income in all five counties is lower than state and national averages. Unearned income, such as social security, welfare, and investments, constitute a significant proportion (>40%) of personal income, on average. For employment related to marine resource extraction, increasing global supplies of many fish products combined with the local salmon crisis, are depressing this sector. Although population is increasing, younger adults are leaving and the age distribution is shifting towards retirees. Despite these trends, surveys indicated that residents valued biophysical characteristics of their estuaries, including proximity to the ocean, views and scenery, and fishing opportunities. Social characteristics, including population, traffic, and job opportunities, were all seen as negative trends. Visitor surveys reinforced the value of biophysical attributes of the estuary, including access to recreational opportunities such as fishing, crabbing, birding, and wildlife viewing. In sum, despite neutral to negative economic and demographic trends, and a minor impact of natural resource-based jobs in the employment base, people in coastal environments value the coastal ecosystem.

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Indicators of West Coast Estuary Health

Julia K. Parrish, Kathleen Bell, Elizabeth Logerwell, and Curtis Roegner

The PNCERS project seeks to develop indicators for coastal estuaries that are useful to the many organizations and individuals involved in planning for, and managing the use of, estuarine resources. To do this we focus on the broad "system" perspective, which recognizes both the biological/ecological state of the estuaries and the economic and social state of the local human communities. This requires incorporating the more limited concepts of ecological or economic or social health into a more complex but meaningful concept of system health. Karr (1996), defined two goals for natural resource management: ecological integrity and ecological health. Ecological integrity – the sum of physical, chemical, and biological integrity – implies an unimpaired condition, corresponding to the "original" state. Biological integrity is defined by a system in which the individual components (from genes to species) interact via processes and resultant functions (e.g., predation, decomposition, metapopulation dynamics, nutrient cycling, etc.) creating ecological communities within a dynamic range expected at a given spatial and temporal scale. Thus, short-term, small spatial scale (e.g., habitat patch) community patterns may differ markedly from decadal to centennial scale and/or large spatial scales (e.g., watershed). The important points are that biological, and ecological, integrity are eden-esque terms which set a goal devoid of societal interaction. Ecological health realizes this conundrum by describing the goal for the ideal condition of sites (highly) modified by society. Healthy sites will continue to produce resources without negatively affecting adjacent sites or degrading future productive capacity. Implicit in this definition is the assumption that natural resource production is dependent on some (non-trivial) measure of ecosystem integrity (i.e., the maintenance of species, and community processes and functions necessary for continued delivery of goods and services). We extend this latter definition to explicitly include society. Thus, "system health" is maintained when the interactions between society and the ecosystem result in sustainable, healthy ecological conditions as well as a sustainable and prosperous local economy and quality of life.

Measuring qualities such as integrity and health are problematic, in part because they are multivariate quantities, and in part because the component parameters are generally known but explicitly vague. As with many multifaceted quantities (e.g., the economy, climate, river quality), the solution has been to develop a set of measures which indicate the status of the system, without detailing all parts of it. Often such indicators are further amassed into single indices (e.g., economy - Index of Sustainable Economic Welfare; climate - Pacific Northwest Index; river quality - Index of Biotic Integrity). We believe the purpose of developing a set of indicators is to encompass both actual change in a system, as well as the driving forces behind that change. Change in a given parameter should not have a value attached to it (i.e., good, bad, neutral), as that judgement is in the eye of the beholder. Rather, the selection of a specific parameter to monitor for change should be based on the importance of that entity to the continued structure and function of the system as a whole. Essentially this means that complete characterization of an estuarine system, including the physical, biological, and socio-economic components, will require development of an indicator set which addresses both ecological integrity and system health. In fact, we may expect that at certain levels of human activity, system health would increase at the expense of ecological integrity. However, as the system is increasingly perturbed, the ability of society to extract useful resources - including both goods and services – will depend on maintenance of some threshold level of ecological integrity.

In this chapter, we attempt to lay out a conceptual framework for indicator selection germane to West Coast estuaries, including those studied intensively by PNCERS researchers. In the latter half of the chapter we offer an annotated list of candidate indicators for each of the three system components: the physical environment, the socio-economic system, and the biological system. A concurrent table presents all candidate indicators, their constituent measures and proxies (if appropriate) and the relevant estuarine types within

which the indicators are valuable (Appendix 1A). Future work will focus on linking candidate indicators to cause and effect relationships producing fundamental change in estuarine systems.

West Coast Estuarine Characterization

Defining the Scope

Most attempts to design a set of indicators of system health, or integrity, have focused first on the development of a conceptual model of how the system works. Indicator selection then follows from that model. Although this approach is certainly essential, with respect to estuaries there are at least three types of problems. First, authors of an indicator set inevitably concentrate on those components of the system with which they are most familiar, irrespective of the central goal – to design a comprehensive set of measurements of system change. This problem is most notable in the division between socio-economic approaches and biological or bio-physical approaches. Thus, the system is for and about people, or, the system is about the ecological community. For instance, selected metrics in the US EPA Watershed Indicators program are driven by specific agency objectives and/or regulatory requirements. Whereas the indicator set meets agency goals, it is likely to miss important influences that characterize the system and how it functions. In PNCERS we have consciously tried to avoid this compartmentalization by representing the estuarine system as an interactive set of components, each influenced by, and influencing, the others. Indicator selection follows from this broad conceptual model.

We characterize the second problem as the "pendulum of relevance" issue. Many of the most rigorous attempts to develop indicator sets or composite indices have based the initial selection, evaluation, correlation, and compilation of metrics on a working model of the system (or part thereof). Final metrics, while well researched and indicative of environmental integrity (Karr 1996) require an agency or organization to begin a new set of measurements. In order to take advantage of the Estuary Biological Integrity Index (Deegan et al. 1997), nekton sampling, identification, and classification must be completed and the total number of species, dominant species, fish abundance, number of nursery species, number of estuarine spawning species, number of resident species, proportion of benthic-associated fishes, and proportion of abnormal or diseased fishes must be compiled. The EQUATION Index (Ferreira 2000), a set of metrics focused on the biological response to anthropogenically-driven change in the physical and bio-physical environment, requires even more detailed physical measurements, such as tidal prism, mass of nitrogen in the estuary, area of contaminated sediments, and bioconcentration of xenobiotics in bivalve filter feeders. Because these types of specific, technical measurements are rarely if ever available from the past, monitoring environmental integrity starts in the present, and must be referenced against clean or pristine sites. Such additional measurements, especially physical ones, cost money, a commodity often in short supply.

The pendulum swings in the other direction when agencies or organizations realize that past effort and current funding levels will not allow them to make use of well-designed indices. In an attempt not to throw the baby out with the bathwater, indicator selection is based solely on availability – what has been measured at our site? Such a compilation is often made out of perceived need rather than based on a conceptual model of the system. For instance, the Oregon State of the Environment Report recognizes the need for indicators of estuarine ecosystems and suggests a few, such as change in overall estuary area, change in area of eelgrass beds, area of estuarine habitats protected, occurrence and extent of aquatic nuisance species, and freshwater inflow (Good 2000). While these indicators stem from available data, they do not represent measures of the complete estuarine system. PNCERS is attempting to carve a middle path between these approaches. Our development of candidate indicators is based on our conceptual model of system structure and function. We intend to winnow the list through a rigorous process of mathematical analysis of relationships among metrics, across a wide range of West Coast estuaries. However, we are well aware that the ability to hindcast is extremely useful, as is the ability to use currently collected data. Thus, we are attempting to create a set of indicators, responsive to system structure and function as we understand it, which are currently measured, can be proxied (that is, substitute parameters can be found), or would have a high benefit to cost ratio if added into a current monitoring scheme.

The third problem with many studies is the implicit assumption that all systems – in this case all West Coast estuaries – are fundamentally the same. That is, do or would behave similarly if human impacts were kept equal (i.e. absent) and do or would behave similarly if natural resources were kept equal. Thus, a set of indicators is equally valid and valuable in all estuaries. However, we know that this approach is false. West Coast estuaries represent a complex assortment of dichotomous states, within which the fundamentals of physical, biological, and socio-economic structures, functions, and interactions differ. In PNCERS, we realize that all West Coast estuaries are not equal, and that fundamental differences need to be sorted out *before* indicators are selected for a given system.

Fundamental Dichotomies

We define both physical and socio-economic dichotomies. Physical dichotomies stem from the long-term (centuries to millennia) interactions between water flow and geomorphology. We define a range of estuarine types (Table 1.1) including:

1. fjords (e.g., Puget Sound, Hood Canal)
2. drowned rivers with residence time measured in months (i.e., San Francisco Bay)
3. well-flushed drowned rivers which are seasonally open to the ocean (e.g., Netarts Bay)
4. well-flushed drowned rivers with predominantly freshwater input (e.g., Columbia River)
5. well-flushed drowned rivers with predominantly oceanic input (e.g., Humboldt Bay)
6. the above subset (#5) which are also influenced by a major river plume, in this case that of the Columbia River (e.g., Grays Harbor)

The physical topology of an estuary dictates the relative influence of riverine versus oceanic input of water and associated nutrients and plankton; the range and modal values of water properties such as temperature, salinity, and dissolved oxygen; and the resulting net annual primary production upon which estuarine biodiversity and biomass are dependent. Indicators of basic physical, biophysical (i.e., habitat), and biological structure and function may thus be appropriate in some estuarine categories, but not in others. For instance, levels of dissolved oxygen are appropriate measures of physical forcing only in estuaries with long residence time. Well-flushed estuaries, with water turnover measured in days to a few weeks may never experience lowered DO levels, even if the input of nutrients increases. However, eutrophication with resultant asphyxiation of aquatic biota is a likely event in estuaries with long residence time. Thus, a low DO measurement in a well-flushed estuary is a meaningless indicator, whereas the same measurement in an estuary such as Hood Canal or San Francisco Bay has high value in characterizing system integrity.

Socio-economic dichotomies stem from the pattern of system use, and the rules constraining that use. We differentiate between estuaries with a major population center, defined as 7,500 people or more, and possibly including a port facility, from those without the same. Operationally, there is a linkage between this division and the physical dichotomies – only large estuaries can house cities and ports. However, the size of an estuary, in and of itself, is not sufficient to characterize it physically. Thus, physical categories 1 and 2 are large by definition, while categories 4, 5, and 6 contain both large and small estuaries. Population center/port estuaries not only house more people, but create more types of pollution, are associated with greater habitat alteration, and may be correlated with a higher incidence of introduced species.

The second socio-economic dichotomy is whether the estuary has been or is being used for bivalve aquaculture, exemplified by oyster aquaculture. Aquaculture can represent a significant source of jobs and income, and may provide recreational opportunities for residents and visitors via state-owned beds. However, aquaculture also results in habitat alteration and an increased incidence of introduced species.

The third socio-economic dichotomy is state within which the estuary is located: California, Oregon, or Washington. Regional location creates differences in management structure, function, and effectiveness, irrespective of the physical category of the estuary. Ownership and management of tidelands and coastal lands is quite different among states. Oregon controls land use planning at the state level whereas planning in California and Washington is conducted at local levels (e.g., county). Washington permits the spraying of carbaryl to control burrowing shrimp, whereas Oregon does not. The superposition of socio-economic dichotomies on the physical dichotomies is illustrated in Table 1.1.

Table 1.1. Classification of West Coast estuaries. Gray indicates estuaries with a population center of at least 7500 people within 5 miles. *Italics* indicates estuaries with oyster aquaculture.

Estuary	1	2	3	4	5	6
California						
San Francisco Bay		X				
Stone Lagoon			?			
Big Lagoon			?			
Klamath River				X		
Tijuana Estuary					X	
San Diego Bay					X	
Mission Bay					X	
Newport Bay					X	
Alamitos Bay					X	
Anaheim Bay					X	
Morro Bay					X	
Elkhorn Slough					X	
Drakes Estero					X	
Tomales Bay					X	
Eel River					X	
Humboldt Bay					X	
Oregon						
Winchuck River			X			
Pistol River			X			
Elk River			X			
Sixes River			?			
Netarts Bay			?	?	?	
Depoe Bay			?	?	?	
New River			X			
Chetco River				X		
Rouge River				X		
Coquille River				X		
Umpqua River				X		
Siuslaw River				X		
Alsea Bay				?	?	
Siletz Bay				?	?	
Salmon River				X		
Nehalem River				X		
Necanicum River				?	?	
Columbia River				X		
Coos Bay					X	
Yaquina Bay					X	
Nestucca Bay					X	
Sand Lake					X	
Tillamook Bay					X	
Washington						
Main Puget Sound	X					
Hood Canal	X					
Skagit Bay/Whidbey Basin	X					
South Puget Sound	X					
Port Orchard System	X					
Quillayute River				X		
Willapa Bay						X
Grays Harbor						X

1. Fjord

2. Drowned rivers with residence time measured in months

3. Well-flushed drowned rivers, seasonally open to ocean

4. Well-flushed drowned rivers, predominantly freshwater input

5. Well-flushed drowned rivers, predominantly oceanic input

6. group 5, also influenced by major river plume

Conceptual Approach

A comprehensive set of indicators for any system must be based on a basic understanding of how the system works. A simple conceptual model can thus guide the selection or rejection of indicators, indicator prioritization, and the interpretation of indicator trends. A central pillar of the PNCERS approach has been the realization that any estuarine system is a complex interaction between these three components – physics, biology, and the human dimension (Figure 1.1).

Physical Environment – The interaction between water and substrate at spatial scales ranging from basin to grain size, and temporal scales ranging from glacial to tidal. Physics is the underpinning of biological structure and function – including human existence – as we know it. Thus, identification and measurement of basic physical parameters, or proxies and indices derived from them, is an essential component in any indicator set.

For estuaries, the physical environment can be further subdivided into the pelagic system and the benthic system, which themselves interact. The pelagic system (i.e., water column), is expressed via measures of change in climate, ocean dynamics, and water quality, and is characterized by properties such as temperature, salinity, turbidity, nutrient and contaminant concentration, oxygen content, and current velocity and direction. Such properties constrain biological distributions (e.g., via species-specific lethal ranges of water properties), determine transport of biogenic materials (e.g., larval organisms and phytoplankton), and define basic biological functions such as growth.

The benthic system (substrate) is expressed as geomorphology (large scale) and abiotic substrate (fine scale), and defines biological functions such as settle-

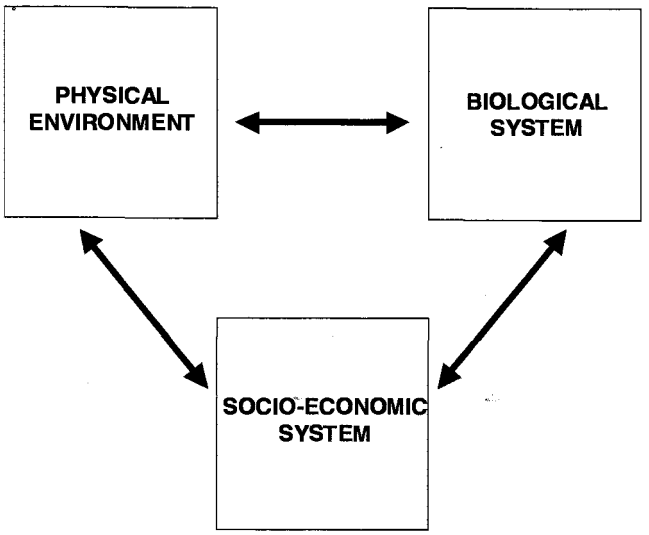

Figure 1.1. Simple conceptual model for PNCERS indicators project.

ment and survival. At intermediate spatio-temporal scales, the benthic physical environment interacts with the biological system creating a mosaic of habitats (see below).

Biological System – The ecological community(ies) within the system are arranged in trophic levels extending from primary producers to top predators. In general, lower trophic levels (e.g., phytoplankton, submerged aquatic vegetation) will be more sensitive to change in the physical environment (bottom-up forcing), although this may also be true of sessile invertebrates. Higher trophic levels will be subject to "top-down" or predator effects. All trophic levels may experience anthropogenic influences, mainly because human effects are multi-level, from climate change (i.e., bottom-up) to predator replacement via fisheries (i.e., top-down). The biological system is measured as the existence, distribution, and abundance of organisms. The cost of monitoring the entire system is prohibitive. Instead, system functions can be proxied within each trophic level by keystone species or groups, where keystone is defined as a nexus point in the structure and function of the biological system (e.g., submerged aquatic vegetation, filter feeders) and/or a focus of socio-economic attention (e.g., *Spartina*, oysters). Individual species may also be chosen because they are particularly sensitive to a certain impact (e.g., stenohaline species, species with high reactivity to chemical pollutants, bycatch species in coastal fisheries).

At higher levels of complexity, the biological system is measured as composite variables. Biodiversity and biomass result from the continued interaction of individual species components. The interaction between biology and physics, creates functional variables such as primary production or species which create habitat (dubbed architecture species) such as oysters or eelgrass.

Bio-Physical System (Habitat) - Although the pelagic system within the physical environment is defined by physics (e.g., water properties), the benthic system is defined by physical properties of the substrate as well as by biology. The interaction between the two create habitat, that structure – both abiotic and biotic - which supports biological communities. Thus, benthic habitat may be mud, oyster reef, or submerged aquatic vegetation. Because benthic habitat is so essential to specific life stages of so many estuarine organisms, monitoring the existence, extent, and quality of benthic habitats is often used as a proxy for the health of the ecological community.

Socio-Economic System - The social system comprises humans, encompassing human activities, human values and perceptions, and governance and management at both local (i.e., within the geographical boundaries of the estuarine system) and larger (e.g., state, national) scales. We choose to characterize the social system using three interacting components: the local economy, the quality of life of residents, and the management of human activities. Whereas human welfare is jointly defined by the first two components, the latter component is responsive to human welfare, seeking to preserve and/or enhance human welfare.

Economy - The local economy is comprised of technological, legal, and social arrangements through which individuals define their material and spiritual well-being. Production and consumption are the two main activities that characterize the economy. The goods and services produced and the methods and inputs used to create these goods and services characterize production. Alternatively, consumption activities involve the distribution of goods and services among individuals and groups. Examining patterns in employment and revenue generation is an essential part of understanding a local economy. Of particular significance is the degree to which the physical and biological components of the estuarine system and the local or regional economy are

connected. Unlike the physical and biological processes whose influences are contained within the Pacific Northwest (with the obvious exception of climate change), there are interactions between the local or regional economy, and national and international economic trends. The local economy is subject to market forces that extend worldwide.

Quality of Life – Quality of life is broadly defined here as social, community, and cultural processes that contribute to the socio-economic system but may or may not be reflected in traditional indicators that describe the local or regional economy. Traditionally, quality of life measures are seen as a complement to regional economic measures, acknowledging the importance of intangible elements of the socio-economic system not traded in markets. Quality of life may include items such as educational attainment, income distribution, and divorce rate. Biological and physical processes of estuarine systems can affect quality of life factors such as sense of place or community, views and scenery or aesthetics, and recreational opportunities.

Management – Governance and management is defined here as the set of codified rules and regulations governing human behavior, including both law and policy, as well as other management instruments such as incentives and voluntary mechanisms. Management actions can affect both the local economy and the quality of life of residents. For instance, regulation of oyster aquaculture will affect the earnings and employment of the oyster grower industry as well as access to oysters for recreational fishers and locals who eat oysters. Because management actions are directed at regulating human activities which impact system health rather than the biological integrity of the system per se, they can inhibit or enhance structure and function within the biological component of the system. For example, the amount spent on habitat restoration and/or the number of personnel assigned to habitat restoration activities may reveal whether or not this is a priority for a given area, whereas the amount of habitat gained may indicate the success of this effort. Similarly, the number of shellfish bed closures in an area may indicate the extent of water quality problems as well as the efficacy of the local governing unit charged with monitoring shellfish beds.

Unlike the Physical Environment and the Biological System, the Socio-Economic System contains the extra element of sentience. The fact that we are aware of the world around us, our interactions with it, and (at least sometimes) the consequences of those interactions, creates the possibility of feedbacks which modify human activities, values, and perceptions. Whereas rising mortality resulting from severe winter storms or increased predator pressure does not cause the physical or biological system to re-assess actions and change the strength of forcing factors, knowledge of unsustainable exploitation rates can cause the human community to impose new fisheries restrictions or change community attitudes about the value of fish and fishing. Therefore, a comprehensive set of system indicators must not only include measurements of actual change, as well as the forces creating that change, but also measurements of socio-economic response to that change.

Component Interactions – How the System Works

We define three fundamental attributes of the system: forces, flows, and state changes. Forces are physical, biological, and socio-economic processes which impinge on the system (Figure 1.2). Forces from one component of the system most often produce effects in another. For instance, oceanic and atmospheric forcing from the Physical Environment can affect organism distribution and abundance, community diversity, and ecosystem structure and function within the Biological System. Forces can also have within-component effects. The forces of competition and predation can also alter organisms, communities, and ecosystems within the Biological System. Finally, forces may come from within the geographic boundaries of the estuary or be exogenous to it. Exogenous forces include regional to global physical forcing, typified by atmospheric forcing, as well as human forces originating outside of the estuary. These latter can be subdivided into local forces, such as upstream pollution or land use change, and regional to global forces, such as the national economy or popular culture. Mapping the forces in the system can help explain basic interactions, and can help visualize the pathways of both direct and indirect effects as the strength of a single force is altered.

Forces result in flows, defined herein as a tangible quantity within the system. All flows result from forces and

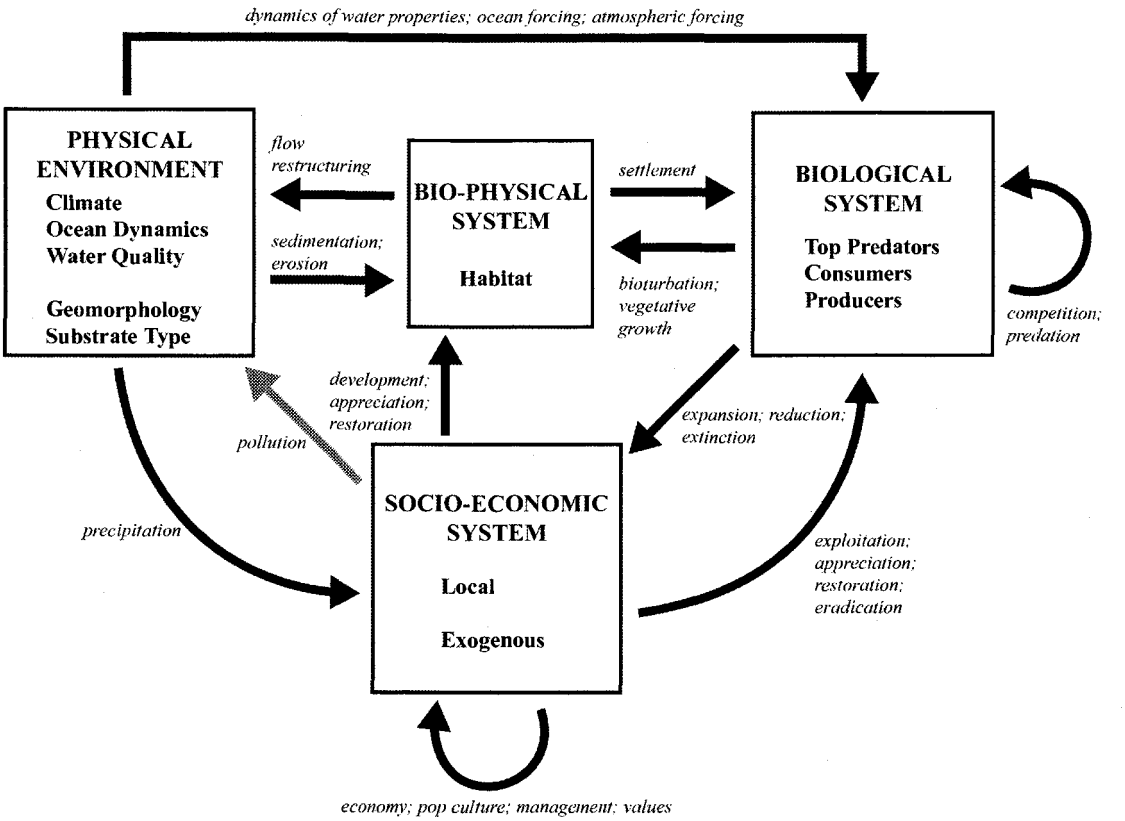

Figure 1.2. FORCES affecting West Coast Estuaries. The gray arrow indicates forces exogenous to the system.

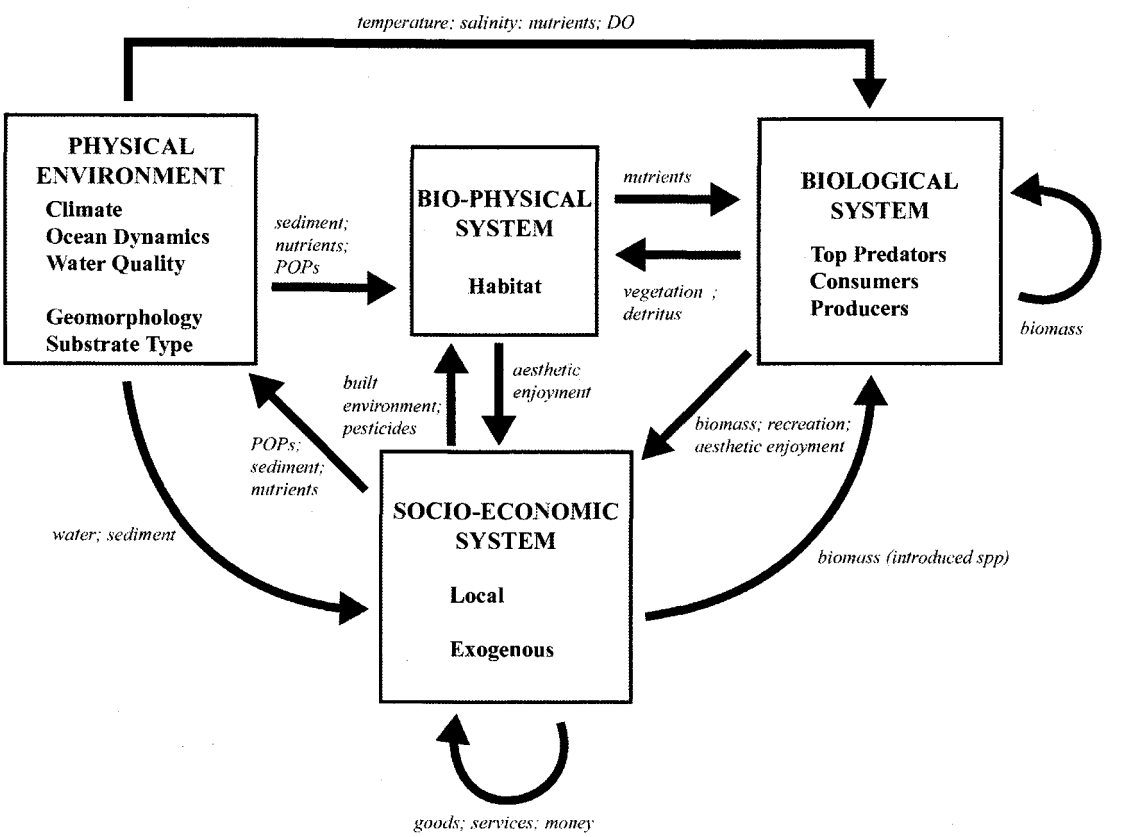

Figure 1.3. Resultant FLOWS of tangible materials and intangible benefits.

are proxies of force strength. Flows, like forces, can also be mapped (Figure 1.3). In some cases, flows are parallel to forces. For instance, oceanic forcing results in changes in water temperature; predation results in a transfer of biomass. However, forces can also produce flows in the opposite direction. For instance, exploitation results in biomass transfer from the Biological System back to the Socio-Economic System. When flows cross component boundaries, as in the last example, they often undergo state changes. Thus, the flow "commercial fish biomass" resulting from the force "exploitation" changes into "price and income," creating a second set of proxies of the original force.

Although it is tempting to think of forces and flows as linear, in fact, multiple forces may contribute to the same flows, and single forces may result in multiple flows. Thus, the forces of exploitation, introduction, and restoration from the Socio-Economic System may all result in the flow of biomass out of the Biological System. Finally, forces and resultant flows will often contribute to a cascade of secondary force-flow interactions. For instance, the force of exploitation results in the flow of biomass, which may in turn result in a change in the strength of predation and/or competition resulting in an alteration in biomass transfer within the Biological System, which may ultimately feedback to the original resultant flow – fished biomass.

From Concepts to Indicators

Estuaries are dynamic systems, exhibiting change in forces and flows episodically, cyclically, and directionally. Differentiating between change which is an inherent property of the system (i.e., a result of system structure and function) and that which degrades the system is difficult. Many forces contribute to singular results and interactions are often nonlinear. Thus, although correlations of force and flow are possible, clearly defining cause and effect is not easy. Finally, encompassing all change within a system is neither possible, nor productive.

As first steps, PNCERS researchers defined the system conceptually, and simultaneously started to amalgamate existing data from PNCERS research estuaries (Grays Harbor, Willapa Bay, Yaquina Bay, Coos Bay). Based on these inputs, we have constructed a set of candidate indicators of forces and flows in each of the three system components: Physical Environment, Biological System, Socio-Economic System (Appendix 1A). Refinement of the list, including quantitative examinations of the linkage between indicators of force and those of flow, concurrence among sets of force and/or flow indicators, and identification of reasonable proxies for candidate indicators for which no data exist, are charges for the coming year.

Indicators of Forces from the Physical Environment

At the largest spatial scale, climate affects the Physical Environment, the Biological System and the Socio-Economic System within each West Coast estuary. Although the local and regional population can not manage climate, and does not have control over anthropogenic impacts to climate (i.e., global warming), tracking climate can be useful when setting management goals for natural resources likely to be affected (e.g., shellfish production, salmon harvest). At smaller spatial scales, a myriad of physical forces set the stage for estuarine primary production, and ultimately estuarine biomass and biodiversity.

Climate – There are many indices of climate readily available. We have chosen two. At large spatio-temporal scales, the **Pacific Decadal Oscillation** measures the change in the Aleutian high as it is expressed in sea surface temperature anomalies. Switches in the predominant mode of the PDO (from positive to negative) has been associated with broad patterns of change in oceanic production, and specifically in the growth and commercial production of species such as salmon. At a regional scale, indices of weather which integrate both temperature and precipitation data, can be useful proxies for river flow, estuarine growing season, and production of specific species. In the PNW, the **Pacific Northwest Index** (PNWI) is an integrated measure of regional air temperature, winter precipitation (measured as snow pack), and sea level precipitation. This index has been linked to cycles of growth in Pacific oysters (oyster condition index). Development of additional regional weather indices is needed to cover Oregon and California.

Flushing Rate – The flushing, or turnover, rate of an estuary will set boundaries on the residence time of dissolved and particulate matter in the system. These

substances include contaminants, nutrients, suspended sediments, phytoplankton, and zooplankton. Rapid turnover tends to export these materials to the coastal ocean resulting in increased water clarity and decreased problems with dissolved oxygen. Conversely, slow turnover favors autochthonous algal blooms and retention of larval organisms, but can also sequester contaminants pulsed into the system. Thus, there should be relationships between flushing rate and primary production, as well as flushing rate and the diversity, abundance, distribution and growth of organisms. Turnover rate can also impact diversity of those species with larval development periods exceeding residence time.

Flushing rate depends on four parameters: **basin volume, basin shape, river flow** (i.e., freshwater input), and **tidal flow** (i.e., ocean exchange). Whereas the first parameter is virtually constant, shape and flow are mutable via physical and anthropogenic forces. Basin shape can be altered by physical forces, such as the incidence and intensity of storm events, as well as anthropogenic impacts such as jetties and groins outside the system, and in-system activities such as channel dredging, diking and filling, and shoreline hardening. River flow and estuarine and oceanic circulation patterns change seasonally, annually, and decadally as atmospheric cycles alter weather systems and the associated wind stress and precipitation patterns. River flow may also be altered by upstream anthropogenic activities such as water withdrawal and/or water flow management.

Dissolved Oxygen – For estuaries with long residence time and incomplete mixing, oxygen limitation can be an important factor limiting production, as well as distribution and abundance of upper trophic levels. Levels of dissolved oxygen are affected by physical processes such as tidal and wind-driven mixing, the latter of which is seasonally cyclic. DO can also be influenced by land-based human activities which increase nutrient flow into the estuary.

Transport Index – For many estuarine types, the nearshore environment is inextricably linked to the estuary via influx of oceanic water and the nutrients and organisms it carries. The degree of influence the ocean has on estuarine biota is largely a function of physical forcing conditions at the local to regional level. Ocean circulation patterns control the types of water that occur near the estuarine mouth, and it is this water that is advected into the estuarine system. Of main importance to West Coast estuaries is the influence of the wind on coastal upwelling/downwelling dynamics. Upwelling-favorable winds cause nutrient-rich ocean water to reach the photic zone, and this can result in intense phytoplankton production. Conversely, downwelling conditions pile water on the coast and limit the vertical transport of nutrients. Material produced during coastal upwelling can be transported to the coast (and into the estuaries) as winds change direction or relax from a northerly to southerly orientation (i.e., an upwelling/downwelling cycle). The intensity and temporal variability of these cycles varies seasonally and interannually, and induces strong responses in biotic systems.

Estuarine primary production may be impacted directly as incoming oceanic water masses transport coastal phytoplankton into the estuary, or indirectly as estuarine phytoplankton and submerged aquatic vegetation utilize imported oceanic nutrients. Transport Index may also be used to monitor advective events that control the import of the larvae of invertebrates and fish, such as Dungeness crabs and English sole, to estuarine nursery grounds.

Transport Index depends on two parameters: **windspeed and direction**, and the **number of upwelling/downwelling episodes** above a significant time length threshold. The former parameter indexes whether phytoplankton production or shoreward transport are occurring, while the latter parameter relates to the number of events likely to transport the phytoplankton to estuaries. Windspeed and direction, and the number of significant episodes vary with season, as well as interannually and interdecadally, and are uninfluenced by local to regional anthropogenic activities.

River Plume Index – River plumes carry land-derived dissolved and suspended material into the coastal environment. The buoyant fresh water also modifies the nearshore circulation patterns and affects the salinity structure, the intensity and duration of upwelling/downwelling events, vertical mixing, and other physical oceanographic processes that influence biological production. The major river system affecting West Coast estuaries is the Columbia River. The position of the Columbia River plume is highly dependent upon wind

stress, and the plume has two primary orientations. During northerly (upwelling-favorable) or low wind stress, the plume tends to spread out and move southwest off the Oregon coast, but when winds blow from the south, the plume is forced against the Washington coast and flows north. Estuaries situated near the Columbia River in Oregon and along the entire Washington coast are subject to influx of this low salinity water into the estuaries during downwelling winds. This process greatly modifies estuarine circulation patterns and the nearshore-estuarine transport of biotic materials, and probably is associated with reduced primary and secondary production, since West Coast river plumes are generally low in nutrients. Additionally, the distribution, abundance, and growth of sessile species may be reduced as they are stressed by brackish water influx events. RPI intensity should be negatively correlated with primary production, as increased plume intrusions limit the import of allochthonous nutrients. River Plume Index depends on three parameters: **river flow, windspeed and direction**, and the **number of downwelling episodes** above a significant time length threshold. As mentioned previously, river flow can change via physical and anthropogenic forcing, whereas the other two parameters are subject to physical forcing only.

In-Situ Production Index – Estuarine biomass and biodiversity will be based in large measure on the annual primary production averaged over the estuary. Primary production is a function of nutrient availability and insolation. Nutrients can come from two sources, upland inputs transported via stream/river inflow and imported oceanic nutrients. Insolation is a function of the amount of photosynthetically active radiation (PAR) and water clarity. We define two production indices, one for estuaries with predominant freshwater influence (category 4), and a second for estuaries with predominant oceanic influence (categories 5 & 6).

For river-dominated estuaries, In-Situ Production Index depends on two parameters: **river nutrients** and **PAR**. Neither of these is easily measured; however, both have proxies. **Rainfall** or **river flow** can be used as a proxy for river nutrients, assuming constant upland input of nutrients into the aquatic system. Upland human activities, such as water withdrawal and changing land use (e.g., deforestation, increased agricultural use) can affect river nutrients. Therefore, the additional proxies of **watershed population, percent of watershed in agriculture**, and **percent of estuarine shoreline in agriculture and forestry**, are needed to estimate change in upland nutrient input. PAR can be simulated by cloud cover, and is only influenced by atmospheric forcing on seasonal and decadal scales.

For ocean-dominated estuaries, In-Situ Production Index depends on two parameters for pelagic production: **ocean nutrients** and **PAR**. A second Production Index for the benthos depends on a third parameter as well: **sediment turbidity**. Ocean nutrients are difficult to measure directly; however **Transport Index** can be used as a proxy. PAR is proxied by cloud cover. Sediment turbidity, important to benthic production, can be measured directly, or **storm intensity** (the total duration of storms above a certain strength threshold) can be used as a proxy.

Pelagic production (i.e., phytoplankton) drives much of the estuarine foodweb as zooplankters and benthic filter feeders consume phytoplankton. Lower In-Situ Pelagic Production Index may be correlated with the density and growth of filter feeders such as Pacific oysters. Benthic production creates living structure and habitat, primarily via beds of submerged aquatic vegetation (e.g., eelgrass) which may play an important role as nursery areas for juvenile salmonids and other fishes.

Habitat Availability Index – For all species, there is a fraction of each estuary within which the organisms can exist, as dictated by physical constraints in the pelagic environment (i.e., range of tolerance of physical parameters such as temperature, salinity, turbidity, etc.) and substrate type – a bio-physical interaction – for those organisms requiring substrate or substrate-associated habitat. We define this area as the **potential habitat** of the species, a dynamic index composed of three parameters: **exposure tolerance, salinity tolerance**, and **required substrate** (if appropriate).

Exposure tolerance is a function of tidal range, estuarine morphology, and the percent of aerial exposure, itself a function of air temperature. For each species, exposure tolerance varies seasonally, annually and perhaps decadally. For sessile species, exposure tolerance can be measured as the tidal range tolerable during the summer maximum spring tides when percent aerial ex-

posure is apt to be longest, air temperatures are apt to be highest, and wave action apt to be lowest.

Salinity tolerance is a function of flushing rate, relative freshwater input, and winter storm events. For each species, salinity tolerance varies tidally, seasonally, annually and perhaps decadally.

Required substrate is the bio-physical structure within which a species can exist, and prefers to exist. Substrate types include:

1. saltmarsh/emergent vegetation (native – e.g., *Carex* versus non-native – e.g., *Spartina*)
2. sand
3. mudflat
4. bioturbated sediment
5. submerged aquatic vegetation (SAV)
6. hard substrate, including rock, cobble, and shell
7. subtidal channels

The occurrence, distribution, and abundance of a given substrate type is itself a function of physical forcing, principally geomorphology and flow, which dictate the deposition of inorganic material along the estuarine benthos. However, substrate type is also a result of subsequent biological actions (e.g., bioturbation, reef-building, growth of submerged aquatic vegetation).

For any species of interest, potential habitat can be calculated as the total area within the estuary where the species could occur, given no adverse biological (e.g., competition, predation) or anthropogenic (e.g., habitat alteration) influence. **Realized habitat** is the portion of the estuary where the species is actually found, and is a subset of potential habitat. The difference between realized and potential habitat is due to constraints imposed by both the biological and socio-economic components of the system. Predators and competitors can constrict habitat usage, even if the potential habitat could accommodate the organism.

Human activities, including species introductions, pollution, and habitat alteration can all restrict both the realized habitat AND the potential habitat of a species. Introductions can cause a change in trophic dynamics (e.g., predator pressure), altering realized habitat. Introductions can also change substrate availability (i.e., potential habitat). For instance, the introduction of *Spartina* in Willapa Bay, WA caused an increase in saltmarsh, at the apparent expense of mudflat (Thom and Rumrill 1999). Pollution can shrink realized habitat by killing species outright. Habitat alteration is multidimensional, and includes diking, dredging, filling, shoreline hardening, overwater structures, in-situ aquaculture, and restoration. These activities can alter the distribution and abundance of substrate type within the system (i.e., change potential habitat) and/or alter the survivability of organisms within potential habitat (e.g., overwater structures shade eelgrass). The dynamic interaction between realized and potential habitat defines Habitat Availability Index.

Although Habitat Availability Index could be calculated for any species, it is most appropriate for "architecture" species – those creating bio-physical habitat, and secondarily, for motile species with distinct habitat requirements or preferences. Examples of architecture species include aquatic vegetation such as eelgrass beds (SAV) and *Spartina* (saltmarsh), as well as benthic invertebrates such as Pacific oysters, infaunal clams, and burrowing shrimp. Examples of motile species dependent on specific habitat types, including the habitat created by the architecture species, include Dungeness crab (prefers shell hash and oyster reef), juvenile salmon (may prefer eelgrass beds), and shorebirds (dependent on sand/mudflat). Rather than specify set species, we advocate choice of a suite of three to five keystone species exemplifying the ecological characteristics of, and socio-economic demands on, individual estuaries.

Indicators of Forces and Flows from the Socio-Economic System

We divide indicators of the socio-economic component into six categories. **Habitat alteration** and **exploitation** are forces generally credited as production activities of the local economy which create jobs and income for the local economy and which may, under certain circumstances, increase quality of life. At the same time, these categories have come to be regarded as negatively affecting the biological integrity of the system. **Pollution** flows into the system as an unintended consequence of a range of local and exogenous activities which also affects the local economy and quality of life. **Appreciation** is a force producing a range of activities with respect to the system, including those which support biological integrity (e.g., habitat conservation).

Human welfare and **management** are categories which speak to the flows into the socio-economic system, and the feedback inherent in this component. Habitat alteration, exploitation, and pollution are affected by management.

Habitat Alteration – The intended and unintentional change in native habitat as a result of human activity has been credited locally with both economic and quality of life successes U.S. residents enjoy and the increasing conservation dilemma we find ourselves in as a consequence. In West Coast estuaries, habitat alteration includes *channel dredging* to allow free passage of ships into ports and waterways; *shoreline hardening* to mitigate wave impacts, increase area available for building, and alter coastal sediment transport; *diking and filling* to increase area available for agriculture and building; *shellfish aquaculture* exemplified by the predominant crop – Pacific oysters; and *overwater structures* such as docks. Altered habitat can have direct and often deleterious consequences on the biological system, principally on those architectural species which make up the bio-physical intersection we define as habitat. However, certain forms of habitat alteration can be beneficial, either to select species, or to species assemblages. Oyster aquaculture is obviously beneficial to oysters. Mitigation and restoration projects may benefit single species (e.g., shell mitigation in Grays Harbor benefits juvenile Dungeness crab) or species assemblages (e.g., dike breeching re-establishes saltmarsh communities). We define three indices of habitat alteration: **areal modification index**, **areal culture index**, and **compensatory expenditures**.

Areal Modification Index: Rather than individually track all activities directly or indirectly affecting habitat, we define the percent of **total wetted area under current modification** as the Areal Modification Index. This index includes aquaculture, introduced vegetation exemplified by *Spartina*, diking, dredged channels, mitigation areas, dredge-spoil islands and built structures including overwater structures, groins, and seawalls. Additional site-specific modifications can also be included. As the areal modification index rises, the functional abilities of the biological and bio-physical system become increasingly compromised. We would expect a negative relationship between this index and the index of habitat availability for most native species.

Areal Culture Index: For those estuaries with shellfish aquaculture, this is the **percent of total wetted area devoted to shellfish aquaculture**, including commercial oyster lease tracts as well as state tidal lands devoted to oyster culture. Increases in the amount of area devoted to shellfish aquaculture can have beneficial effects on the socio-economic system (i.e., jobs, income, and consumption) and system health (i.e., a functioning ecosystem which continues to produce oysters), and neutral or negative effects on biological integrity, depending on the extent of culture. Oyster culture has been associated with a decline in eelgrass cover and a decline in infaunal biomass through the intentional application of pesticides. Finally, estuaries housing oysters are more likely to have been invaded by *Spartina*, which has the ability to massively alter upper tidal flat habitat.

Compensatory Expenditures: Habitat alteration can occur as a side effect of intentional species introduction, as is exemplified by Pacific oysters and *Spartina*. Because *Spartina*, as well as other architectural species (e.g., burrowing shrimp), create habitat which is considered bad, increasing effort, and expense, is put into eradication, or at least control of, these species. When habitat alteration is intentional, but also detrimental, the compromise is often mitigation, or the required creation of new or improved habitat for species negatively affected by the original activity. In Grays Harbor, WA channel dredging which may negatively affect Dungeness crab populations is mitigated by the creation of shell hash habitat in lower intertidal mudflat areas. We define the **total expenditures**, in dollars spent, **on eradication and mitigation** as Compensatory Expenditures.

Exploitation – The continued ability of the system to produce biomass and biodiversity for extraction is a measure of system health, and beyond that, health of the socio-economic system. However, continued extraction of select resources may alter ecosystem integrity, even as the system continues to produce the required biomass. At extremes, exploited species can become rare, threatened, or commercially extinct. Exploitation can be commercial and recreational, spanning a wide range of species from algae to shellfish to finfish. We define exploitation indices for commercial and recreational harvest, respectively. For both indices, exploitation depends on two parameters: **biomass**

and **biodiversity**. Biomass is measured as **landings**. Biodiversity is measured directly for many commercial fisheries – for both target and bycatch species - and reported as a percent relative to the most speciose year. For recreational fisheries, **fishing licenses** can be used as a proxy.

Pollution – Pollution is experienced as an unintended flow of harmful materials into the system. Locally, pollution can be generated from any number of sources, including industrial sites, shipping-associated and other urban sites, agricultural sites, and generally from non-point sources such as run-off. Pollution inputs can also come from sources outside the estuary, including upstream forestry and agricultural sites, upstream urban sites, and integrated regional pollution via wet and dry deposition. Pollutants include:

- *Toxics*, which can increase mortality and/or slow growth of sensitive organisms, and potentially create a health hazard for humans consuming seafood which have bioaccumulated and biomagnified these compounds. Our indicator of toxic levels is the **Toxic Release Inventory (TRI) Emissions** data from U.S. EPA.
- *Sewage*, which changes the dynamics of primary production and may, in extreme cases, create unacceptably high levels of bacteria, anoxic conditions, and harmful algal blooms. Our indicator of sewage is the U.S. EPA **NPDES Discharge** data. For those estuaries with commercial and recreational shellfish beds, a substitute indicator is percent of in-season days beds are closed due to pollution concerns.
- *Sediments*, which can affect benthic primary and secondary production via increased turbidity, and may change habitat characteristics such as tidal elevation. We use **number of building permits** and **timber harvest** within the drainage as a proxy of sediment input.
- *Biological Introductions*, which can reduce native species diversity and abundance as well as alter bio-physical habitat availability, via a cascade of ecological effects in the biological system, including competitive dominance and keystone predation. Unintended introductions may also have deleterious effects on intentional introductions, as in the case of oyster drills (a snail predator) on Pacific oysters. Parameters of introductions include: **shipping activity**, especially of large vessels which exchange ballast water; and **aquaculture**, especially introduction of foreign organisms. The latter category includes activities such as importation of oysters, cultch, or other shellfish from outside the system, importation of finfish for netpen aquaculture, and importation of unprocessed bait for netpen aquaculture.

Because each estuary will have a different subset of pollution flows, our proxy index of pollution combines nine parameters: **population** within the drainage, number of **building permits** within the drainage, board feet of **harvested timber**, number of **permitted dischargers**, percent of total drainage devoted to **agriculture**, percent of total **shellfish harvest area closed** over the season, and **number of vessels** docking at all port and marina facilities. These potentially negative influences are balanced by the **total volume** of the estuary and the **flushing rate**.

Appreciation – Many human influences on natural systems are adverse, unintended consequences of activities which promote regional economic performance and quality of life. However, some human activities are directed at preserving and conserving natural habitat and ecosystems for the purposes of enjoyment. Appreciation of the natural environment encompasses a range of categories including personal recreation, views and scenery, and coordinated efforts at the local, state, and federal government levels such as habitat restoration (e.g., Coastal America Program restoration of urban estuary sites) and preservation (e.g., creation of local and state parks, National Estuarine Research Reserves, or National Wildlife Refuges). In PNCERS, we define appreciation as any activity in which the participant is directly acting to preserve or conserve natural resources and/or benefits directly from such activities. In some systems, the force of appreciation may conflict with other socio-economic forces, such as exploitation or development. Over time, the balance of these potentially conflicting forces may shift, as the demographics and socio-economics of local communities change. For example, in many of the coastal counties of Oregon and Washington, changes have included shifts away from extraction-based industries to industries with non-consumptive or extractive connections to local natural resources (e.g., ecotourism).

Appreciation depends on a number of parameters which will change in relevance and strength among estuaries: **recreational opportunity and use**, **demographics**, and **habitat allocation**. Recreation is measured by at least two of the following: number of **visitors to local, state, and federal parks** and other natural recreation areas; number of **recreational fishing and shellfishing permits** issued within the county; and **membership in local chapters of non-governmental organizations** aligned with habitat and ecosystem appreciation (examples include Audubon, Ducks Unlimited, Sierra Club). Demographics includes the **age distribution** of the local population, **median income**, and the **proportion of "second" or vacation homes**. Habitat allocation measures include percent of total wetted **area devoted to recreation or conservation** (e.g., public shellfish beds, marine parks), and percent of adjacent shoreline – including islands – in **habitat set-asides**. Set-asides include parks, refuges, wilderness areas, and natural areas.

Human Welfare – The degree to which residents are succeeding financially or materially (e.g., **regional economic performance**), the proportion of that **success which is dependent on estuarine resources**, and sense of **societal well being** are three central components of human welfare. Communities which are succeeding financially and socially, and retain a socio-economic connection to the estuary may treat the system differently than communities which are struggling and/or which have lost that connection. Regional economic performance is measured using indicators of **total earnings** and **total employment**. System-dependent economic performance is measured using indicators of natural resources earnings (e.g., timber harvest, commercial fishing, appreciation-related employment, natural resource management) and employment within those sectors, relative to overall regional earnings and employment. A simple proxy may be **total value of extracted marine resources** – both commercial and recreational – relative to total regional earnings. Societal well being, or quality of life, is a blend of economic well being (proxied as **local median income** relative to that of the state) and measures of social stability including average **education** level attained, **crime rate** and **divorce rate**.

Management – Unlike the Physical and Biological components of the system, the Socio-Economic component has the ability to monitor its activities, predict the course and consequences of future activities, and react accordingly. Humans manage the system by imposing limits on themselves. Within the Socio-Economic System, this is expressed as the effort put into proactive and reactive strategies of natural resource management, and scope of those activities. We define an index of management efficacy as including the total number of **employees and contract workers in relevant management agencies** (e.g., USFS, state Fish and Wildlife, state Departments of Ecology or Environment, aquatic lands managers, etc.), **annual cost of habitat restoration**, number of state and federal **species of concern, threat, or endangerment** which are monitored and the subset of the latter which are increasing in population size, and the number of **water quality violations**.

Indicators of Flows from the Biological System

Physical and Socio-Economic forces often result in changes in the dynamic balance within the Biological System. Negative change – reduced biomass or biodiversity – has been the basis for conservation concern. However, the degree to which the system changes, whether those changes are "natural," and whether the system is resilient to the forcing factors creating change are all issues for which there are no set benchmarks. In fact, thresholds of acceptable change are often stakeholder specific, unless the change is truly drastic. Thus, change does not, in itself, signal a value judgement.

We divide indicators of the Biological System into categories, based on trophic structuring and degree of ecological complexity, from measures of individual species demographics to measures of ecosystem structure and function.

Primary Production – Phytoplankton production drives the estuarine ecosystem, utilizing nutrients from riverine and oceanic sources, and fueling the zooplankton and filter feeding communities. Production can be affected by both physical and anthropogenic forces which change water properties, including nutrient levels, salinity, and temperature. Relevant measurements include **net annual primary production** integrated over the entire estuary, and **net Spring-Summer primary production** (April-September – between the spring and fall transitions). Although actual measures of produc-

tion are rarely available, primary production can be inferred from satellite data (e.g. SEAWIFS) and may be proxied with **In-Situ Production Indices**.

Harmful Algal Blooms (HABs) – Blooms of phytoplankton producing toxins can not only affect the resident biota, but can impact humans as well. HABs result in shellfish bed closures, in fish kills, and in health problems in seabirds, marine mammals, and humans. Changing nutrient conditions, among other factors, are thought to be related to HAB occurrence. In lieu of direct measurements of HAB species presence, relevant measurements include **number of days shellfish beds are closed** and **percent of total shellfish bed area closed**.

Architecture Species - We define architecture species as benthic organisms which themselves either become habitat – as in submerged aquatic vegetation or oyster reef – or substantively alter physical substrate to create bio-physical habitat – as in bioturbating shrimp. The presence and abundance of architecture species creates the physical foundation for many organisms within the benthic community, as well as more mobile species dependent on a specific habitat type (e.g., shorebirds dependent on mudflats). Because architecture species are both native and introduced, the latter both intentionally and inadvertently, an increase in population is not necessarily indicative of ecosystem integrity, or even ecosystem health. Architecture species include:

Submerged Aquatic Vegetation: Upper intertidal vegetation provides habitat for a range of estuarine species, from fish to birds. Presence of native marsh grasses, such as *Carex* spp., may be indicative of relatively undisturbed systems, whereas loss of marsh or replacement with the introduced cordgrass *Spartina* is evidence of loss of ecosystem integrity. Lower in the intertidal and upper subtidal, eelgrass, *Zostera* spp., provides habitat for juvenile fish and crustaceans. Loss of eelgrass has been associated with channel scouring, increased sediment turbidity, overwater and other shading structures, and oyster aquaculture. Index of SAV depends on four parameters: ***Spartina* cover** as a percent of total mudflat area, **cover of tidal marsh** and **edge to interior ratio** of native marsh, and **eelgrass cover** as a function of lower intertidal and subtidal area.

Oysters: Pacific oysters, introduced from Japan, form the basis of a flourishing aquaculture industry in the Pacific Northwest. Oyster aquaculture has created jobs, income, and quality of life for coastal residents, and a valued commodity at the regional and national level. However, preparation and maintenance of optimal oyster beds has been associated with loss of some native species, including eelgrass and burrowing shrimp. Introduction of Pacific oysters, and eastern oysters before them, have resulted in a raft of introduced species, some of which are deleterious to the system. In some estuaries, oyster production represents a significant fraction of tidal area.

Oysters are filter feeders, which makes them dependent on phytoplankton primary production to sustain growth, as well as susceptible to waterborne pollutants. Annual changes in production, as a consequence of physical forcing, has been shown to affect oyster growth. Degradation in water quality, as a consequence of both point and non-point source pollutants, has been linked to closure of oyster beds.

Oyster measurements include **bed cover** as a function of total intertidal area, **number of oyster leases**, and **oyster condition index** – a measure of oyster body size to shell volume.

Salmon Survival – Juvenile salmon, particularly chinook and chum, selectively utilize estuarine habitat throughout the majority of West Coast estuaries. The greatest abundance of chinook smolts in Oregon estuaries are fall run chinook. Alterations in water quality as well as habitat quantity and quality, can all affect smolt survival. There are indications that juvenile salmon preferentially utilize eelgrass habitats. Because salmon survival is usually measured in hatchery stocks as the loss of fish integrated over the average lifetime (from release to return), estimates of survival in the estuarine phase of salmon life history are difficult to measure. However, by assuming that all salmon of a given species migrating through the estuary sustain relatively equal survival in the ocean, stock-specific differences in survival can be used to categorize differences as a function of integrated estuarine quality. **Survival** for wild fish is proxied by **hatchery stocks with coded wire tags**. We rank relative survival into three categories – low, medium, and high – based on dispersion from mean values, by year.

Aquatic Biomass and Biodiversity – Higher order indicators of system health and ecological integrity include changes in biomass and biodiversity. Biomass may represent both the productive capacity of the system, as well as the average trophic level. As relatively more biomass is represented in upper trophic levels, total biomass should fall. Within a trophic level, higher biomass may represent either added production within the system, and/or reduced predation/exploitation of the fish in question. Higher values of biodiversity are generally acknowledged to be desirable. However, in perturbed systems, added diversity may represent introduced species. Thus, it is important that biodiversity measures separate endemics (defined as native species with restricted ranges), natives, and introductions.

Ideally, measures of biomass and biodiversity would be estimated from repeated scientific sampling. However, these data are rare in most systems. Therefore, potential proxies include **biomass and biodiversity of total commercial catch** (both target and bycatch), and of **total recreational catch**.

Upper Trophic Biodiversity – Beyond aquatic biomass and biodiversity, the presence, abundance, and diversity of upper trophics, including seabirds and marine mammals, may also be indicative of ecological integrity. On the other hand, the increasing presence of species which potentially compete with humans for access to commercial and recreational resources can be seen by some as an indicator of declining system health. We define a range of diversity and abundance measures, including:

Shorebird Diversity: Many species of shorebirds use the Pacific coast as a flyway, stopping at estuarine and other foraging sites to and from the breeding colonies to the north. Reduced foraging habitat, chiefly intertidal mudflat, and/or increased disturbance, are all factors which may affect shorebird migration density. Although official monitoring programs are rare, much data are collected by local birders, often organized by local Audubon chapters. Shorebird diversity index depends on three parameters: **number of species present** in the fall and spring, respectively; **abundance** of each species, and **total mudflat area** available.

Aquatic Bird Diversity: A broader measure of ecological integrity is the total number of aquatic bird species, including shorebirds, seabirds, and waterfowl, the system supports. Aquatic birds are dependent on a wide range of estuarine habitats, from emergent marsh to open water column, and forage on a wide range of prey, including seagrass, planktonic and benthic invertebrates, and fish. Finally, society has multidimensional responses to aquatic birds. Birds represent a significant source of recreation (from hunting to birdwatching) for residents and visitors. Some aquatic birds represent potential competitors for marine resources. Data are available in many localities from 4th of July and Christmas bird count data. To account for system differences, diversity must be standardized by two measures. First, aquatic bird species which have experienced population explosions as a result of human influence, or been introduced by humans, should be removed to a separate **Index of Avian Pest Species**. Such species include domestic goose, Canada goose, mallard, glaucous-winged gull, and double-crested cormorant. Second, to account for species-area relationships, diversity should be standardized by the total wetted area.

Harbor Seals: Marine mammals represent a pinnacle of trophic structure in the estuarine system. Pinnipeds, unlike other marine mammal groups, have adapted to human presence, making use of built structures for haul-out sites and fisheries for additional foraging opportunities. As such, pinnipeds are seen by some stakeholders as a threat to society's quest for marine resources. Pinnipeds are also subject to population depression as a consequence of both anthropogenic and physical factors. Pollution, specifically persistent organic pollutants and harmful algal blooms, can affect pinnipeds. Dramatic changes in climate signals, such as the El Niño-Southern Oscillation signal, can also create short-term stress as trophic structuring supporting pinniped populations shrinks. Measures of harbor seals include **abundance** standardized by total wetted area, and **toxic load**, if available.

Conclusion

This chapter is a preliminary step in the development of an integrated set of indicators and indices of estuarine system health. Although categorized by system (i.e., physical, socio-economic, and biological), many of our candidate indicators can act as proxies of each other, as they correspond to linked forces and flows. For

instance, Habitat Availability Index and Habitat Alteration Index will potentially track each other. In-Situ Production Index and Primary Production may do the same. This conceptual overlap should allow us the flexibility to choose proxies (either forces or flows), or even do so in a site-specific manner.

As we move forward with the Indicator Project, it will be important to resolve two basic issues. First, all candidate indicators need to be "tested" across a broad range of estuaries. Specifically, are measurements or proxies available, and how do indicators vary, and covary, relative to our conceptual understanding of system function. Second, assignation of value needs to be addressed. It is fairly easy to determine that ecological integrity and system health are not synonymous, or even parallel, states. It is much more difficult to determine the goal, or baseline state, from which deviations (either positive or negative) should be measured. Thus, realization that the ecological system has been degraded by human activity is not necessarily relevant to system management (or even system function) as removal of humanity is ludicrous. However, in order for indicators to be useful, decisions must be made about whether increase (or decrease) in a parameter is good for the system.

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Appendix 1A. Physical, socio-economic, and biological indicators, their constituent parameters, and likely proxy measurements as a function of estuarine type (1 through 6). Xs indicate the indicator would be relevant in a given estuarine type. Right justified indicators are subsets of larger (left-justified) indicators. Gray indicates indicators that should be used in estuaries with a population center (at least 7500 people) within 5 miles. *Italics* indicates indicators that should be measured in estuaries with oyster aquaculture.

Estuarine types: 1. Fjord; 2. Drowned river mouths with residence time measured in months; 3. Well-flushed drowned river, seasonally open to ocean; 4. Well-flushed drowned river, predominantly freshwater input; 5. Well-flushed drowned rivers, predominantly oceanic input; 6. group 5, also influenced by major river plume.

1	2	3	4	5	6	Indicator	Constituent Parameters	Proxies
x	x	x	x	x	x	Climate	Pacific Decadal Oscillation	
x	x	x	x	x	x	Regional Weather	Pacific Northwest Index (Washington only?)	
	x	x	x	x	x	Flushing Rate	Volume Shape River Flow Tidal Flow	
x	x					Dissolved Oxygen	Dissolved Oxygen	
				x	x	Transport Index	Windspeed & Direction Downwelling Episodes	
					x	River Plume Index	River Flow Windspeed & Direction Downwelling Episodes	
		x	x			In-Situ Production Index	River Nutrients	Rainfall or River flow Population Agricultural area Agriculture and forestry adj estuary
							PAR	Cloud Cover
				x	x	In-Situ Production Index	Ocean Nutrients PAR Turbidity	Transport Index Cloud Cover Significant Storm Events
x	x	x	x	x	x	Habitat Availability Index	Potential Habitat Realized Habitat	
						Potential Habitat	Exposure tolerance Salinity tolerance Required substrate	
x	x	x	x	x	x	Habitat Alteration	Areal Modification Index Areal Culture Index Compensatory Expenditures	
						Areal Modification Index	Total wetted area under current modification	
						Areal Culture Index	*Shellfish aquaculture area*	
						Compensatory Expenditures	Cost of eradication and mitigation	
x	x	x	x	x	x	Exploitation: Commercial harvest*	Biomass Relative biodiversity of target species Biodiversity of bycatch species	Landings

x	x	x	x	x	x	Exploitation: Recreational harvest*	Biomass Biodiversity	Fishing licenses
						Pollution Index	Population Building permits Timber harvest Permitted dischargers Agricultural area % shellfish harvest area closed Number of vessels Estuary volume Flushing rate	
x	x	x	x	x	x	Appreciation Index	Recreational opportunity and use Demographics Habitat allocation	
						Recreational Opportunity and Use	Visitors to local, state, and federal parks Recreational fishing and shellfishing permits Membership in environmental NGOs	
						Demographics	Age distibution Median income Proportion of "second" homes	
						Habitat Allocation	% wetted area as recreation or conservation area % shoreline in habitat set-asides	
x	x	x	x	x	x	Human Welfare	Regional economic performance Economic dependence on estuarine resources Societal well being	
						Regional economic performance	Total earnings Total employment	
						Economic dependence on estuarine resources		Total value of extracted marine resources
						Societal well being	Local median income Average education attained Crime rate Divorce rate	
						Management	# of employees in management agencies Annual cost of habitat restoration # of species of concern, threat, or endangerment Water quality violations	
x	x	x	x	x	x	Primary Production	Net annual primary production Spring-Summer net primary production	In-Situ Production Index
x	x	x	x	x	x	Harmful Algal Blooms		Shellfish bed closures

x	x	x	x	x	x	Submerged Aquatic Vegetation	Spartina cover Tidal marsh cover Eelgrass cover Edge to interior ratio of native marsh	
						Oyster Index	*Bed cover* *# of oyster leases* *Oyster condition index*	
x	x	x	x	x	x	Salmon Smolt Survival		Standardized hatchery smolt survival
x	x	x	x	x	x	Aquatic Biomass and Biodiversity	Biomass Biodiversity	In commercial and recreational catch In commercial and recreational catch
x	x	x	x	x	x	Upper Trophic Biodiversity	Shorebird Diversity Aquatic Bird Diversity Harbor Seals	
x	x		x	x	x	Shorebird Diversity	# of species Abundance Total mudflat area	
x	x			x	x	Aquatic Bird Diversity	# of species Abundance Total wetted area	
x	x	x	x	x	x	Index of Avian Pest Species	# of species Abundance Total wetted area	
x	x			x	x	Harbor Seals	Abundance Toxic load	

Spatio-Temporal Patterns of Physical Forcing in the Nearshore .....Chapter 2

Elizabeth Logerwell, David Armstrong, Barbara Hickey, Julia K. Parrish, Curtis Roegner, Alan Shanks, Gordon Swartzman, Vera Agostini, Robert Francis, Peter Lawson, Nathan Mantua, and Jan Newton

Setting The Stage: Physical Oceanography of the Nearshore Pacific Northwest

Temporal and spatial variability of physical forcing

The oceanography of the U.S. West Coast is dominated by the California Current System, a system of currents with strong interannual, seasonal and several day (event) scale variability (Hickey, 1998). In contrast to most East Coast environments, the West Coast 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. Also 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 dominated by seasonal and event-scale patterns in the upwelling processes (Hickey 1989; Landry et al. 1989) (Figure 2.1). 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. Larval organisms in the nearshore may also be advected offshore during upwelling unless they have behavioral attributes (such as vertical migration to depths of reduced offshore flow) that can aid in their retention. 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 (Figure 2.2). In contrast to the East Coast, alongshore topography of

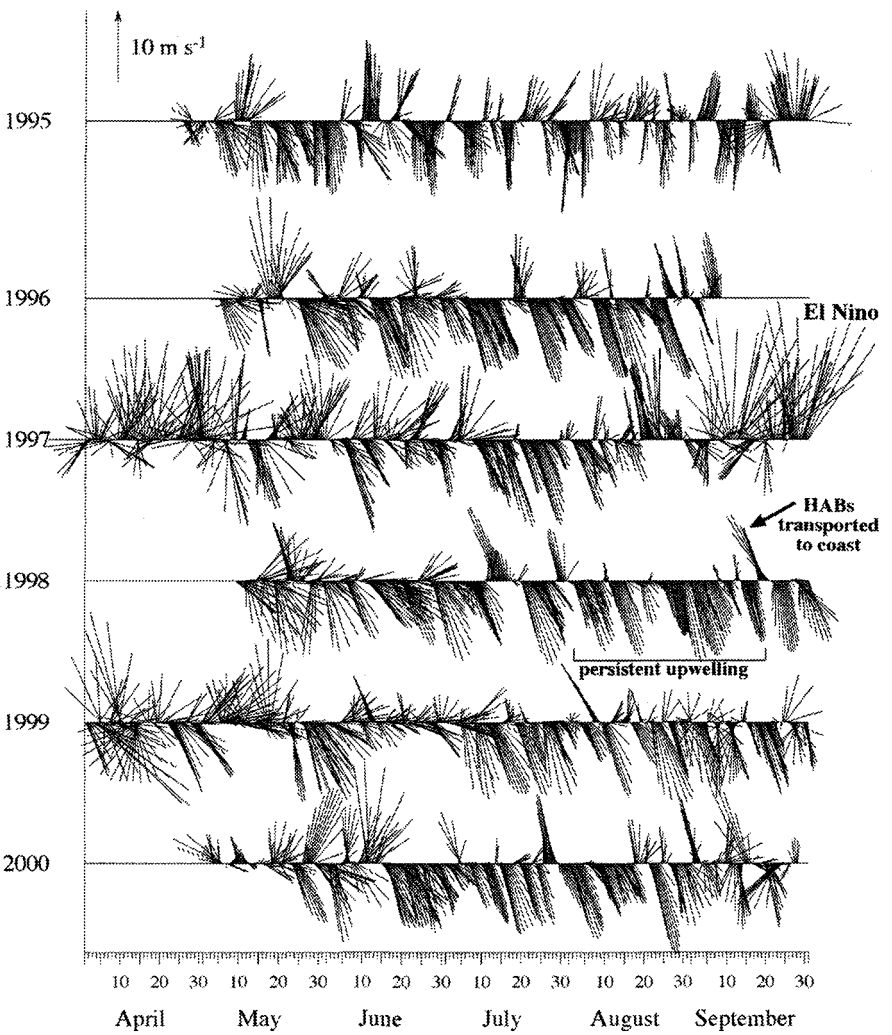

Figure 2.1. Time series of wind (positive northward) at one site off the Washington coast (Buoy 46029 near the Columbia River) from April to September 1995 to 2000, illustrating the large degree of interannual variability. Note the large winter storms in fall of 1997 (northward winds), indicative of El Niño conditions. Note also the persistent upwelling in summer of 1998 (southward winds). Currents associated with the fall storm on about September 20 following persistent upwelling brought toxic algae to the Washington coast where they infected razor clams along the beaches.

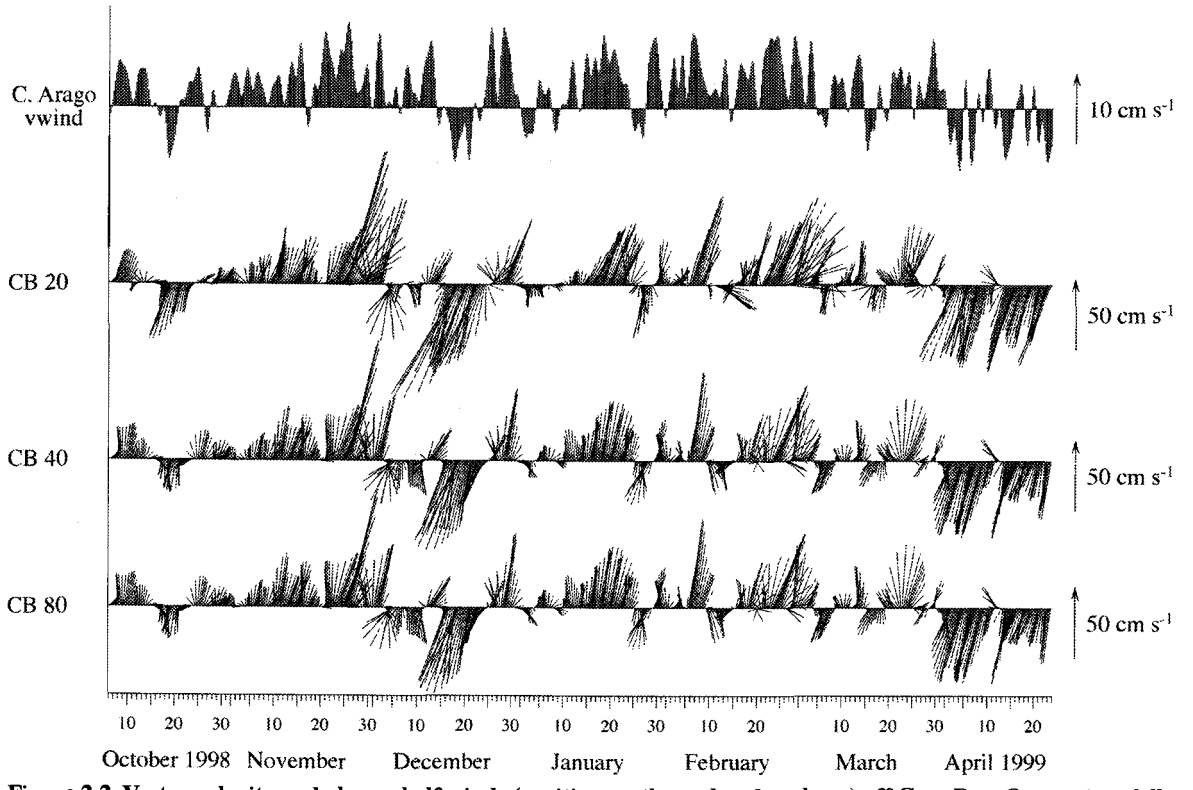

Figure 2.2. Vector velocity and along-shelf winds (positive northward and onshore) off Coos Bay, Oregon in a fall-winter period. Currents reverse direction every few days in concert with changes in wind direction.

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.

Mesoscale features: eddies, plumes and canyons

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 may be particularly important to phytoplankton/zooplankton production, growth and/or retention, as well as larval transport and/or retention. For example, in regions where large coastal promontories occur such as off southern Oregon, 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 off the central Oregon coast (the Hecate/Stonewall bank), retention areas are more likely. Under certain wind conditions, 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 and the Juan de Fuca eddy has been documented (Trainer et al. 2001). Retention areas may provide particularly favorable growth conditions for larval fish.

The Columbia River plume is particularly important in the Pacific Northwest coastal regions, both nearshore and in the estuaries. During years of high snowpack in the Pacific Northwest, very fresh water from the plume can flood the major coastal estuaries just north of the

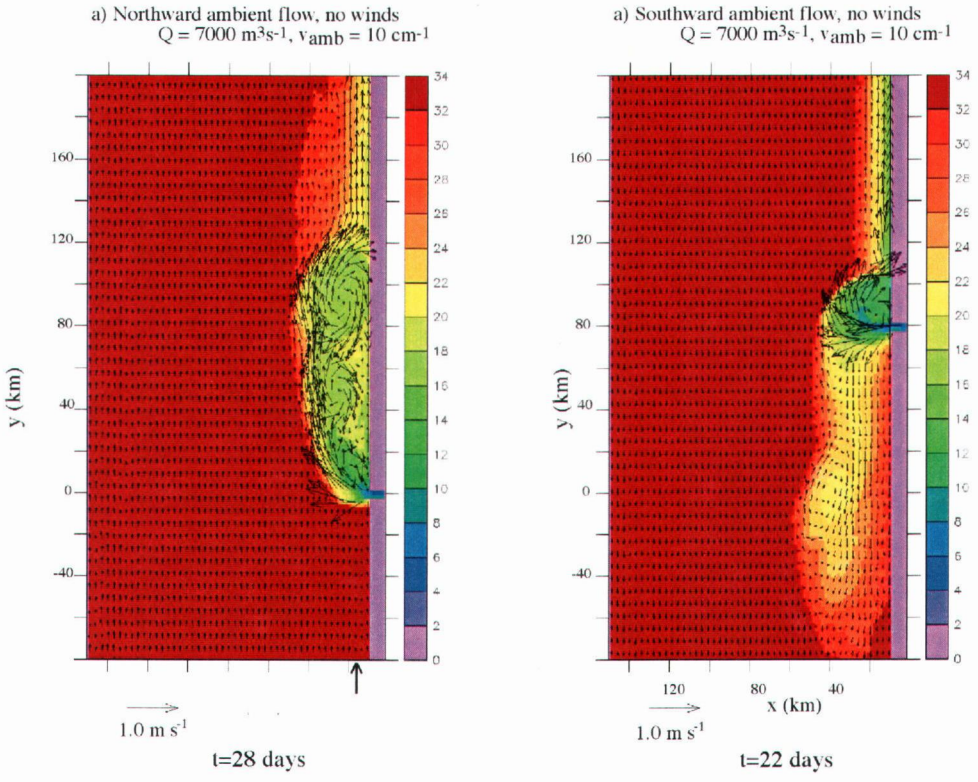

Figure 2.3. Results from a model study of the Columbia River plume, showing semi-closed (retentive) circulation patterns associated with the plume. Surface salinity (psu) contours and surface velocity vectors (m s-1) for mean winter conditions (left), a northward ambient flow of 10 cm s-1 and mean summer conditions (right), a southward ambient flow of 10 cm s-1 at t = 28 days are shown. The river discharge for both cases is 7000 m3 s-1. The semi-closed patterns are a result of interaction between the mean flow and a river plume with constant discharge. (Garcia-Berdal et al. 2001)

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 environmental distinction between these estuaries as well as between nearshore coastal regions. Inshore of the plume on the Washington coast, a retentive circulation pattern occurs (Hickey et al. 1998; Figure 2.3). 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.

The entire Washington coast is indented by submarine canyons (Figure 2.4). 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). 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 the Astoria canyon offshore of the mouth of the Columbia, are also known to have retentive capabilities. Each canyon tends to have a semipermanent counterclockwise eddy over and within the canyon (Hickey 1997). Zooplankton densities are frequently denser over the submarine canyons in the regions.

Seasonal and interannual variability of these mesoscale features can be significant. For example, the retentive capabilities of a feature such as the Juan de Fuca eddy likely depends on outflow from the strait (thus snowpack and rainfall) as well as the strength of upwelling winds that produce the coastal jet along the British Columbia/Washington continental slope. Retention in the lee of the Columbia plume depends on the strength of the plume and wind-driven nearshore currents, thus snowpack and wind. Retention over canyons as well as

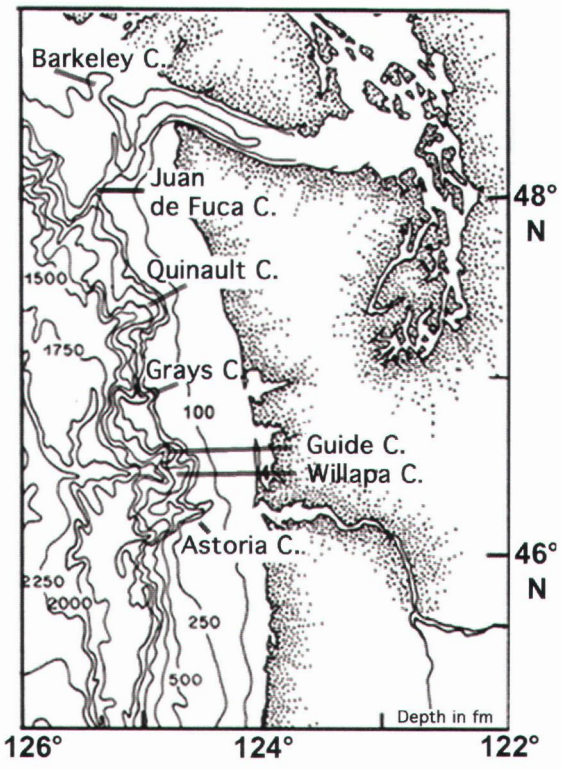

Figure 2.4. Bottom topography in the coastal Pacific Northwest. The topography illustrates the occurrence of numerous features such as submarine canyons and banks, which tend to cause retentive patterns in the coastal circulation as well as enhanced coastal upwelling. Such features occur more frequently off the Washington coast than off Oregon.

upwelling from canyons depends on wind-driven and ambient currents; however, the production of nutrients by canyon topography also depends on the depth of the mixed layer in a given year.

Spatial Variability of Large-Scale Forcing

Because alongshore gradients in the larger scale environmental forcing occur in the Pacific Northwest, we examined latitudinal differences in prey (zooplankton) abundance and availability. Acoustic data were collected at two frequencies during summer 1995 and 1998 along the Washington and Oregon coasts.

The results from these surveys show a consistent offshore zooplankton layer between 100 and 250 m depth (Figure 2.5). This layer is shallower further north and appears to be in water temperatures of approximately 7.5 deg C. The shallowing of the layer to the north follows a shallowing in contours of sigma-t (a measure of water density). There is also the suggestion of an association between the depth of the plankton patches and of the California undercurrent, which is also the depth of maximal northward flow. The plankton may be riding the undercurrent to travel north to conditions of higher summer phytoplankton production.

The plan views show fish (mostly Pacific hake) and zooplankton (mostly euphausiids) biomass garnered from acoustic survey data at two frequencies (38 and 120 kHz) and at two different depth strata, 10-150m and 140-400m. In 1995, fish, both deep (Figure 2.6a) and shallow (Figure 2.6b), were more abundant in the south (off California) than off Oregon or Washington. Plankton below 140 m, on the other hand, were more evenly distributed north to south (Figure 2.6a). Shallower plankton (Figure 2.6a) were more abundant in Oregon and Washington than in California. There were some areas off Oregon that had relatively high zooplankton abundance on the shelf, while in Washington the zooplankton abundance was shifted more offshore and to the shelf break. 1998, the end of an El Niño period, showed the highest fish abundances to the north both in the shallow layer (Figure 2.7a) and deep layer (Figure 2.7b). Deep plankton abundance in 1998 (Figure 2.7b) was also somewhat higher north of the Columbia River.

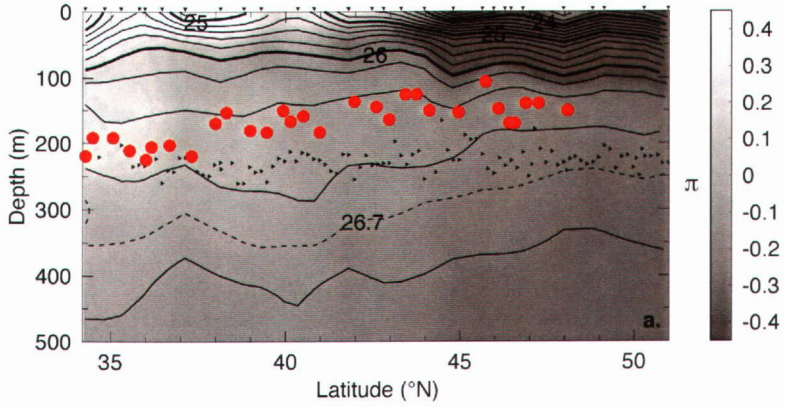

Figure 2.5. Distribution of zooplankton, water properties and currents with depth and latitude during summer 1995 and 1998 along the Washington and Oregon coasts. The tops of layers of zooplankton are indicated by red dots. The line contours are sigma-t (density) and the shading (scale shown at right) is spiciness. The small triangles show the depth center of the California undercurrent - the depth of maximal northward flow. Data on water properties and currents provided by Steven Pierce, Oregon State University.

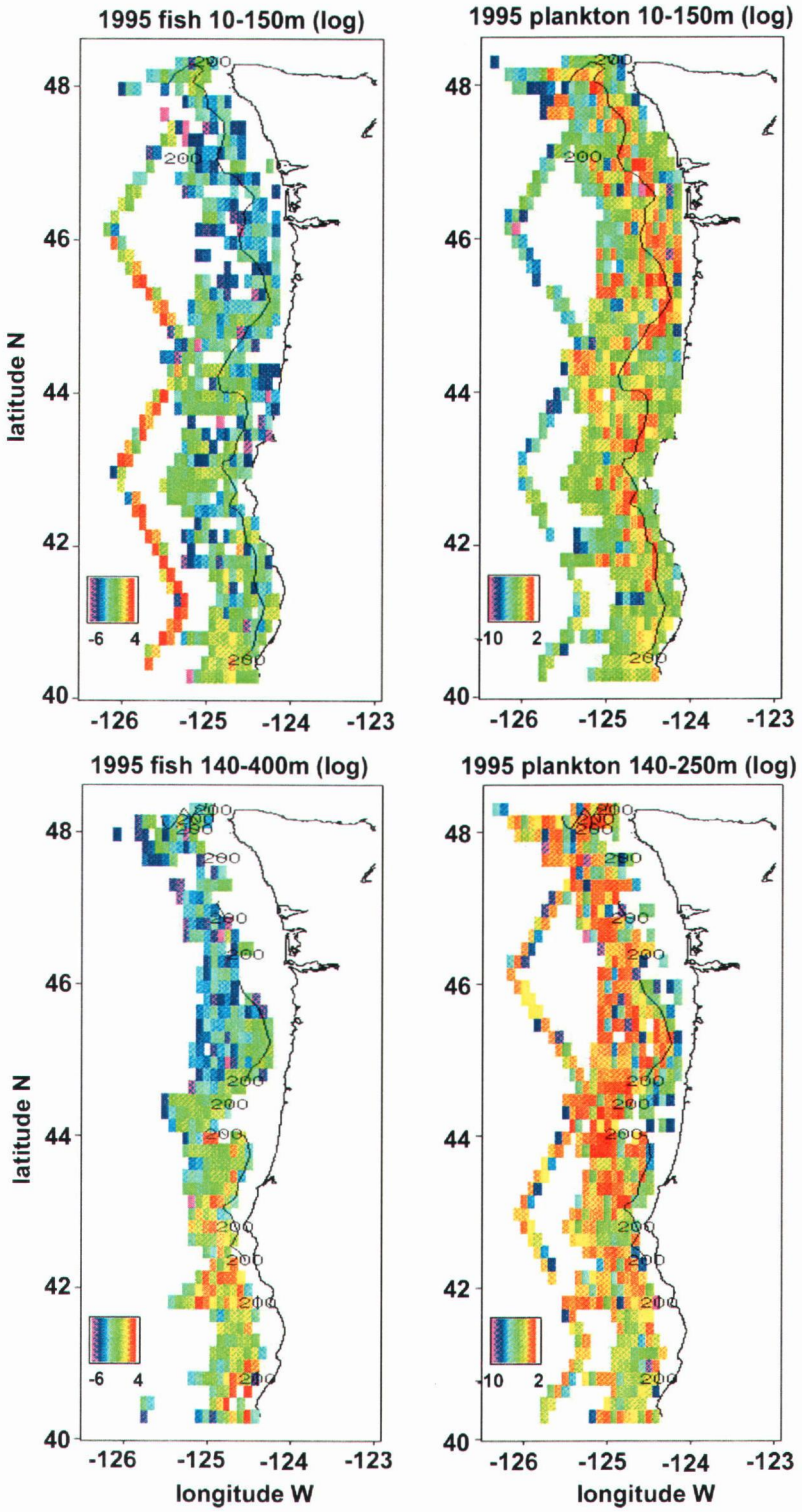

Figure 2.6. Horizontal distribution of fish and zooplankton biomass from the 1995 acoustic survey data at 2 frequencies (38 and 120 kHz) and at two different depth strata, a. 10-150m and b. 140-400m. The scale (inset at lower left) is the logarithm of an abundance index.

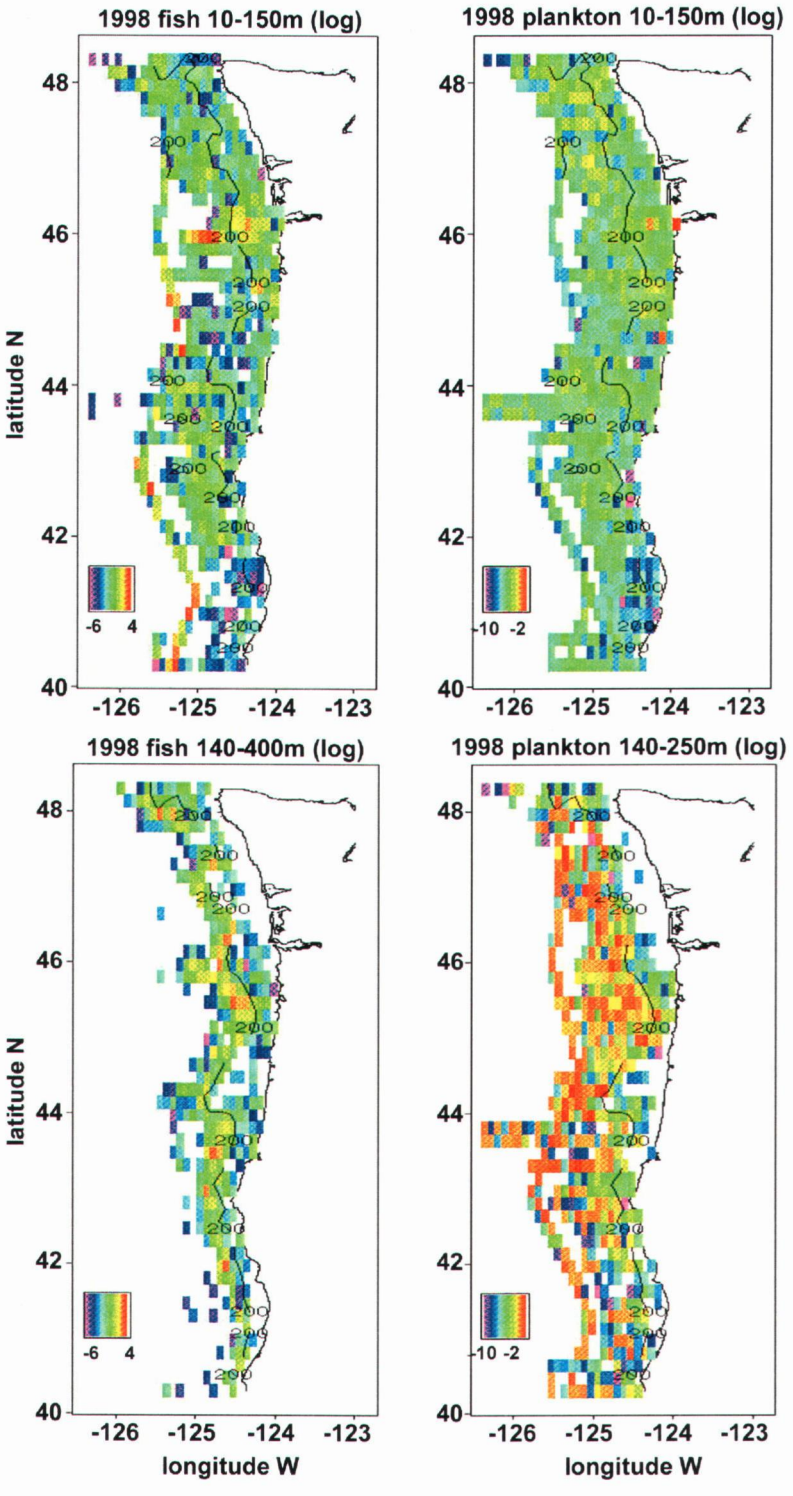

Figure 2.7. Horizontal distribution of fish and zooplankton biomass from the 1998 acoustic survey data at 2 frequencies (38 and 120 kHz) and at two different depth strata, a. 10-150m and b. 140-400m. The scale (inset at lower left) is the logarithm of an abundance index.

Shallow plankton abundance in 1998 (Figure 2.7a) appeared to shift from primarily on the shelf south of the Columbia River and offshore north of the Columbia River. These patterns in fish and plankton abundance are not clearly related to the general latitudinal trends of greater duration of upwelling towards the south and stronger storms towards the north. Nonetheless, upwelling, cross-shelf flow and north-south flow vary with depth and are thought to strongly affect the distribution of zooplankton and thus their fish predators. Future work will entail examining these relationships and developing a model of plankton abundances as a function of these environmental conditions.

Fine-Scale Spatio-temporal Forcing: Phytoplankton Blooms and Larval Transport

A coastal cruise in May 1999 illustrates the rapidity with which the coastal ocean and target biota can respond to variation in wind stress. During this cruise, we surveyed the area off southern Washington along a grid of 5 cross-shelf transects extending from 1 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 grid pattern was sampled twice; Survey 1 from 23-24 May and Survey 2 from 29-30 May. Survey 1 transects were made from north to south, while the order was reversed during Survey 2. At each station, a Seabird 25 conductivity (salinity)-temperature-depth sensor (CTD) with fluorometer and oxygen sensors was lowered to within 5 m of the bottom on the shelf and to 100 m elsewhere. A neuston net sampled a 100 to 200 m^3 volume of sea surface for invertebrate and fish larvae.

The cruise period coincided with a downwelling to upwelling transition in wind stress, and the response of the nearshore ocean was dramatic (Figure 2.8). Surface plots of salinity during downwelling reveal the Columbia River plume near the coast and in the upper 10 m of the water column. Estuarine moorings recorded this plume water entering Willapa Bay (see Estuarine section). In the 2 m surface the plume tapers to the south, indicating a separation from the main flow. This is consistent with wind stress which had already switched to upwelling conditions during that section of the survey. By the second survey period, 5 days later, strong upwelling conditions were ongoing. The plume had vanished, but the direction of the isohalines in the 2 and 10 m surfaces suggest a southwest propagation of the plume water. High salinity water was upwelling near the coast, and was imported into the estuary. These results indicate a large water mass exchange in the nearshore zone.

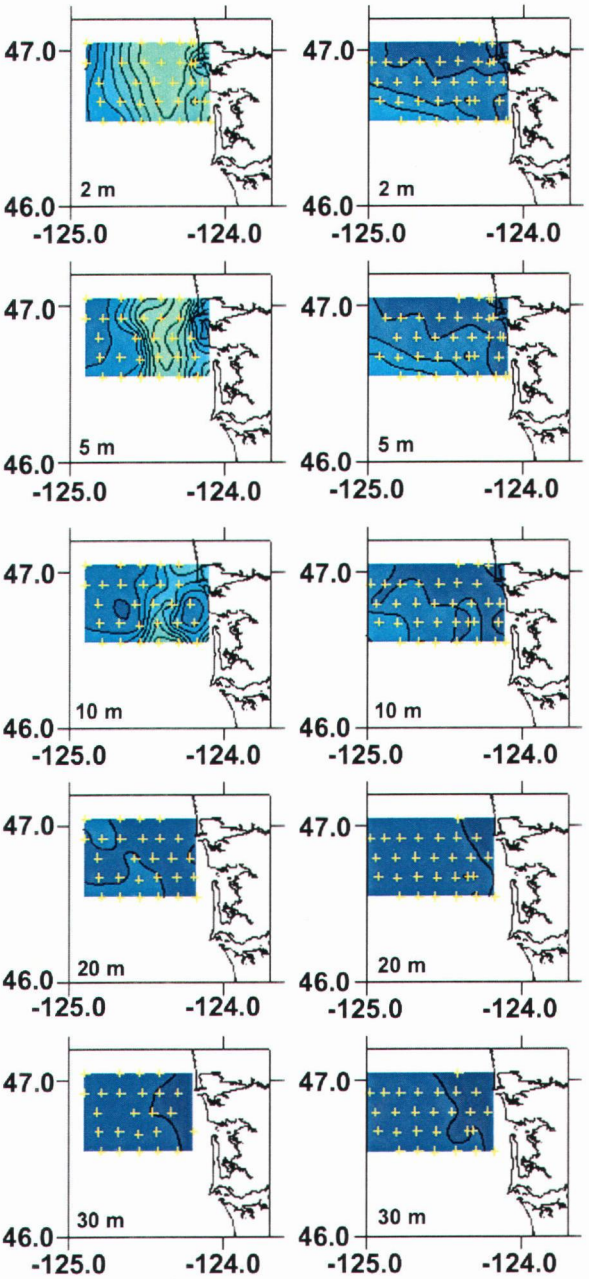

Figure 2.8. Surface plots of salinity during downwelling (left column) and upwelling (right column) condition at each of the indicated depths. Little variation in any water quality constituent occurred below 30 m. Stations are indicated by crosses; colored sections outside crosses are interpolated data. Note the structure of the Columbia River plume during downwelling.

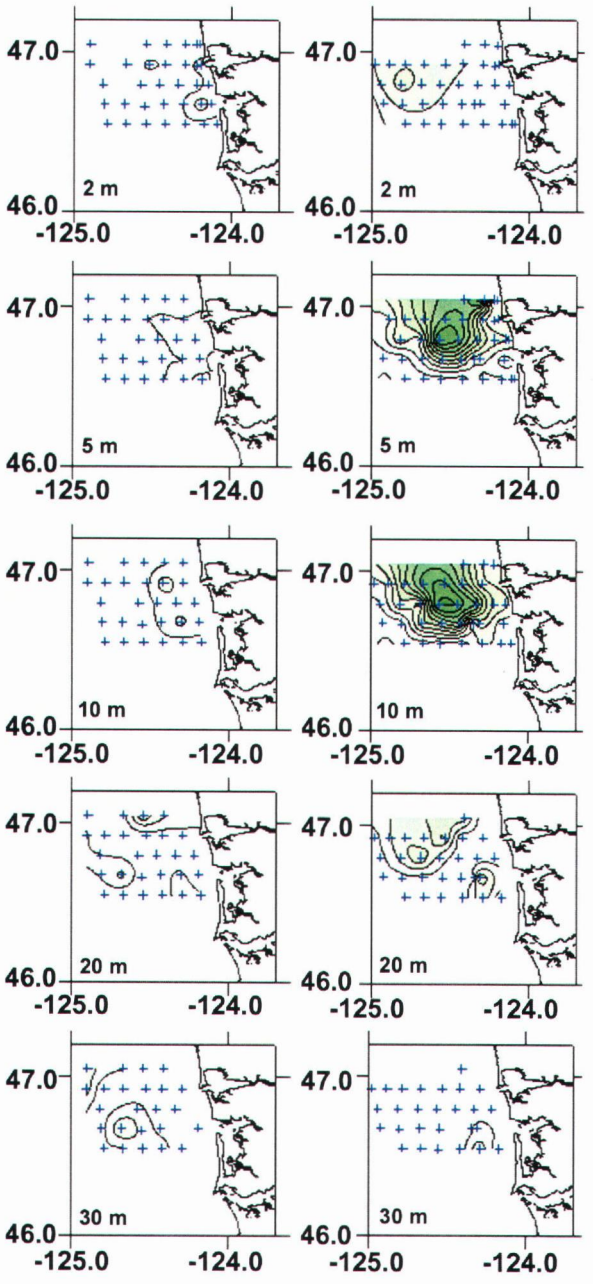

Figure 2.9. Surface plots of chlorophyll during downwelling (left column) and upwelling (right column) condition at each of the indicated depths. The bloom was not spatially continuous.

There was a striking affect of these ocean conditions on the coastal primary production. Plume water was deficient in chlorophyll, while the upwelled water supported a dense phytoplankton bloom (Figure 2.9). The bloom formed a large patch with an offshore core, and relatively low chlorophyll was found directly adjacent to the coast. This is presumably due to the lag in phytoplankton growth in newly upwelled waters coupled with offshore transport of this water mass. The 2 m surface was deficient in chlorophyll, perhaps due to photoinhibition, and the concentration was also reduced at depth. There was no bloom signal in the estuary during the cruise period, consistent with the seaward genesis of the phytoplankton.

Invertebrate larvae sampled in the neuston exhibited varying responses to the changing ocean conditions (Figure 2.10). Two examples contrast the extremes. Megalopae of *Cancer magister* were widely distributed but the majority were found in a few high density patches. There was little spatial change in the position of the patches between downwelling and upwelling states. Note that larvae were found in approximately the same location outside Willapa Bay during both surveys. As this water mass was initially the Columbia River plume, it is evident this feature posed no barrier to megalopae reaching nearshore sites. While we cannot tell to what extent alongshore advection affected the distributions (i.e., whether this was the same patch), megalopae of brachyuran crabs are proficient swimmers and may have avoided seaward advection during upwelling through vertical migration. In contrast, cyprid distribution changed considerably during the downwelling-upwelling cycle consistent with passive advection offshore with Ekman drift.

The coastal survey shows that wind-driven upwelling of nutrients from deeper layers fuels coastal productivity, but it can also result in offshore advection of planktonic larvae (cyprids) whose nursery areas are in the nearshore or in coastal estuaries. We investigated whether planktonic larvae, through vertical migration, could control their cross-shelf transport such as to not be swept offshore in the face of strong offshore currents. We used data from ADCP moorings off Coos Bay in spring (May-June) 1995 and 1996 and modeled various vertical migration patterns. Assuming that the current patterns in the mooring are typical of current patterns over the local region, we demonstrated that, through vertical migration, larvae could maintain net onshore movement. Figure 2.11 compares net onshore-offshore and north-south movement over a 2 month period in 1995 for: vertical migration in synch with the tidal cycle; optimal onshore vertical migration (i.e. the larvae being at the depth for minimum offshore, or maximum onshore movement at any time); no vertical migration with constant depth of, 7 m, 39 m, and 71 m;

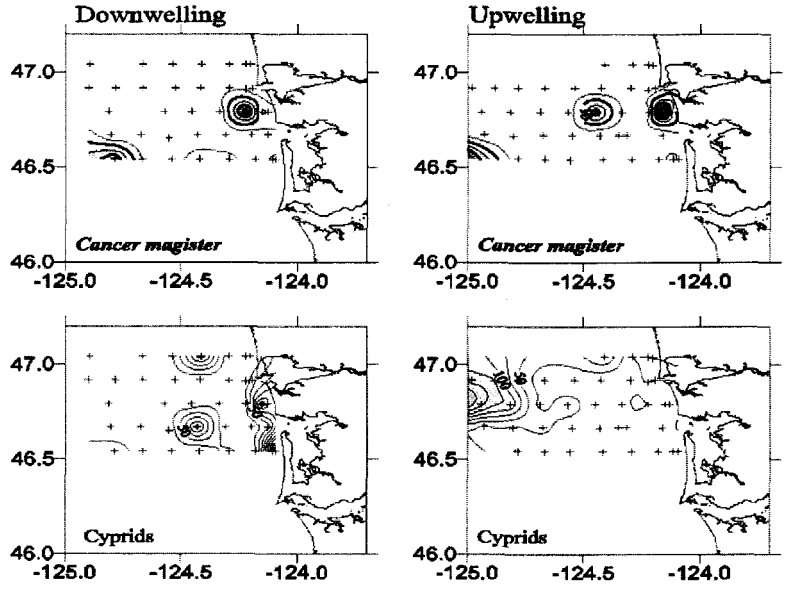

Figure 2.10. Surface plots of *Cancer magister* megalopae (top) and cyprid larvae (bottom) during downwelling (left column) and upwelling (right column) condition in the neuston layer.

and diel vertical migration (upward at night and downward during the day). The least net migration is to remain at 71 m. However, if vertical migration is necessary for feeding, the larvae can maintain the same net migration through tidal vertical migration as they can remaining at 39 m, below the thermocline. This study demonstrates the importance of diel migration as a possible mechanism for aiding inshore migration.

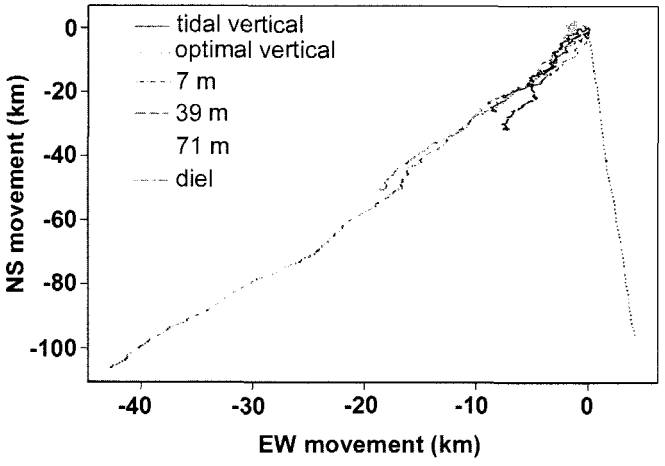

Figure 2.11. Model results of different vertical migration behaviors given currents as measured by ADCP moorings off Coos Bay in spring (May-June) 1995. The figure shows net E-W (onshore-offshore) and N-S movement over a 2 month period for: vertical migration in synch with the tidal cycle; optimal onshore vertical migration; constant depth of 7 m, 39 m and 71 m; and diel vertical migration.

Interannual to Event-Scale Forcing: Pacific Northwest Coho Salmon Survival

Interannual, seasonal and event-scale variability in the productivity of the nearshore ocean is important for the entire trophic chain. Our study of coho salmon (*Oncorhynchus kisutch*) survival illustrates this point. Because their ultimate fishery and spawning production seems to strongly relate to ocean conditions during their first several months in the ocean, Pacific Northwest coho salmon have served as a bellweather species for variability in the Pacific Northwest coastal physical and biological environment. Since the early 1980s, much has been written about this relationship (e.g. Nickelson 1986; Pearcy 1992; Emlen, et al. 1990; Coronado & Hilborn 1998; Lawson 1993; Ryding & Skalski 1999; Cole 2000).

To examine the role of ocean variability for coho survival we analyzed a time series of coho survival and a suite of oceanographic variables. Pacific northwest coho salmon live three years: 18 months in freshwater and 18 months in the ocean (Sandercock 1991). The first three months of ocean residency are generally regarded to be a critical period because the majority of marine mortality occurs at this time (Pearcy 1992). Thus we focused on oceanographic conditions during April through June. We did not, however, entirely ignore other seasons. Ocean conditions during the winter after juveniles migrate to sea have also been shown to influence survival (Lawson 1997).

Our time series of coho survival was from hatcheries in the Oregon Production Index (OPI) region. Because the data are from hatchery fish, freshwater mortality is a negligible proportion of total mortality. Although the OPI region extends from California to southern Washington, the majority of smolts are released from lower Columbia River hatcheries (Pearcy 1992). Coho are not as migratory as other species of salmon. As late as July, most juvenile coho from the Columbia River are found in coastal waters of Washington and Oregon and do not move to Vancouver Island or California (Pearcy

& Fisher 1988). Thus, we examined oceanographic conditions off Washington and Oregon.

Smolt-to-adult survival of OPI coho has been declining since the beginning of the time series (1969) and there is substantial interannual variability (Figure 2.12).

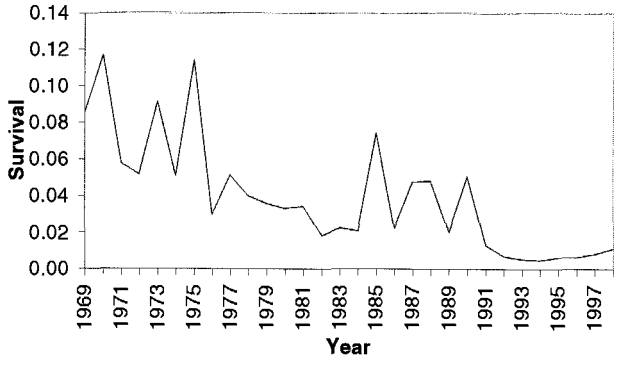

Figure 2.12. Time series of Oregon Production Index (OPI) coho smolt-to-adult survival.

Because the relationships between ocean variables and OPI coho survival were not always linear, we used generalized additive models (GAM) to quantify the effect of ocean variability on survival. Statistics were carried out with S-plus software (MathSoft, Inc. 1999).

The ocean variables used to formulate the GAM model represented the sequence of processes we hypothesized to be important for survival of OPI coho. The variables were (shown in seasonal sequence and with model shorthand):

1. SST.JFM.t0 - Sea surface temperature at the Charleston, OR (43.3°N) shore station; Jan-Feb mean; winter before ocean migration. SST during the winter before ocean migration was used to indicate the effect of winter winds on water column stability. Exceptionally strong southerly (downwelling) winds in winter can create a deep surface layer of relatively warm water. Because more wind energy is required to mix through a strongly stratified water column (Mann & Lazier 1991, p.69), spring upwelling winds may be less effective at bringing cold nutrient-rich water to the surface following a winter of strong downwelling.
2. TRANS - Date of the spring transition in regional sea level and wind, from Bilbao 1999. A delay in the onset of spring and the associated increase in ocean productivity could result in insufficient food for smolts upon arrival in the ocean (Ryding & Skalski 1999).
3. UW.AMJ - Bakun upwelling index at 45°N; Apr-June mean; spring of ocean migration. Wind-driven upwelling of nutrients fuels coastal productivity and should thus be related to the amount of food available for coho smolts (Nickelson 1986).
4. CV - Coefficient of variation in daily Bakun index, spring transition to June. Variability in the strength of upwelling winds may result in periods of stratification which would hold nutrients and phytoplankton near the surface, alternating with periods of upwelling, which would then refresh the nutrient supply (Sverdrup 1953).
5. SST.JFM.t1 - Sea surface temperature at the Charleston, OR shore station; Jan-Feb mean; winter after ocean migration. SST during the winter following ocean migration has been shown to be correlated with coho survival (Lawson 1997), perhaps because cooler SST indicate higher ocean productivity.

Plots of the GAM model partial residuals show the shapes of the relationships between coho survival and each environmental variable (Figure 2.13). Survival was linearly related to winter SST before ocean migration, with higher temperatures associated with lower survivals. There was a nonlinear relationship between survival and spring upwelling, survival increased rapidly at upwelling indices greater than 25. A b-spline (indicated by bs() in the S-plus model and output) provided a good fit for spring upwelling. The relationship between spring transition and survival was linear, later springs were correlated with lower survival rates. There was a dome-shaped relationship between daily variability in upwelling winds and survival, the optimum CV was around 2. A natural spline was the best fit in this case. The relationship between winter SST after ocean migration was nonlinear, survival increased rapidly at temperatures lower than around 10°C. The GAM combining the linear and nonlinear terms portrayed in Figure 2.10 explained 76% of the variance in OPI coho survival (R^2=0.76), and the fit was statistically significant (F=7.465, df=8,19, p<0.001). Figure 2.14 compares the time series of observed survival to that predicted by the GAM model.

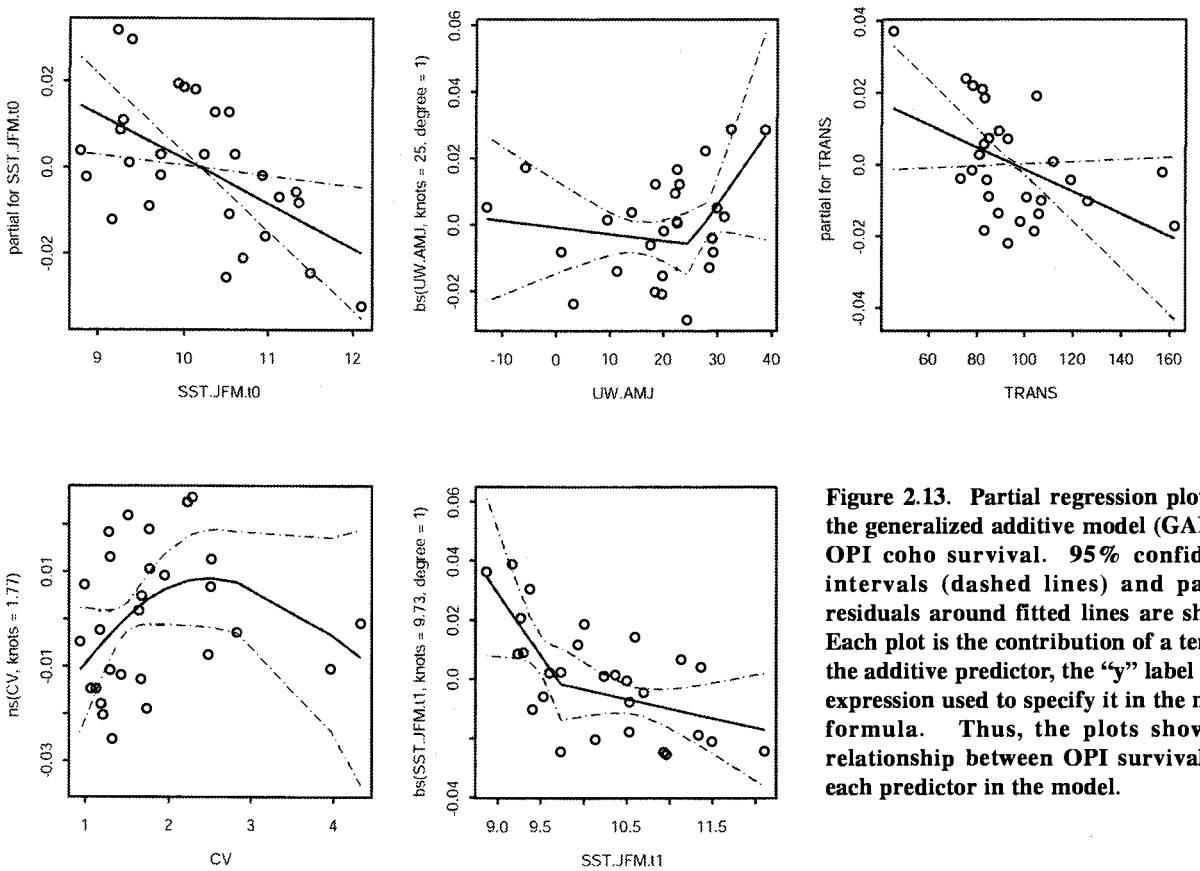

Figure 2.13. Partial regression plots for the generalized additive model (GAM) of OPI coho survival. 95% confidence intervals (dashed lines) and partial residuals around fitted lines are shown. Each plot is the contribution of a term to the additive predictor, the "y" label is the expression used to specify it in the model formula. Thus, the plots show the relationship between OPI survival and each predictor in the model.

The model results show that interannual variability in ocean conditions plays an important role in determining ocean survival of coho off Washington and Oregon. The model suggests that variability in spring productivity, as indicated by the Bakun upwelling index, and variability in winter productivity, as indicated by sea surface temperature, influence coho survival during their first year at sea.

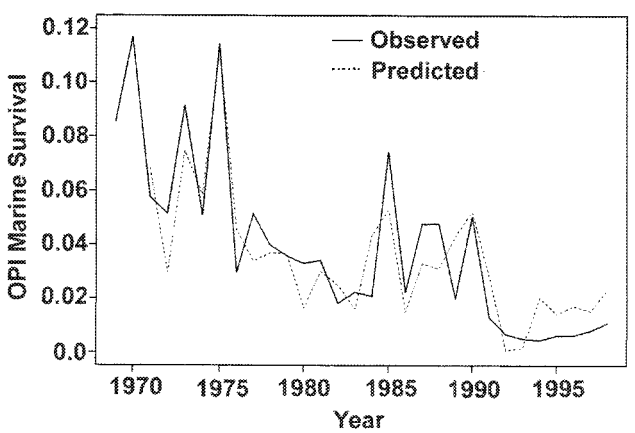

Figure 2.14. Time series of observed OPI coho survival compared to survival predicted by the GAM model.

Our results also show that ocean conditions during the winter before the smolts migrate to sea influence survival. To illustrate the mechanism, which we have termed "winter preconditioning," we examine two years in detail, 1990 and 1998. These were years with contrasting ocean conditions and OPI survival during which profiles of water temperature with depth were available in the Washington or Oregon region. In 1990 winter downwelling was weak, January-March SST was cool (Figure 2.15a), and there was little stratification (Figure 2.15b). In 1998 the opposite was true, winter downwelling was strong and the vertical profile shows a warm mixed layer down to at least 100 m. The following spring 1998 upwelling winds were above average (Figure 2.16a) but the temperature profile shows that temperatures at the surface and at the base of the mixed layer (~ 35m depth) were relatively warm compared to 1990 (Figure 2.16b). This suggests that strong stratification in the winter of 1998 decreased the effectiveness of upwelling the following spring (less cold-nutrient rich water advected to the surface). In spring 1990 upwelling winds were below average (Figure 2.16a), but the temperature at the base of the mixed

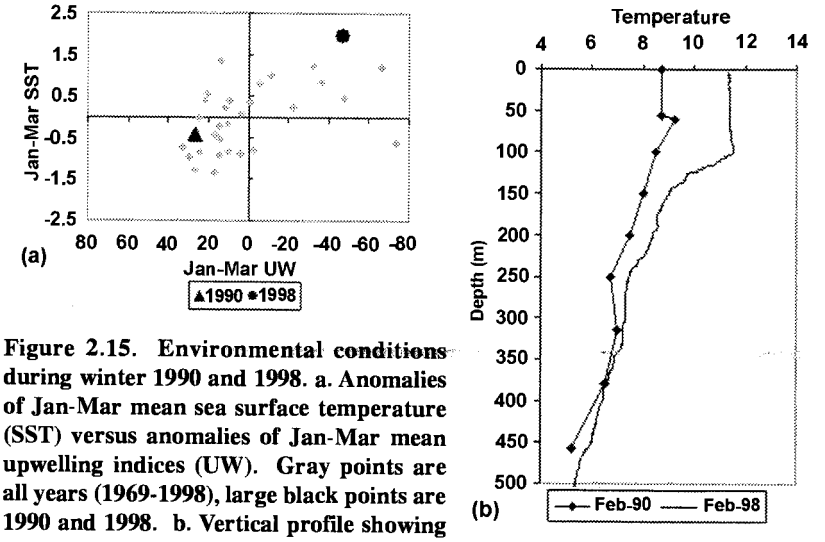

Figure 2.15. Environmental conditions during winter 1990 and 1998. a. Anomalies of Jan-Mar mean sea surface temperature (SST) versus anomalies of Jan-Mar mean upwelling indices (UW). Gray points are all years (1969-1998), large black points are 1990 and 1998. b. Vertical profile showing temperature (°C) with depth for Feb 1990 and 1998. Data are from the NODC Oceanographic Profile Database (http://www.nodc.noaa.gov/General/profile.html). Feb 1990 station located at 44.8°N, 125°W. Feb 1998 station located at 44.7°N, 125°W.

Mesoscale Features: Canyons

The entire Washington coast is indented by submarine canyons. Because these are mesoscale features of increased upwelling and retention, we expect that zooplankton and fish abundance should be relatively high near canyons. The Oregon coast does not feature canyons. However, the shelf-break is a topographic feature along both Washington and Oregon coasts that may also be an area of increased production and predator aggregation. Figure 2.17 shows plankton and fish abundance (> 50 m depth) for Oregon and Washington coasts from acoustic surveys conducted during summer of 1995. Figure 2.18 shows the same for 1998. The Washington coastal transects were separated into those entering canyons (Astoria, Willapa, Guide, Grays, Quinault, Juan de Fuca and Ninitat; Figure 2.4) and those not near canyons. These results suggest that, except for the non-canyon transects off Washington coast, abundance density for both fish and plankton

layer was relatively cool (Figure 2.16b), we suggest as a result of weak winter downwelling and a well-mixed water column previous to spring transition. We hypothesize that the result of the interaction between winter and spring conditions was that OPI coho survival was above average in 1990 despite the fact that spring upwelling was below average. In contrast, OPI coho survival was below average in 1998, when spring upwelling was above average (Figure 2.16a).

Finally, our results show that in addition to mean winter and spring conditions, event-scale processes such as the timing of spring transition and daily variability in upwelling winds influence coho survival.

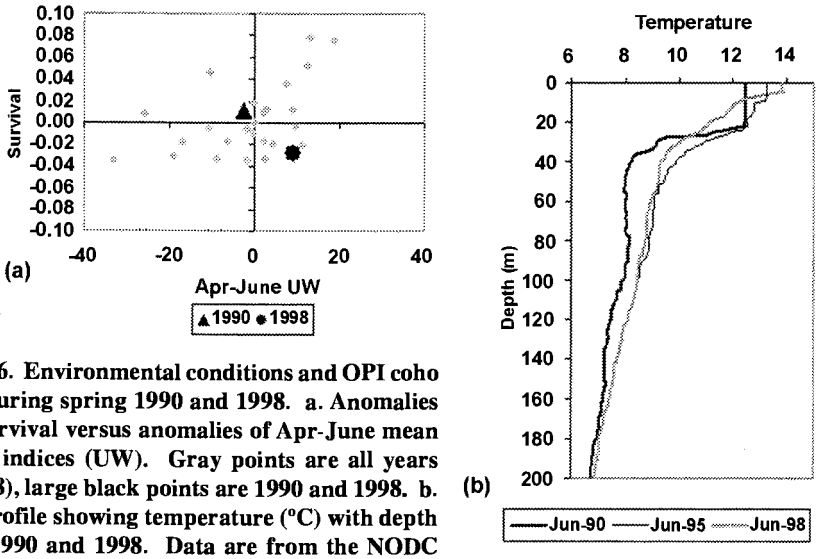

Figure 2.16. Environmental conditions and OPI coho survival during spring 1990 and 1998. a. Anomalies of coho survival versus anomalies of Apr-June mean upwelling indices (UW). Gray points are all years (1969-1998), large black points are 1990 and 1998. b. Vertical profile showing temperature (°C) with depth for June 1990 and 1998. Data are from the NODC Oceanographic Profile Database (http://www.nodc.noaa.gov/General/profile.html). June 1990 station located at 48°N, 125.8°W. June 1998 station located at 47.9°N, 125.4°W.

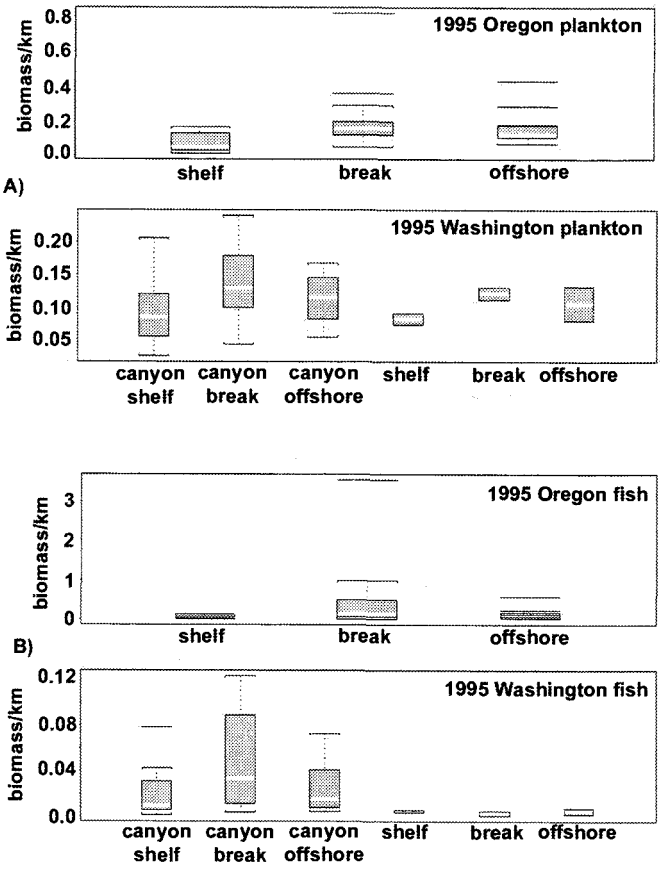

Figure 2.17. (a) Plankton and (b) Fish biomass (> 50 m depth) for Oregon and Washington coasts from acoustic surveys during summer 1995. Data are categorized according to location of the transects. "Shelf" transects were located on the continental shelf, "break" transects were located at the shelf break, "offshore" transects were located offshore of the shelf break. "Canyon shelf" transects pass through a canyon that is on the continental shelf (adjacent to the canyon), "canyon break" transects were located at the edge of the canyons, and "canyon offshore" transects pass over canyons that are in deep water. The solid horizontal line is the median, and the upper and lower ends of the box are the upper quartile and lower quartile of the data. The whiskers are located at 1.5 times the inter-quartile range and points beyond (outliers) are plotted individually.

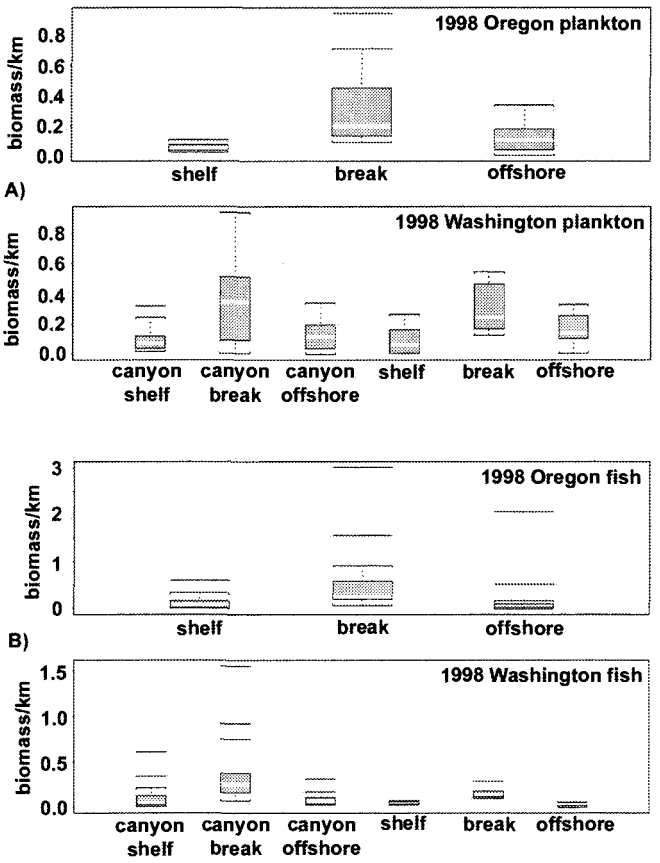

Figure 2.18. Same as Figure 2.17 for acoustic surveys during summer 1998. (a) Plankton and (b) Fish biomass (>50 m depth).

off both Oregon and Washington is highest on the shelf break and the canyon break, respectively. The fish and plankton abundance in the Washington transects crossing canyons appear to be greater than in the Washington transects not crossing canyons in all regions (shelf, shelf or canyon break and offshore) although the plankton differences are not statistically significant. These results demonstrate that the shelf-break and mesoscale topographic features such as canyons can aggregate production, predators and prey.

Temporal Variability vs. Mesoscale Features: Seabird Demography

Our research on interannual patterns in seabird reproductive success at two Pacific Northwest seabird colonies illustrates the influence of temporal variability of physical forcing on these apex predators. Our results also show that different colonies respond to physical forcing at different spatial scales, from local (upwelling winds) to regional (atmospheric climate indices).

Upper trophic level species in nearshore systems should respond to both "bottom-up" (physical) and "top-down" forcing, as mediated by a host of human influences. Coastal Oregon and Washington is home to both seabirds and marine mammals. Among seabirds, the most prevalent species is the common murre (*Uria aalge*), a small duck-sized seabird which nests on offshore islands and seastacks. Murres are piscivorous – consuming forage fish and juvenile groundfish up to approximately 25 cm in length - and can dive to a depth of

several hundred meters (Burger 1991) in search of these prey. With a daily energy demand of 323 kcalories (field metabolic rate, Birt-Friesen et al. 1989), an adult murre needs to consume an average of 160 grams of high lipid fish (e.g. herring, anchovy, smelt) each day. Because murres are gregarious and nest in high densities (shoulder to shoulder in groups of tens to tens of thousands), total colony demand can be quite high, exceeding 11 billion kcalories over the course of a four month breeding season (Parrish & Logerwell unpubl.). Changes in productivity within the system, including annual events such as El Niño, or interdecadal events such as a change in sign of the Pacific decadal oscillation (PDO), may have cascading effects which reach to murres, as changes in nearshore production alter the distribution and abundance of forage fish. Such an effect is most likely to be demonstrated in colony demographics (both colony size and annual reproductive effort), as nesting murres are restricted to foraging within a proscribed area.

Within the PNCERS study area, the distribution and abundance of seabirds, including murres, is striking. Along the Washington coast, the majority of seabirds nest along the rocky shoreline, north of Grays Harbor. Murres number in the upper thousands (Wilson 1991, Parrish et al. 2001). By contrast, along the Oregon coastline seabirds are widely distributed, and murres number in the hundreds of thousands (R. Lowe, USFWS, pers. comm.).

The effect of ocean-atmosphere forcing on upper trophics, including seabirds, has been well established, especially for intense episodic events such as El Niño (Graybill and Hodder 1985). The response of area-restricted, long-lived species, such as murres, is to skip breeding in stressful years (with the demographic effect of lowering apparent colony size) or fail at breeding (with the demographic effect of lowering colony-wide reproductive success). Note that both effects are short-term relative to the life of an individual adult, which may reproduce over a 20+ year period. More subtle forcing factors, such as low-level chronic change in wind stress or upwelling strength, can also produce change in the distribution and abundance of seabirds (Aebischer et al. 1990, Veit et al. 1996).

However, the linkages between physical forcing and biological response remain largely unclear. In part, this is due to the fact that biological response variables are inherently noisy, and that they represent nonlinear responses to a variety of forces, only some of which are physical in nature (e.g., demographic parameters such as population size or reproductive output are responses to physical forcing as well as biological interactions such as predation). Another potential explanation for the lack of lockstep between physical forcing and biological response (especially for upper trophic levels such as seabirds), is the cursory nature of many analyses. Thus, while large scale events such as El Niño can be linked to large demographic responses, spatially and temporally explicit models are currently lacking.

As part of the PNCERS program, we have studied the interactions between bottom-up and top-down (i.e., predators) forcing at two common murre colonies – Tatoosh Island, located at the NW tip of the Olympic Peninsula (48° 24' N 124° 44' W), and Yaquina Head – located immediately north of Newport, Oregon (44° 40' N 124° 05' W). Demographic data on seabirds nesting on Tatoosh have been collected since 1991, whereas seabird demographics at Yaquina commenced with the PNCERS study in 1998. Among the parameters collected are average annual colony size during the height of the breeding season (i.e., during the period of egg and chick presence), the average reproductive output of all murres within standardized plots (where minimum plot size is >15 pairs and multiple plots represent each colony), and chick diet composition.

For a long-lived, low fecundity species such as the common murre, colony size, or annual attendance, should vary the least of all measured parameters, as a function of low amplitude physical forcing. This is because long-lived species in a dynamic environment have a range of behavioral and ecological mechanisms to ameliorate annual "noise." On the other hand, long-term differences in average, or maximal, physical signals may translate into significantly different population sizes – such as those found in Washington versus Oregon. Reproductive output should be a more reliable mirror of annual physical forcing, as parents restricted to a discrete area around a breeding colony must locate sufficient resources to fledge young, as well as feed themselves, within a given amount of time. Because each colony is subject to varying predator effects which principally effect reproductive success (Parrish et al. 2000), it is difficult to determine the impact of physical versus bio-

Table 2.1. Pearson Correlation Coefficients among attendance and reproductive success of common murres nesting on Tatoosh Island (1992 to 2000), and several regional and local measures of physical forcing.

Average Monthly Values of:	Attendance	Reproductive Success
NPI breeding year	0.337	-0.182
NPI off season	0.400	0.180
NOIx breeding year	0.302	-0.202
NOIx off season	0.301	-0.053
Upwelling Anomaly breeding year	0.327	0.642
Upwelling Anomaly off season	0.280	0.696
Upwelling Anomaly breeding season		-0.529

logical forcing on reproduction. To account for this, we chose to report the reproductive output of that plot *least* effected by eagle disturbance, as assessed annually by our observers. Diet composition may be the most sensitive measure of physical change, as even short-term changes in production should be reflected in forage fish diversity and distribution. However, diet of a generalist species, such as the murre, is a complex interaction between total production and prey choice, such that diet switching may not necessarily indicate changes in production.

For the Tatoosh colony, for which we have the longer dataset, attendance has varied widely, from a high of 4200 in 1991 to a low of 2750 in 1998. In general, colony size has been decreasing at a rate of 150 murres per year (Parrish et al. 2001), although the population appears to have stabilized from 1999 to 2000. Regional measures of climate forcing, typified by the North Pacific Index (Trenberth and Hurrell 1994), do not explain the attendance pattern (Table 2.1). Monthly NPI values were averaged over two periods: the breeding year, starting in the month immediately after breeding had ceased (October for Tatoosh, August for Yaquina), and the off-season – measured as the months during which no overt breeding activity occurred (October to April for Tatoosh; August to February for Yaquina). As would be expected, highly correlated indices, such as the extratropical Northern Oscillation Index (NOIx) were also uncorrelated with attendance. Local measures of forcing, typified by offshore upwelling anomalies (measured at 48°N 125°W for Tatoosh; 44°N 125°W for Yaquina) were similarly unable to explain Tatoosh attendance patterns (Table 2.1).

Patterns of reproductive output have been similarly variable over the decade, ranging from a low of 28% in 1998 and 1999, to a high of 97% in 1997, where these data refer to success in plots least subject to eagle disturbance. Whereas the regional measures of physical forcing were uncorrelated with reproductive success, local upwelling, especially during the nonbreeding months leading into the year's breeding season were positively and significantly correlated despite noise in the signal (one way ANOVA, $F = 6.610$, $P = 0.037$, $R^2 = 0.412$; Table 2.1). This effect is primarily driven by the relationship between strong downwelling and low reproductive success (Figure 2.19). Note that local monthly upwelling anomaly was not correlated with either regional measure.

Data from Yaquina only span three years, making correlation difficult. At this colony, attendance has more than tripled from 1998 (approximately 8000 birds) to 2000 (25,000 birds; Parrish unpub. data). Reproduc-

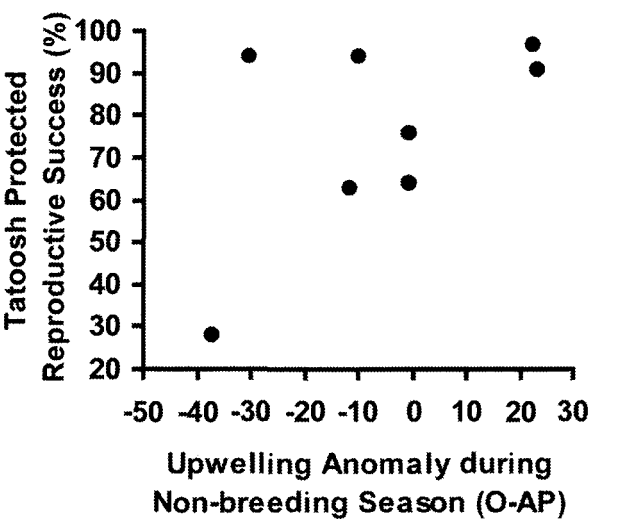

Figure 2.19. The relationship between local average monthly upwelling anomaly (cubic meters per second per 100 meters of coastline; measured at 48°N 125°W; PFEL website) during the non-breeding season and the average reproductive success (in percent of pairs fledging a chick) of pairs of Tatoosh Island Common murres nesting in plots least affected by local predators. Data are from 1992 through 2000.

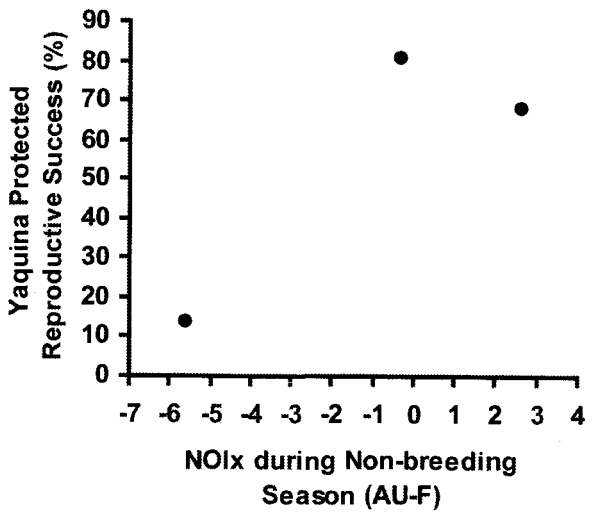

Figure 2.20. The apparent relationship between monthly average extratropical Northern Oscillation Index (NOIx) during the non-breeding season and average reproductive success (in percent of pairs fledging a chick) of pairs of Yaquina Head common murres nesting in plots least affected by local predators. Data are from 1998 through 2000.

tive success in areas least affected by eagles has also steadily increased from a low of 14% in 1998 to a high of 81% in 2000. Although neither regional measure explains attendance, both appear to be related to fledgling production, with the stronger relationship between reproductive success and non-breeding monthly averages (Figure 2.20). Local upwelling anomalies during the non-breeding season appear to explain both annual attendance and reproductive success, although the latter relationship is not immediately apparent (Figure 2.21).

Interestingly, at both the Tatoosh and Yaquina colonies, local upwelling during the breeding season is negatively correlated to reproductive success. That is, the murres appear to produce more chicks during anomalously strong downwelling spring-summers. This apparent relationship may be merely correlative. At both locations, years of anomalously strong upwelling during the non-breeding months leading into the breeding season presage months of downwelling during the breeding season (Figure 2.22). This relationship appears to breakdown beneath a certain threshold of the strength of monthly upwelling during the non-breeding season. This suggests that reproductive success – presumably a function of local productivity – is also a threshold response variable. Only in years of strong downwelling (see especially Tatoosh) will reproduction suffer.

These results also appear to suggest that whereas the Yaquina colony is responding to a mixture of regional and local signals, the Tatoosh colony mirrors only local forcing. Although the reasons for this apparent pattern are unknown, one potential explanation is the occurrence of local geomorphologies which produce upwelling, specifically canyons. Because the Juan de Fuca canyon is immediately north of Tatoosh Island, localized eddy-produced upwelling may actually buffer the biological system from the influence of negative regional signals.

At larger space and time scales, patterns of physical forcing and biological response remain unclear. Although

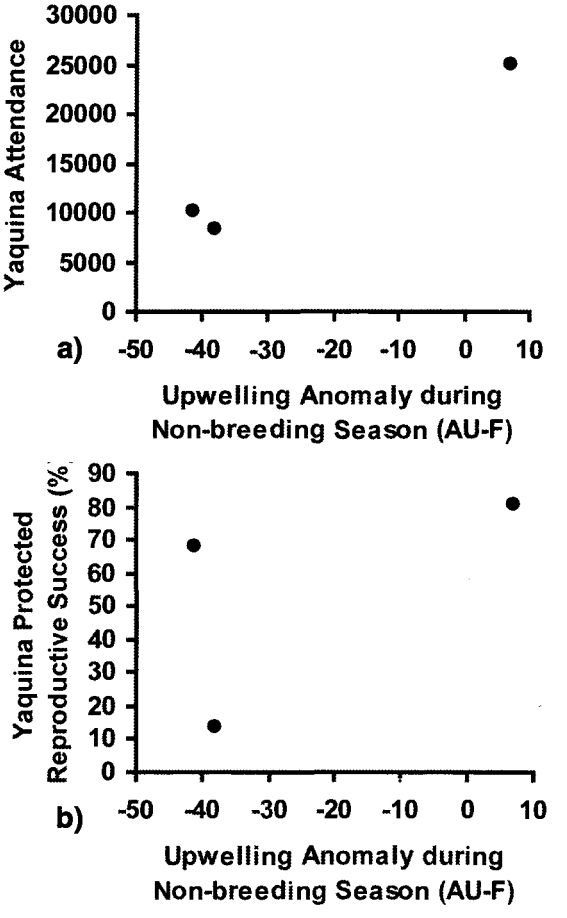

Figure 2.21. The apparent relationship between local average monthly upwelling anomaly (cubic meters per second per 100 meters of coastline; measured at 44°N 125°W; PFEL website) during the non-breeding season and the (a) colony attendance and (b) average reproductive success (in percent of pairs fledging a chick) of pairs of Yaquina Head Island common murres nesting in plots least affected by local predators. Data are from 1998 through 2000.

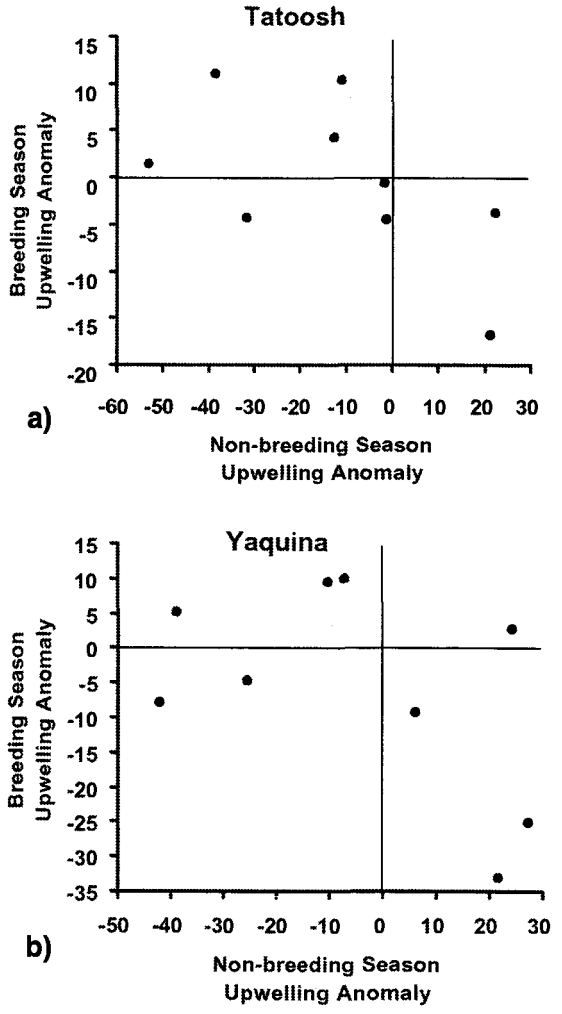

Figure 2.22. Average monthly upwelling anomalies during the breeding season as a function of average monthly upwelling during the non-breeding season for (a) Tatoosh and (b) Yaquina. Data are from 1992 to 2000.

the Washington coastline has numerous canyon features which should contribute to local upwelling, thereby increasing seabird and other upper trophic predator abundance, in fact, the Oregon coastline supports almost two orders of magnitude more murres. Additional analyses, perhaps using the relationships discovered herein between physical forcing and seabird response as a starting point, need to be explored with decades to century-long physical datasets (as biological datasets on seabird demography are not directly available).

Conclusions

The role of temporal variability of physical forcing in the nearshore is a dominant research theme throughout the nearshore component of PNCERS. Coastal surveys off Willapa Bay and Grays Harbor showed that coastal phytoplankton respond rapidly to variation in coastal upwelling, forming a dense bloom upon the onset of upwelling winds. These surveys also showed that planktonic larvae are influenced by variation in winds. Weakly swimming larvae were advected offshore during upwelling periods, perhaps away from inshore nursery areas. Strongly swimming larvae were able to remain inshore despite the offshore transport associated with upwelling. Simulation modeling shows how various vertical swimming behaviors could result in retention in the nearshore in the face of observed current patterns. At a larger temporal scale, analyses of trends in seabird reproductive success and coho salmon survival showed that interannual variability in upwelling explains variability in production of upper trophic levels. These two studies also showed that seasonal and event-scale processes are important. Winter conditions were found to be equally or more important than spring conditions for predicting seabird and coho production. Timing of the spring transition and daily variability in spring upwelling winds, both event-scale processes, influenced coho survival along with mean wind strength.

Currents and water properties are similar over relatively large distances along the coast and are reasonably predictable, given information about the coastal wind field. The results above show how coast-wide processes can impact phytoplankton, planktonic larvae, seabirds and salmon. Mesoscale features embedded in the coastal environment are also important for ocean productivity. For instance, acoustic surveys off Washington and Oregon show that plankton and fish biomass density is greater over ocean canyons than over the surrounding shelf areas. The results of the seabird study suggested that the Juan de Fuca canyon, immediately north of Tatoosh Island, produces localized upwelling which may buffer breeding seabirds from the influence of negative regional signals.

In addition to mesoscale spatial variability, alongshore gradients in environmental forcing occur in the Pacific Northwest. For example, the duration of coastal upwelling decreases towards the north whereas the strength and occurrence of winter and spring storms increases toward the north. In addition, the Washington coast is indented with numerous canyons, whereas

the Oregon coast is not. PNCERS researchers have begun to address the role of latitudinal variability. Acoustic surveys off Washington and Oregon show differences in depth and abundance of plankton and fish with latitude. Seabird population abundance and reproductive success also vary between Washington and Oregon colonies. However, linkages between these patterns and alongshore gradients in the environment are not clear. Future analyses that build on the relationships between physical forcing and upper trophic level responses summarized here will help establish these linkages.

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Biophysical Dynamics in Pacific Northwest Estuaries ..... Chapter 3

Curtis Roegner, David Armstrong, Brett Dumbauld, Kristine Feldman, Donald Gunderson, Barbara Hickey, Chris Rooper, Jennifer Ruesink, Steve Rumrill, and Ronald Thom

Physical forcing

The biophysical characteristics of Pacific Northwest (PNW) estuaries vary strongly on several temporal scales related to dominate physical forcing mechanisms. Tidal forcing causes mixing and the direct advection of materials within the system as well as transport of materials between estuary and ocean. Density differences cause subtidal circulation patterns. Wind forcing induces coastal upwelling/downwelling, strongly influences estuarine-nearshore exchange, modifies estuarine circulation patterns, and affects the distribution of coastal larvae and phytoplankton advected from the nearshore to various subregions of the estuary. Seasonal variation in wind stress and precipitation induce strong variation in salinity structure and flushing rates. Climatic-scale variation, particularly ENSO events, has large impacts on the ocean circulation and thermal structure. We find evidence for all these scales of variability, including a strong El Niño from fall of 1997 through spring of 1998, in the biophysical processes in the PNCERS study estuaries. There are several important general physical characteristics of PNW estuaries:

First, large seasonal variation occurs in most physical oceanographic parameters. In the summer dry months, water properties in PNW estuaries are controlled primarily by processes occurring in the adjacent ocean rather than by estuarine-riverine processes. These coastal processes are large scale, typically reflect an upwelling regime, and affect all PNW estuaries. For example, time series of temperature data collected simultaneously from estuaries separated by over 400 km demonstrate that both respond to upwelling/downwelling wind cycles in a similar manner. 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, up to the spring transition, weather patterns largely result in downwelling along the Pacific Northwest shelf, and may have higher variability along the coast depending on the location of the jet stream. For example, storms may occur off Washington but not off southern Oregon. During these periods, similar habitats in different estuaries may be subjected to greater differences due to both offshore forcing and the increased importance of the particular river flow patterns.

Second, there is a strong link between coastal upwelling/downwelling and estuarine-ocean material transfer (Figure 3.1). The type of water present at the mouth of the estuary during flooding tides reflects the nature of water available near the coast at that time. The biophysical properties of that water (temperature, salinity, nutrient levels, and phytoplankton content) are largely gov-

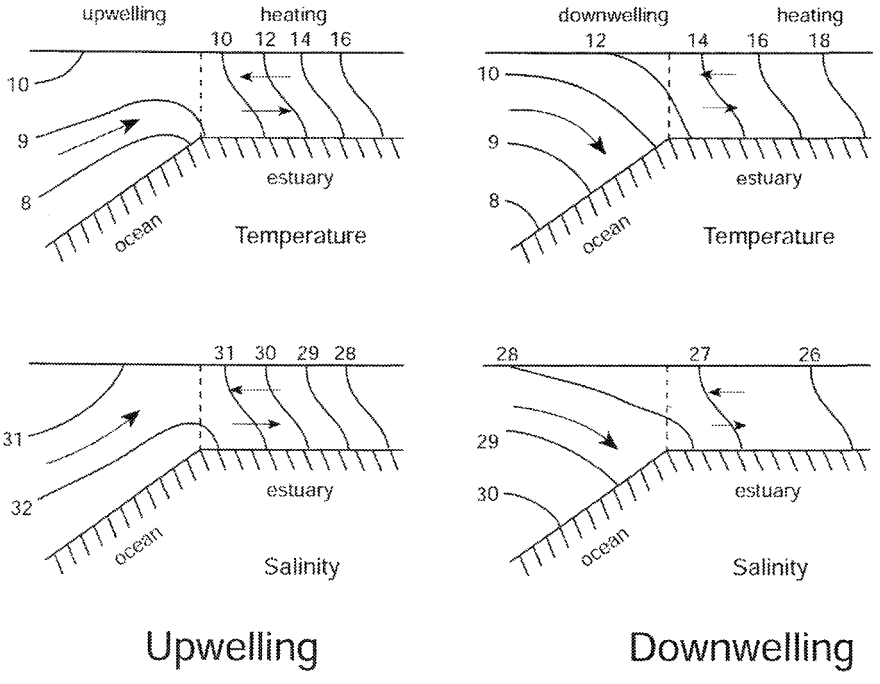

Figure 3.1. Schematic illustrating baroclinic coupling processes between the coastal ocean and a coastal plain estuary during upwelling and downwelling events for a low river flow, summer period in an eastern boundary system. From Hickey, Zhang, and Banas (2000).

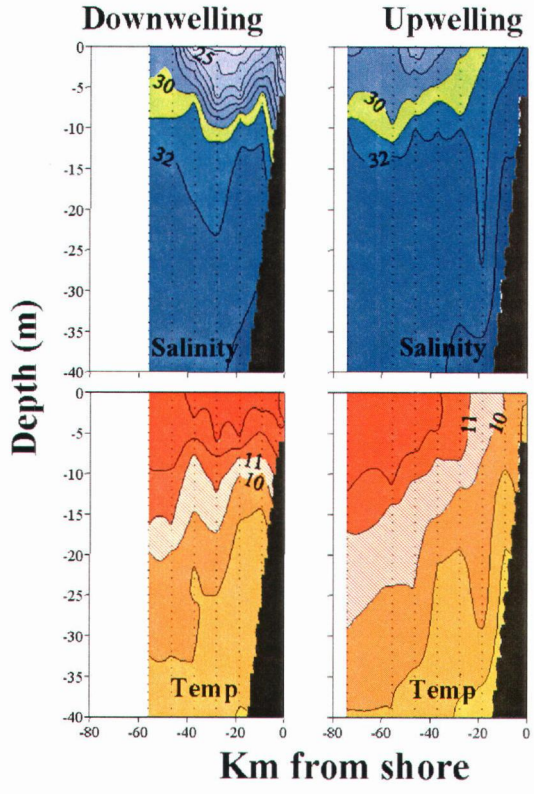

Figure 3.2. Cross shelf transects of temperature and salinity during downwelling (left) and upwelling (right) conditions off the Washington coast. The seafloor is shaded dark gray. Note the presence of the Columbia River Plume at the coast during downwelling, and the vertical isotherms and isohalines during upwelling.

erned by wind-induced coastal upwelling or downwelling. During upwelling, surface waters move offshore and colder, higher salinity, nutrient-rich water is moved upward within a few kilometers of the coast (Figure 3.2). During downwelling, surface waters move onshore and warmer, lower salinity, 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 present at the mouth of the estuary at the onset of a particular flood tide event (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.

Third, the Columbia River plume has a direct effect on estuarine circulation in Washington estuaries but a lesser or no effect in Oregon (particularly the southern estuaries such as Coos Bay). During periods when ambient coastal flow is to the north (as typically occurs in winter), the plume tends north or northwest off the Washington coast; conversely, during periods of southward ambient flow (as typically occurs in summer), the plume tends to the southwest off the Oregon coast well seaward of the shelf. The plume orientation is rapidly changed in accordance with variation in the equatorward wind stress. In particular, the plume thins and moves offshore during periods of northerly winds that cause upwelling, and thickens and moves onshore during downwelling favorable winds. Plume water enters Washington estuaries during downwelling events and results in the unusual condition of a reversed salinity gradient, (higher salinity inside the estuary than in the immediate nearshore) (Figures 3.3 and 3.4). The plume water also tends to be nutrient-poor. Changes in the volume and/or location of the Columbia 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 cause significant differences in conditions in the physical environment in estuaries north and south of the Columbia River.

Fourth, the flushing rate of PNW estuaries, especially during the summer growing season, is likely to depend more on oceanic exchange processes than on river-driven exchange processes. 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 North American coastal-plain estuaries, PNW estuaries are driven by strong tidal stirring and relatively weak summer river flow. 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 indirect ways (e.g., by frictionally retarding tidal flows and generating large residual tidal eddies).

Finally, nutrient supply to PNW estuaries is determined primarily by upwelling from the adjacent deep ocean. Input from rivers and/or the effects of the spring-neap cycle with respect to mixing, are comparatively negli-

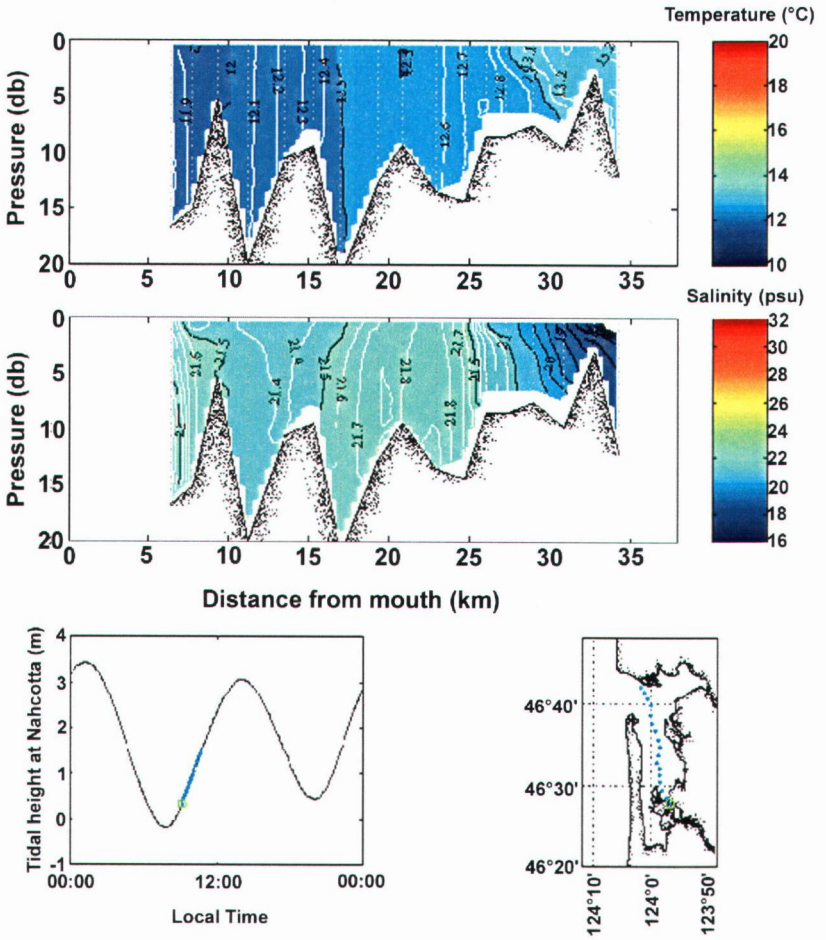

Figure 3.3. Temperature and salinity for main-channel Willapa Bay transects in May 2000 showing a strong Columbia River plume intrusion. This state is characterized by a well-mixed water column, salinity reversals in the along-channel gradients, and low salinity at depth.

gible. There is an undetermined degree of benthic-pelagic recycling within the estuary. Thus, interannual variability in estuarine primary productivity is largely determined by interannual variability in the coastal ocean, which varies on El Niño and much longer period timescales such as Pacific Decadal Oscillation (PDO).

Estuarine-nearshore links in phytoplankton supply

Determining the source of new phytoplankton production is crucial for understanding estuarine food webs. In most estuaries studied to date, the supply of phytoplankton appears to be autochthonous production supported by nutrient additions from riverine pathways. Estuaries of the PNW deviate from this pattern. In Coos Bay and Willapa Bay, the wind-induced coastal upwelling-downwelling cycle influences estuarine phytoplankton by two potential routes. During upwelling events, nutrients brought into the estuary with the upwelled water can stimulate autochthonous blooms. Depending on flushing rates, a local bloom may be generated and be transported up the estuary with the patch of water at a rate of approximately 10 km per day. During downwelling events, coastal phytoplankton blooms are transported to the coast and pulled into the estuary through tidal advection. The estuarine-nearshore link in phytoplankton supply distinguishes PNW estuaries from most other systems studied to date.

The processes leading to the import of coastal phytoplankton blooms were elucidated during a cruise on the *Lady Kaye* off southern Washington in 1999 when we measured the physical oceanography and chlorophyll distribution in Willapa Bay and the adjacent coastal ocean during a relaxation-upwelling-relaxation wind cycle. Coastal conditions were measured shipboard during a series of cross-shelf transects, while instrument moorings simultaneously recorded biophysical properties at estuarine sites. The results confirm that estuarine water quality parameters were determined by the nearshore ocean properties, which were in turn forced by variation in wind stress.

During the study period, southerly winds produced downwelling conditions which forced the Columbia River plume against the coast, and low salinity water was advected into Willapa Bay by tidal action (Figure 3.5 and 3.6). This water was relatively low in chlorophyll (< 2 mg m^{-3}). As the winds switched to equatorward, coastal upwelling ensued and the Columbia River plume was replaced by cold, high salinity water nearshore. A phytoplankton bloom exceeding 10 mg m^{-3} was generated on the shelf, 10 to 20 km from the estuarine mouth. As upwelling winds relaxed, the bloom was apparently advected across the shelf to the coast and subsequently

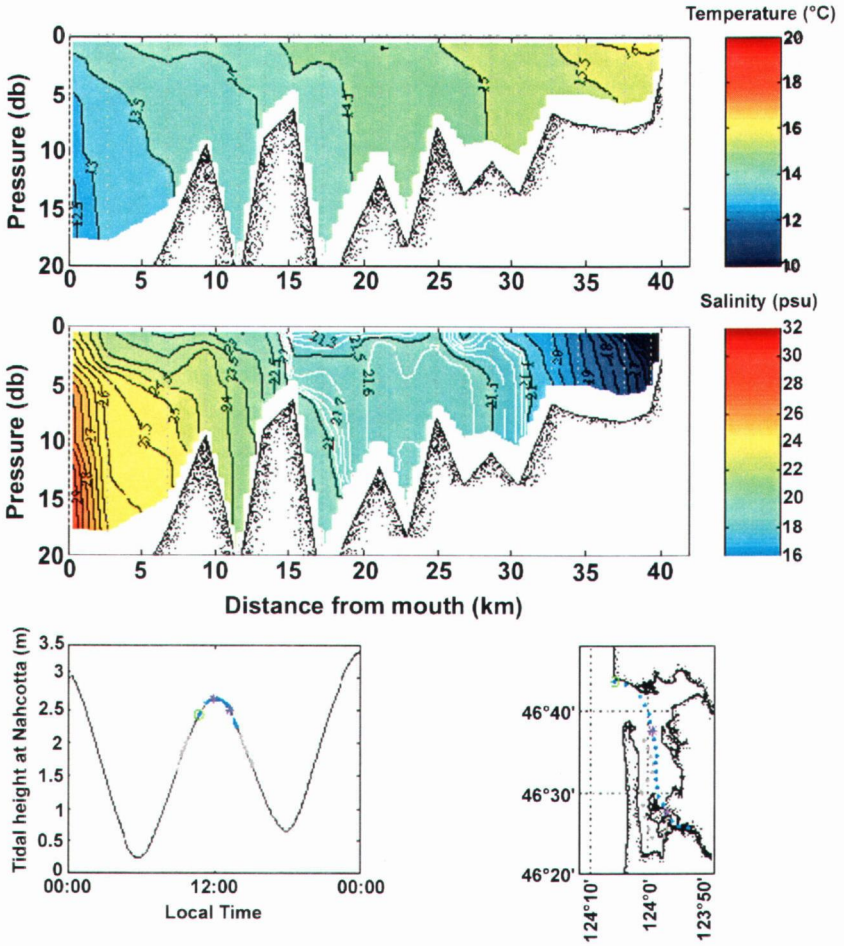

Figure 3.4. Temperature and salinity for main-channel Willapa Bay transects during an upwelling event. Intruding high salinity water will tend to flush the plume from the bay. Willapa can flip between the upwelling and downwelling states in a week or less, in response to the offshore winds.

into the estuary. Weak downwelling followed the relaxation event, and the Colombia River plume returned to the coast and mixed with the chlorophyll in the bloom water. Finally, low salinity, low chlorophyll plume water again dominated the estuarine signal. Most temporal variation in these parameters was in the tidal band, indicating the highly advective nature of estuarine tidal currents.

An excerpt of the estuarine mooring time series illustrates the close correspondence of salinity, fluorescence and tidal height (Figure 3.7). This confirms the coastal origin of the fluorescence signal. Note also the salinity reversals that accompany the plume intrusion. Given the variation of the estuarine signal during the upwelling-downwelling cycle, this coastally-derived phytoplankton is likely an important, yet episodic, food source for estuarine suspension-feeding fauna.

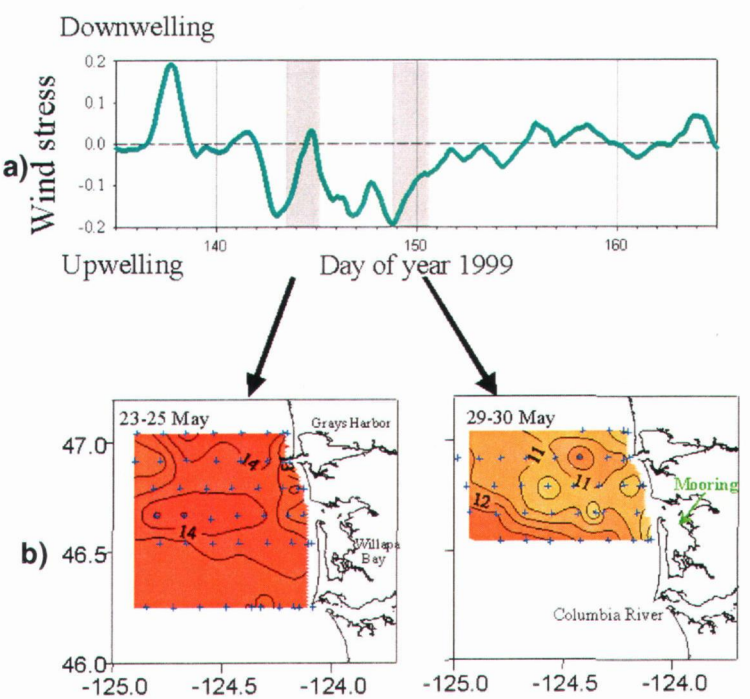

Figure 3.5. Effect of wind stress on sea surface temperatures (SST) in the nearshore zone. (a) Northward wind stress measured at the Columbia River buoy during the period surrounding the *Lady Kaye* cruise (gray bars). (b) SST values during downwelling (left) and SST values during upwelling (right). Note the location of the estuarine instrument mooring.

Benthic-pelagic coupling

Many benthic filter feeders feed on resources produced in the water column and transported to the benthos by estuarine currents. There is a strong link between pelagic production and the growth and biomass of the benthos, probably best exemplified in PNW estuaries by the exotic Pacific oyster (*Crassostrea gigas*).

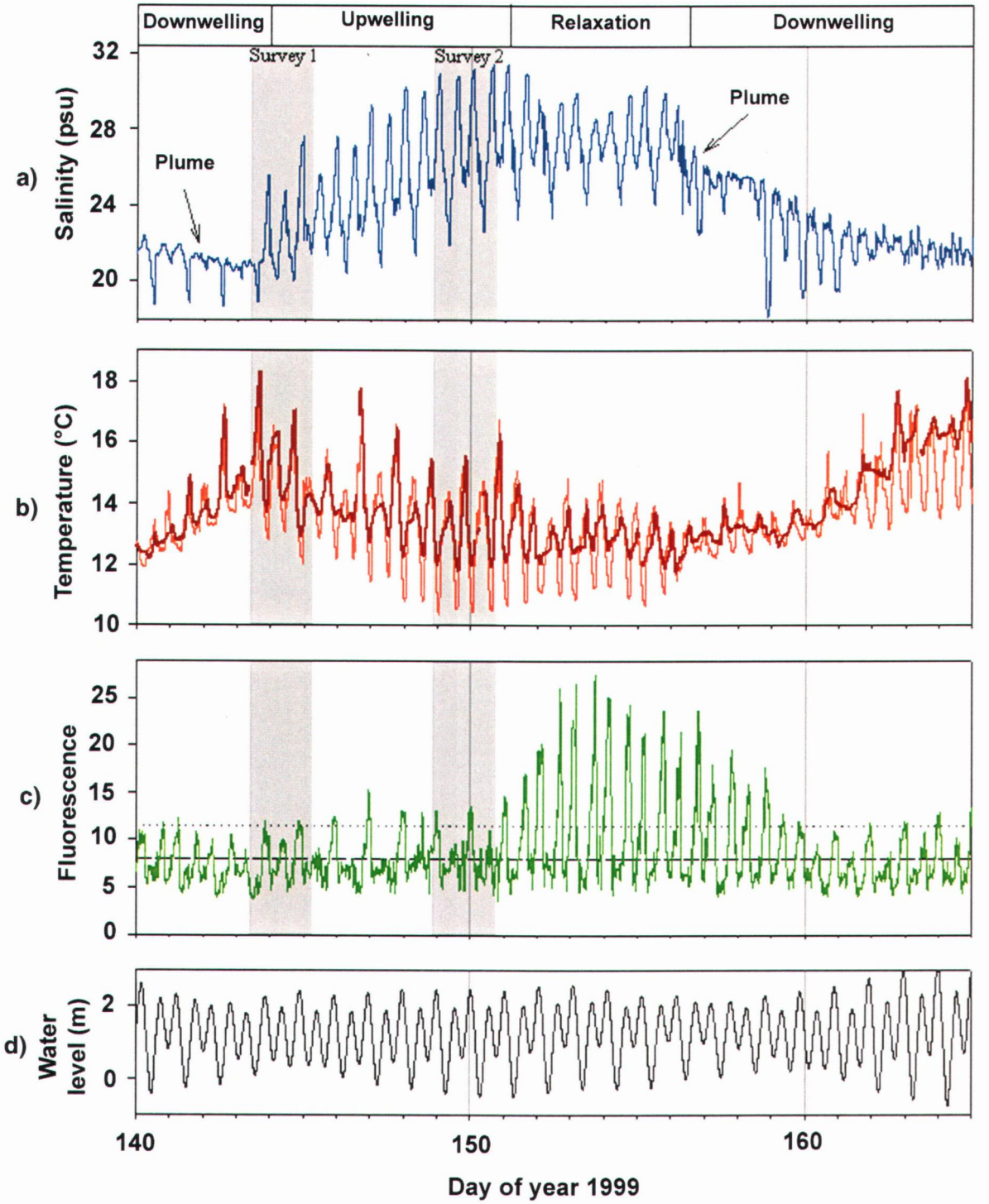

Figure 3.6. Time series of biophysical parameters measured at estuarine instrument moorings. (a) Salinity recorded at Bay Center. (b) Temperature recorded at Toke Point (brown) and Bay Center (red). (c) Fluorescence recorded at Bay Center. (d) Water level recorded at Toke Point. The origin of the water masses is labeled above.

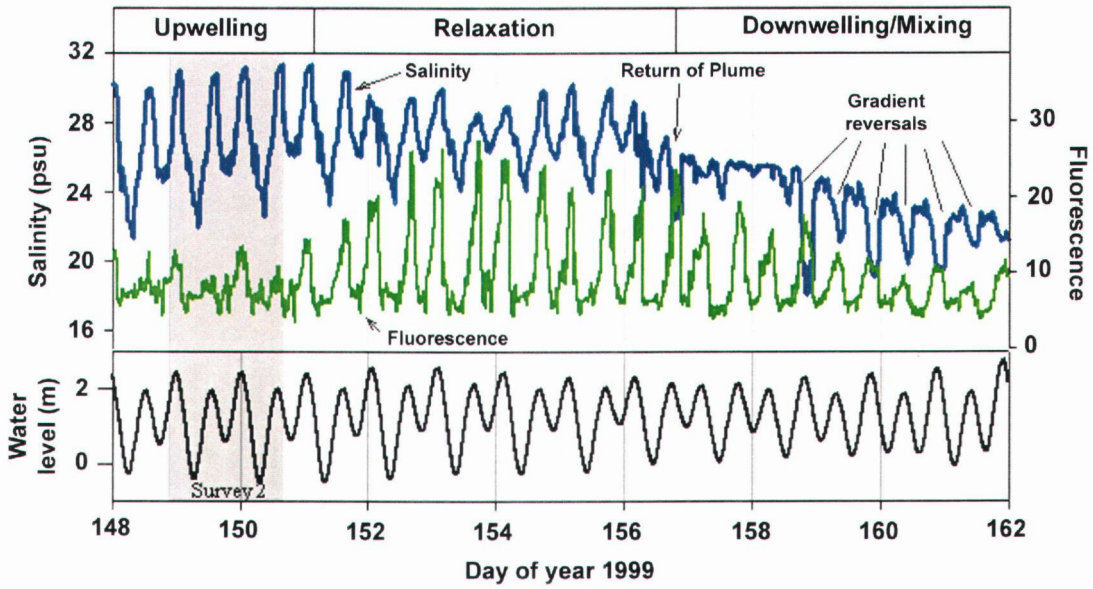

Figure 3.7. An excerpt of Figure 3.6 highlighting the transport of a coastal phytoplankton bloom into Willapa bay by tidal currents during the relaxation period. Fluorescence, salinity, and high tide signals are synchronous. Note also the salinity gradient reversals as the Columbia River plume returns to the estuary.

This is the dominant bivalve cultured in the PNCERS estuarine systems. In Willapa Bay, the primary production areas used in aquaculture are near the mouth of the estuary, suggesting an important role for marine resources in driving oyster production. Two data sets reinforce the apparent importance of marine resources for benthic production: long-term information on oyster condition indices at four sites in the northern half of Willapa Bay, and a transplant study examining oyster growth at multiple tidal elevations throughout the estuary.

Spatially-explicit information on oyster condition has been collected in Willapa Bay since the early 1950s (Figure 3.8). At Stony Point and Nahcotta, oysters have been collected by hand on a monthly basis, whereas oysters from Stackpole and Oysterville have been dredged. Condition Index (CI) is a quantitative measure of the "fatness" of an oyster relative to its shell size and is generally highest from June to August, when oysters have high feeding rates and prior to reproduction. A time series of the maximum condition index observed at each site during the period 1960 to the present reveals three important patterns (Figure 3.8).

First, there is a strong spatial gradient in oyster condition. CI values tend to decline with decreasing marine influence. CI at Stackpole, near the estuarine mouth, is generally higher than at Oysterville or Nahcotta, sites to the south and farther into the estuary.

Second, temporal variation in CI exhibits apparent negative correlations with ENSO events. Low CI is coincident with known El Niño years, particularly at Stackpole. Years of lowest CI are 1982-83, and 1997, which are also El Niño years.

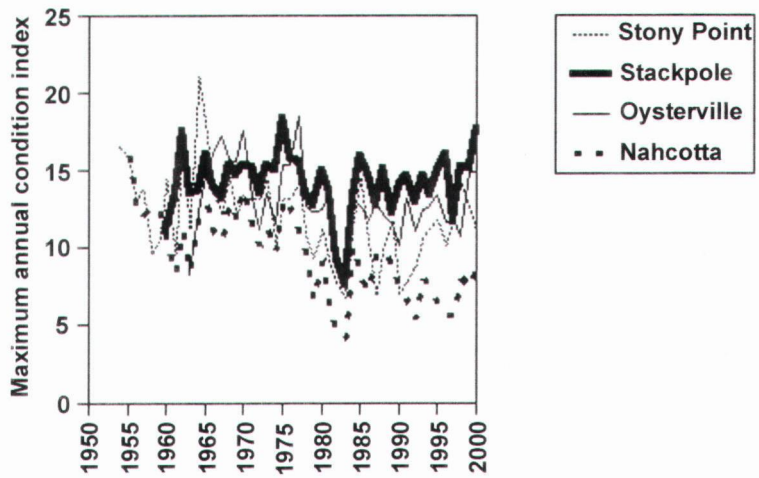

Figure 3.8. Condition index of oysters collected at four sites in Willapa Bay, 1954-2000 (from Washington Department of Fish and Wildlife). Graph shows maximum annual CI values.

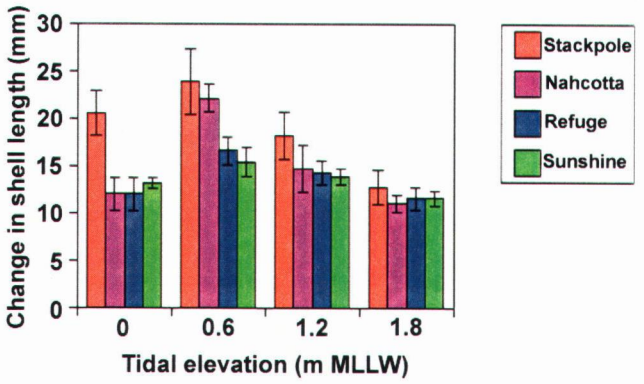

Figure 3.9. Growth rates (linear shell extension) of juvenile oysters transplanted to four locations in Willapa Bay, August to October 2000. Graph shows mean change in length ± s.e. Cultch at 0 m MLLW were near the substrate, and those at higher elevations hung in the water column.

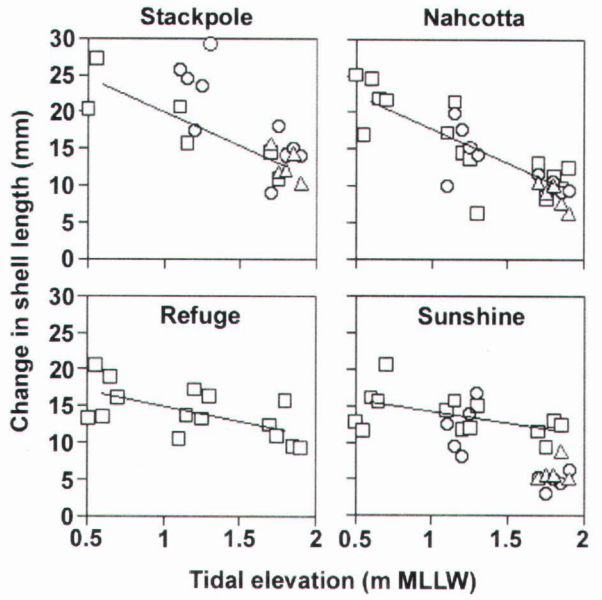

Figure 3.10. Growth rates of juvenile oysters transplanted to four locations in Willapa Bay, August to October 2000 as functions of tidal height and location.

Third, there is a declining long-term trend in CI at Nahcotta. CI's at Nahcotta were higher in the first part of the time series (10 to 15) relative to the latter part of the time series (5 to 10). This change may reflect a shift in the "fattening line" noted by oyster growers: north of this line, oysters can reach marketable size, and to the south they do not. Interestingly, the shift in CI at Nahcotta appears to occur in the late 1970s, at the same time as the shift from high to low offshore productivity associated with the PDO. However, oysters at other sites within Willapa Bay do not shift synchronously with those at Nahcotta. This reflects overall lower ocean productivity coupled with resource depletion within the estuary, with the result that oysters sited further from the estuarine mouth receive less food or lower quality food. Other possible causes include different collection methods (dredging at Stackpole and Oysterville) or the community interactions (e.g., densities of other filter feeders) that may have altered local food availability at Nahcotta over time.

We measured spatially-explicit growth of juvenile oysters in Willapa Bay during late summer 2000. Stackpole was the northernmost site, closest to the mouth of the bay. Approximately 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 (Refuge) was in the southwest. At each site, oysters on cultch were attached to posts at varying heights above the mudflat. Cultch hung just above the substrate (0 m MLLW) were almost always immersed, whereas those above the mudflat (+0.6 m, +1.2 m, and + 1.8 m MLLW) were immersed 80%, 60%, and 40% of the time, respectively. The experiment thus tested for growth differences along an exposure gradient and distance from the estuary mouth. Two important patterns are apparent (Figures 3.9 and 3.10).

First, there was a strong spatial position effect. For oysters near the substrate, growth rates were over 60% higher at Stackpole, close to the estuary mouth, than at other locations. For oysters 0.6 m off the substrate, growth rates at Nahcotta corresponded with spatial location, that is, intermediate growth rates at an intermediate distance from the estuary mouth.

Second, there was a strong vertical position effect. Oysters tended to grow better off-bottom than near the substrate, even though off-bottom oysters were more exposed to air. However, growth slowed at heights still further above the substrate, probably due to reduced feeding time and increased stress. The differences in growth rates among locations disappeared high in the water column. At +1.8 m, oysters grew at equivalent rates regardless of their spatial location within the estuary.

Together, these patterns suggest that oceanographic conditions controlling the supply of marine-derived re-

sources interact with local topography (and tidal elevation) to determine benthic productivity. Additional likely influences include local flow conditions, benthic-derived food concentration, and gradients in salinity and temperature.

Larval Supply

Many of the important invertebrate species utilizing estuarine habitat have pelagic larvae, and most of these are apparently exported from the estuaries and develop in the coastal ocean. The population dynamics of these species can depend strongly on the relative numbers of mature larvae that return to estuarine systems. Variation in larval supply can limit recruitment levels.

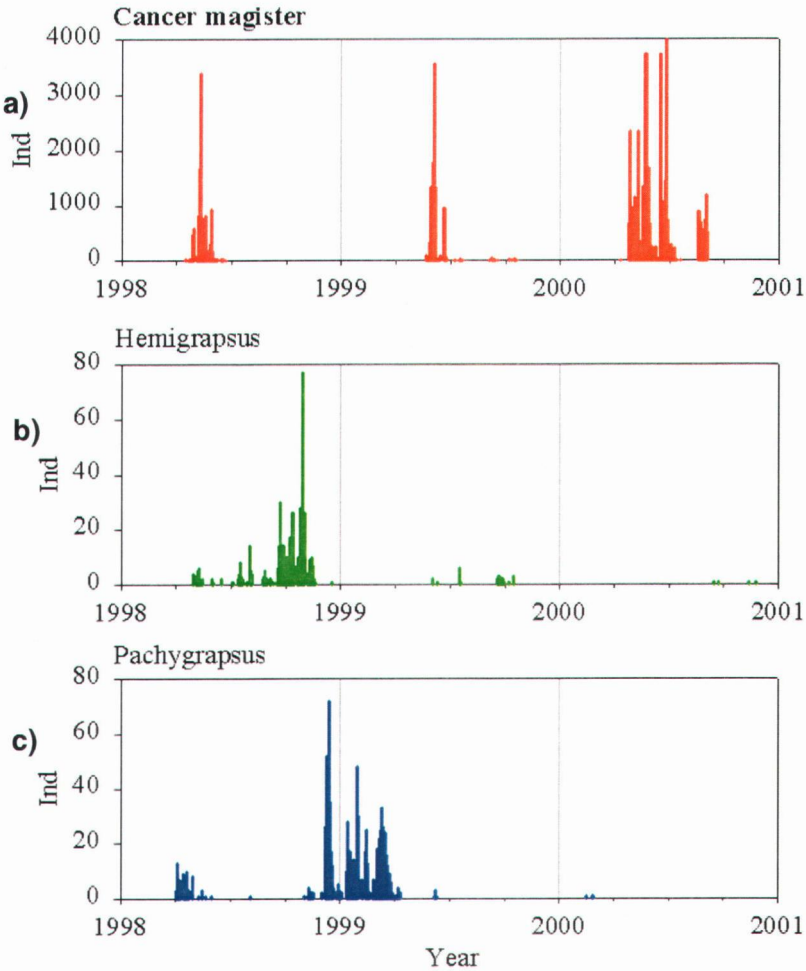

Figure 3.11. Time series of three species of brachyuran crab megalopae sampled from light traps at the mouth of Coos Bay 1998 to 2000. (a) *Cancer magister*. (b) *Hemigrapsus oregonesnsis*. (c) *Pachygrapsus crispus*. Evident are the seasonal differences in the recruitment period

The light trap deployments have continued to provide insight into the recruitment dynamics of brachyuran crabs. In Coos Bay, we now have a continuous record spanning from March 1998 to the present from the Charleston site (Figure 3.11). In 1999, an additional array of light traps was deployed from March to July in Grays Harbor and Willapa Bay (Figure 3.12). This period encompassed the *Lady Kaye* cruise described above. All these traps were located near the estuarine mouths and recorded recruitment events driven by estuarine-nearshore exchange. The results from the light trap studies indicate both species-specific and interannual variation in recruitment patterns are occurring. Four major results are clear.

First, crabs recruit to estuaries in distinct pulses. The number and timing of these recruitment peaks varies amongst species and years. For example, annual recruitment of red rock crab (*Cancer productus*) in 1998 was confined to a 2 day window (PNCERS 1999 Annual Report). In contrast, most species recruit over a broader period composed of several pulses which last 4 to 10 days. We interpret these pulses of enhanced abundance as signaling the advection of oceanic larvae into the estuary and their subsequent settlement to the benthos.

Second, the timing of the recruitment period differs among species, and, in general, brachyuran megalopae can be found at all times of the year. For example, grapsid crabs recruit predominantly in the autumn and winter, when seasonal wind patterns generate downwelling conditions. *Cancer* species recruitment occurs after the spring transition to upwelling conditions. Megalopae of the lined shore crab (*Pachygrapsus crassipes*) are similar in size and swimming ability to Dungeness crab (*Cancer magister*) megalopae; this interesting contrast will be revealing when the timing of abundance is analyzed in relation to the seasonal variation in oceanography recorded from instrument moorings. Additionally, we have also discovered that, while the majority of *C. magister* megalopae recruit between April and June, pulses of megalopae were sampled as

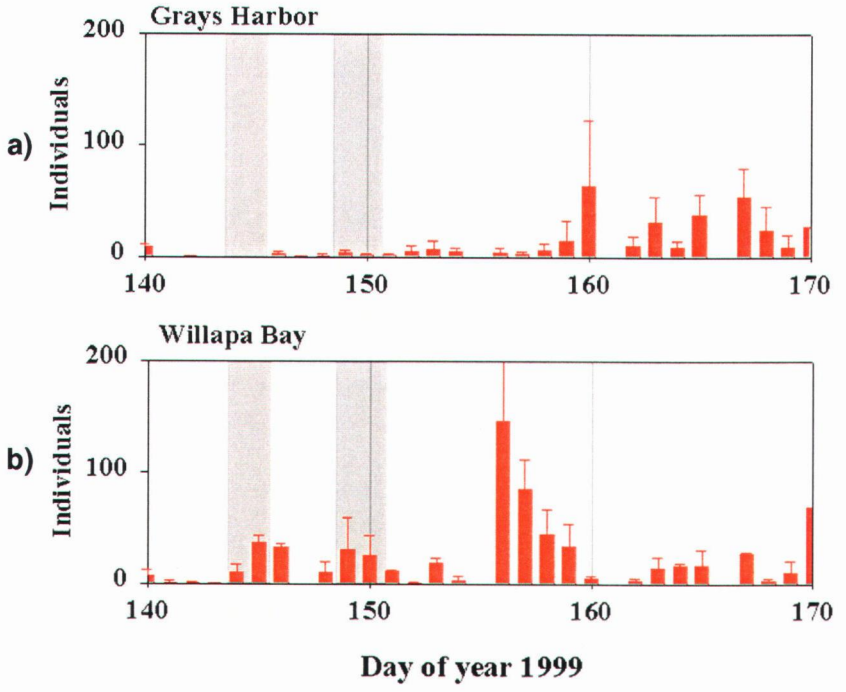

Figure 3.12. Time series of *Cancer magister* megalopae (+ sd) sampled from light traps in A. Grays Harbor and B. Willapa Bay during a period surrounding the *Lady Kaye* cruise (gray bars), May 1999. Recruitment was not synchronous between estuaries.

late as November. We do not at present know the significance of these late arriving megalopae.

Third, there is large interannual variation in the magnitude of larvae entering PNW estuaries. *C. magister* megalopae exhibited similar abundance patterns in 1998 and 1999 but exhibited a much broader temporal distribution in 2000, including a large autumn pulse. In contrast, the grapsids *Hemigrapsus oregonensis* and *Pachygrapsus crassipes* failed to recruit to Coos Bay during 1999 or 2000, and *Cancer productus* megalopae did not occur during summer 2000. These are examples of recruitment limitation due to lack of larval supply. We suspect large-scale ocean processes such as the 1997-1998 ENSO event affected larval transport or survival in the ocean. These climatic effects appear to influence different species in different ways.

Finally, recruitment pulses are not synchronous between estuaries (Figure 3.12). Light traps deployed in Grays Harbor and Willapa Bay did not show similar temporal patterns of larval abundance despite a distance of less than 50 km. We hypothesize the interaction of plankton patch size and estuarine tidal prism influences the timing of larval delivery to estuaries. Further insight into the mechanism of larvae delivery to estuaries was generated by examining the light trap data in Willapa during the days surrounding the *Lady Kaye* cruise. *C. magister* recruitment pulses occurred during both upwelling and downwelling conditions, but the largest pulse of the series occurred in synchrony with the advection of the Columbia River plume into the estuary. Our ocean studies confirm that *Cancer* megalopae are often found in plume water. Larval swimming behavior appears to affect dispersal: larvae are not simply passive particles.

Most brachyuran crabs and fishes undergo larval development in the coastal ocean and recruit to estuaries to undergo metamorphosis into the juvenile form. In contrast, other species, apparently, are retained within the parental estuary throughout larval development. One example is the exotic Pacific oyster (*C. gigas*). In Willapa Bay, recruitment of oysters is highest at sites further south, and few oysters recruited to the site near the estuary mouth (Figure 3.13). Note that this distribution is opposite from the best growing areas. This pattern is consistent with retention, since no oyster reproduction occurs for many hundreds of kilometers around this area, and is probably due to a com-

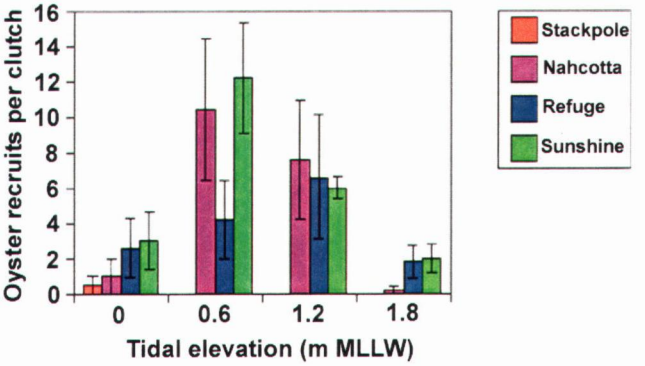

Figure 3.13. Spatial pattern of oyster recruitment in Willapa Bay, late summer 2000. Graph shows mean number per cultch ± s.e. (n=5 in most cases). Cultch at 0 m MLLW were near the substrate, and those at higher elevations hung in the water column.

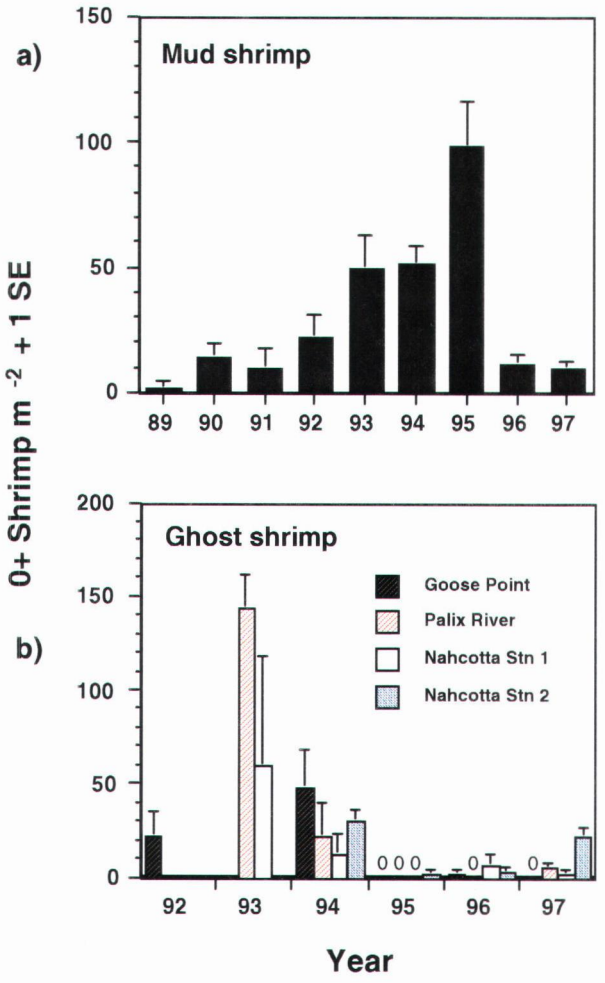

Figure 3.14. Recruitment variation in thallasinid shrimp. (a) Mean density (± se) of 0+ mud shrimp (*Upogebia pugettensis*) at the Cedar River station from 1989-1997. (b) Mean density (± se) of 0+ ghost shrimp (*Neotrypaea californiensis*) at four locations in Willapa Bay from 1992-1997. The absence of a bar indicates that no samples were taken, whereas the presence of a "0" indicates samples were taken, but no 0+ ghost shrimp were found at those locations (Source: Feldman et al. 1997).

bination of estuarine circulation and larval behaviors. Critically, the flushing rate of the estuary must not greatly exceed the development time of the larvae. The lack of analogous naturally reproducing oyster populations in Coos Bay and Grays Harbor likely reflects the shorter residence times of these estuaries.

The time series of recruitment of other species of benthic invertebrates lend credence to the notion that variation in the magnitude and timing of recruitment pulses is reflected in population parameters. Densities of newly settled burrowing shrimp show wide ranges in density presumably determined by larval supply (Figure 3.14). Trawl survey data indicates that English sole also display very different temporal recruitment patterns between PNCERS estuaries (see below). Some of this variation within an estuary is probably due, in part, to forces that distribute larvae to various estuarine subregions. Cancer megalopae and other larvae may concentrate in flood-tide axial convergence fronts that track trajectories of prevailing winds. Larval crab density in these "conduits" is much higher than in water landward or seaward of these structures, and so the subregion receiving larval supply on a particular day depends, in part, on the wind stress. These circulation patterns determine, in part, whether larvae reach high quality or inferior benthic refuge habitat. Larval swimming behavior also plays a role in these distributional patterns, and is critical for habitat selection during the settlement phase. Survival of juveniles appears to depend to a large degree on whether they reach a suitable nursery site.

Habitat Quality and Secondary Production: The examples of Crab and Sole

A major feature of the PNCERS program has been work to describe and characterize the dominant habitat types that may support variable species mixes contributing to secondary production within the systems. Particularly interesting in this respect are species that use the estuaries as nurseries during part of their life cycle, in light of the habitat features that enhance or constrain survival and production. Dungeness crab and English sole have been well-studied since the mid-1980s, and remain as major research elements within PNCERS to date. Several aspects of recruitment, life history, habitat utilization, and production distinguish these meroplanktonic species:

Tens to hundreds of millions of larvae recruit to estuaries in mid-spring to early summer at very small individual size and weight (a few mg dry wt). Mortality is high across many habitats, but so too is growth. This results in tremendous production and an increase in biomass of several orders of magnitude. Both crab and sole increase in population biomass to the point of being major fractions of the grazing epibenthic fauna within estuaries (other dominate groups such as burrowing shrimp and bivalves feed at lower trophic levels). Both species emigrate from the estuaries as larger, older juveniles thereby affecting large export of in situ estuarine production back to the nearshore zone. The mag-

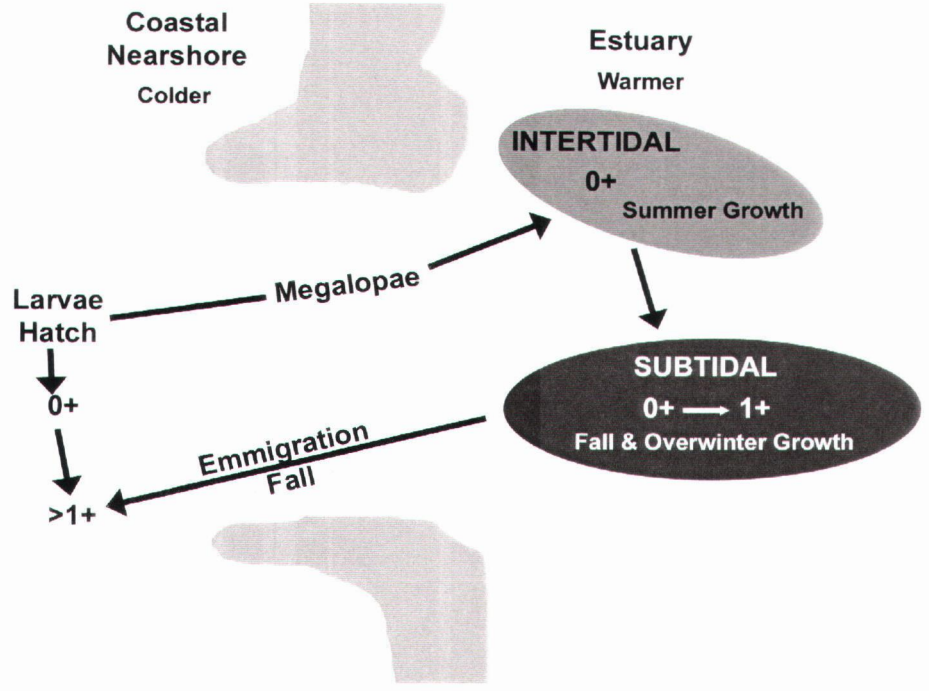

Figure 3.15. Schematic representation showing generalized movements of juvenile Dungeness crab to and from Grays Harbor and the nearshore environment. Some larvae settle directly in the nearshore, while others are transported into the estuary. Megalopae settle broadly within the estuary, but small EBP survive primarily in intertidal refuge habitat. Larger crabs (1+, >100 mm) remain offshore, enter the fishery, and reproduce.

nitude of juvenile production in the large Washington estuaries provides a significant fraction of the total year class strength (compared to juveniles developing directly in the nearshore zone) and eventually contributes to coastal commercial fisheries; more so in the case of English sole than Dungeness crab. There are similar sets of features across PNCERS estuaries that account for relatively high/low abundance and production of both crab and sole. Most notably are higher summer temperatures in estuaries than nearshore; refuge habitat for early benthic phases (EBP) of small, newly settled juveniles; high seasonal production and diversity of prey; and relatively rapid attainment of a "size refuge" that constrains predation to a few remaining predators (i.e., after a couple of months of rapid growth, surviving crab and sole are generally too big for most predators other than a few fish and older crab).

These species of crab and flatfish represent very transient populations that arrive at very low levels of biomass, graze extensively on autochthonous production, then leave en masse to complete life cycles in the nearshore ocean. But within the estuary there are some important differences in required habitat and residence time.

English sole that recruit in spring-early summer grow so rapidly that they emigrate the same year as larger 0+ in fall. Many fish arrive as late pelagic larvae, but in some years large numbers immigrate into estuaries shortly after settling directly offshore. Fish begin to exit at a size of approximately 80 mm, and fish >100 mm are uncommon in the system. Work by Gunderson and colleagues during the 1980s estimated that abundance of English sole in Grays Harbor and Willapa Bay was always much higher than in a substantially larger adjacent area nearshore. Midsummer abundance was ranked as Willapa Bay > Grays Harbor > nearshore. The two estuaries support approximately 2.5 times more juvenile fish than computed for an adjacent nearshore area approximately 7 times larger than the combined estuarine area. Shi et al. (1994) estimated that 78-98% of juvenile fish in the 1985-88 year classes (mid summer size mode approximately 55 mm) were in the estuaries.

Dungeness Crab have very different ontogeny in several respects within estuaries. Following larval recruitment within the systems, crab production is largely predicated on spatial features of the systems, and there is marked contrast in spatial distribution and habitat use between small early benthic phase (EBP) juveniles (early 0+ age class) and older juveniles.

0+ Juveniles: A generalized nearshore-estuarine ontogeny for larvae-juveniles is shown in Figure 3.15. As described above, hundreds of millions of megalopae may be advected into estuaries and distributed widely across estuarine subregions. While megalopae settle and metamorphose in both intertidal and subtidal habitats, it seems that mortality is extremely high in the latter. Very small size (approximately 7 mm) makes these crabs highly vulnerable to predation by a number of fish species,

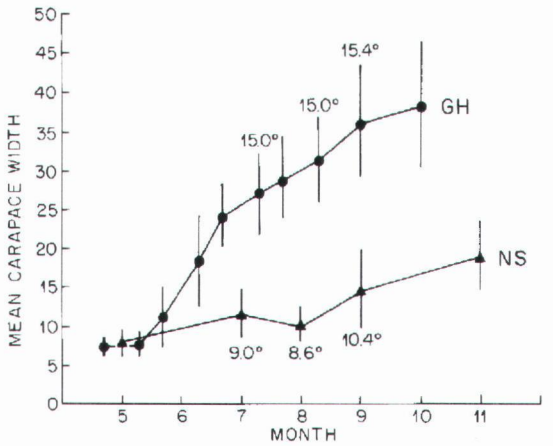

Figure 3.16. Comparison of juvenile Dungeness crab growth during the first year inside an estuary (Grays Harbor) and nearshore-outside the estuary. Differences in growth may be due to temperature differences shown (Armstrong and Gunderson 1985).

birds, and older crab (cannibalism). Armstrong et al. (1995) found that staghorn sculpin shift a large fraction of their diet to 0+ crab immediately as cohorts settle, but only consume up to the fourth instars, at which a size refuge is acquired.

Our interpretation of EBP crab dependence on refuge habitat is that most survival occurs within intertidal shell material comprised predominately by two exotic species: 1) the eastern soft-shell clam (*Mya arenaria*), which occurs as extensive "death assemblages" and supports initial recruitment densities >100/m^2, and 2) Pacific oyster habitat created through aquaculture activities and also as purposeful habitat constructed by the Army Corps to mitigate subtidal loss of older age crab during dredging. Shell, and to a lesser extent eelgrass, are limiting habitats within intertidal zones. These habitats provide both shelter and support prey such as amphipods, polychaetes, and small bivalves. A blend of processes and events, including wind forcing (see above) and number and spacing of recruitment pulses within a season, determine the extent to which these habitat are saturated (or not) and the number of cohorts that might be supported per year.

Older Juveniles: After growth within intertidal habitat for approximately two months, EBP crab (J4-5) are between 20-30 mm; too big for most shell matrices, but also large enough to escape many predators. Juveniles emigrate from intertidal to subtidal habitats and are sampled in the trawl surveys (see below) at a size mode of approximately 35-40 mm. Interestingly, the distinct growth advantage of estuarine recruitment (in contrast to direct settlement nearshore) is a disparity in mean size of approximately 40 mm and 15 mm, respectively, by September (Figure 3.16). This imparts huge survival advantage to the larger crab of the year class. 0+ crab overwinter in the subtidal and continue growth through the following spring and second summer (a year longer than English sole). At that time, and around a size of 100 mm and greater, crab emigrate from the estuary to the nearshore.

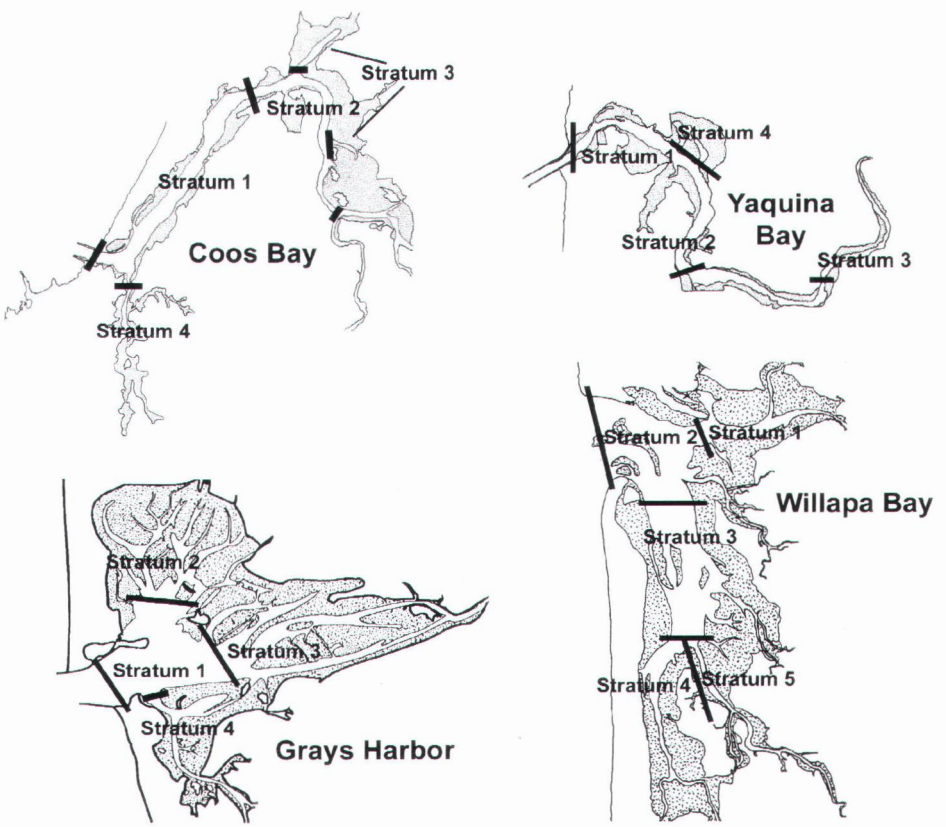

Figure 3.17. PNCERS estuaries and stratum divisions utilized in trawl surveys 1998-2000.

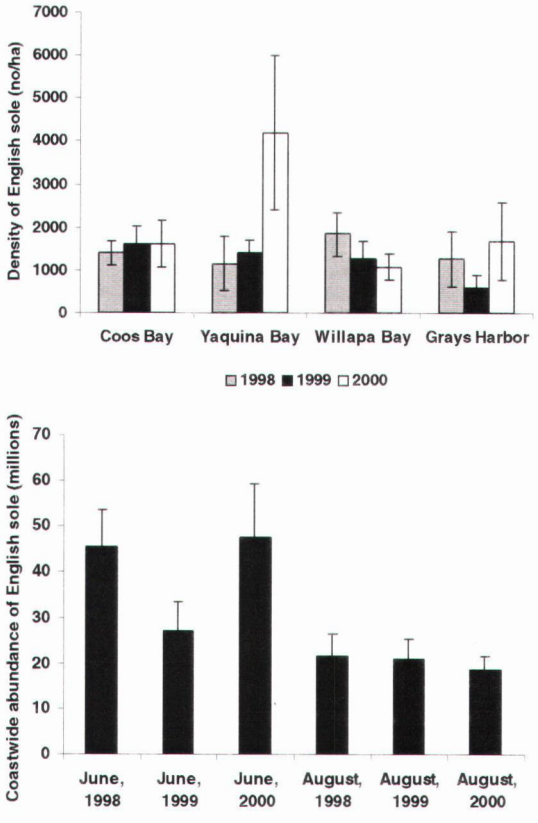

Figure 3.18. Density of English sole (± se) for each study estuary and year (top). Abundance of English sole summed over all estuaries for each of the trawl survey periods (bottom).

As motivated by these earlier studies, the PNCERS program examines the spatial/temporal distribution and abundance of dominate macrofauna in Oregon and Washington coastal estuaries. Benthic trawl surveys were conducted during June and August in Coos Bay (CB) and Yaquina Bay (YB), Oregon, and in Willapa Bay (WB) and Grays Harbor (GH), Washington using a stratified random survey design. Stations were sampled in each estuary within 4-5 strata (Figure 3.17). Catch per hectare was determined for all fishes and crustaceans collected. Density and size compositions were obtained for age 0+ and age 1+ Dungeness crab and all species of flatfish, most notably juvenile English sole. Mean density and abundance for each stratum and the entire subtidal area in a given estuary were calculated according to stratified random sampling formulae. Major findings, patterns and trends include:

First, English sole densities have been higher in Oregon estuaries compared to Washington estuaries during the last two field seasons (Figure 3.18). Densities ranged from 0 to >35,000/ha over all estuaries and months, but significant interannual differences do occur; for example, average densities in GH in 1999 were significantly lower than most of the other year-estuary combinations. Mean English sole density was typically between 1200-1800/ha in most estuaries both years, but was less than half this range (600/ha) in GH during summer 1999, and double this range (4000/ha) in YB during summer 2000. Although June abundance estimates for all estuaries combined ranged from approximately 30 to nearly 50 million fish in 1999 and 2000, respectively, abundance by August is more stable at approximately 20 million in all three years.

Second, densities of age 0+ Dungeness crab in GH and WB were much higher during 1998, during the el Niño period, compared to 1999 and 2000 (Figure 3.19). Densities of age 0+ Dungeness crab in the subtidal are highly variable among estuaries, months, and years of sam-

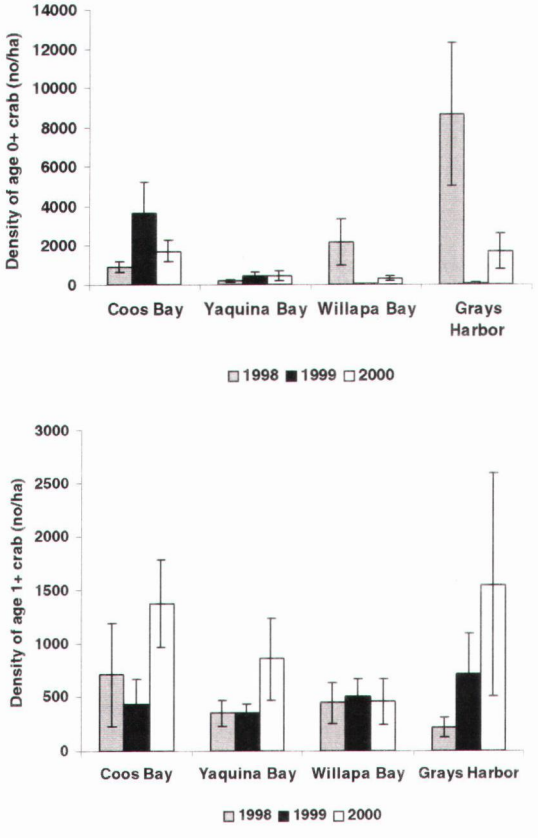

Figure 3.19. Density of age 0+ Dungeness crab (± se) for each PNCERS estuary 1998-2000 (top). Density of age 1+ crab (± se) for PNCERS estuaries in 1998-2000 (bottom).

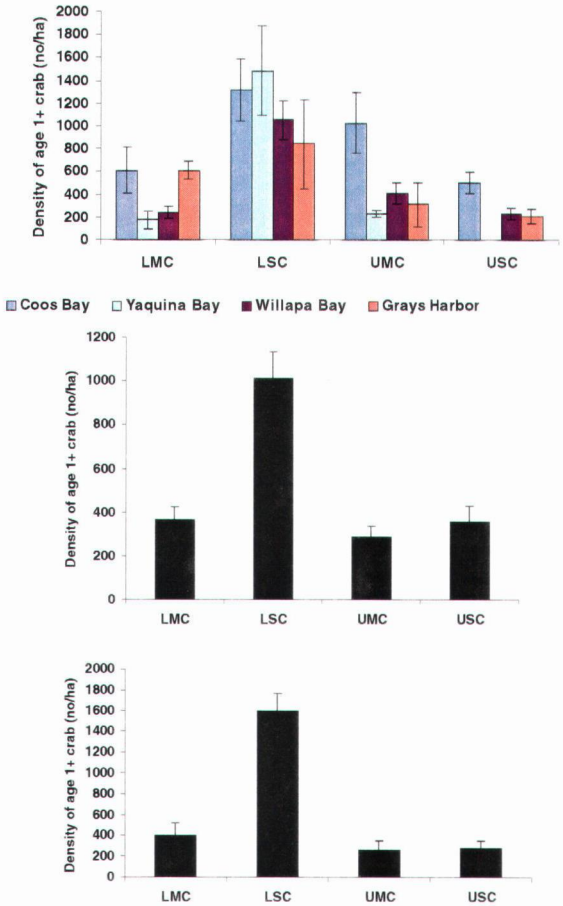

Figure 3.20. Average spatial distribution (± se) of age 1+ Dungeness crab in each spatial location within estuaries. Top panel depicts results from combined analysis of all estuaries from 1998-2000, the middle panel is Willapa Bay data from 1985-1988 and 1998-2000, and the bottom panel is Grays Harbor data from 1983-1988 and 1998-2000. Averages are from lower main channel (LMC), lower side channel (LSC), upper main channel (UMC) and upper side channel (USC) locations from all estuaries.

pling, and ranged from 0 to >46,200/ha at individual stations over 1998-2000. Average densities have been lowest in YB, intermediate in CB, and most extreme in range within GH, where mean summer densities were approximately 8000, near zero, and 1500 crab/ha.

Finally, density of age 1+ crab showed some variability in GH in 2000, while densities were similar across all other estuaries and years (Figure 3.19). Densities ranged from 500-1,500/ha in both June and August. Across all estuaries, densities in 2000 (survivors of the 1999 year class) were approximately double (mean approximately 1000/ha) densities found in the previous two years (mean approximately 500/ha).

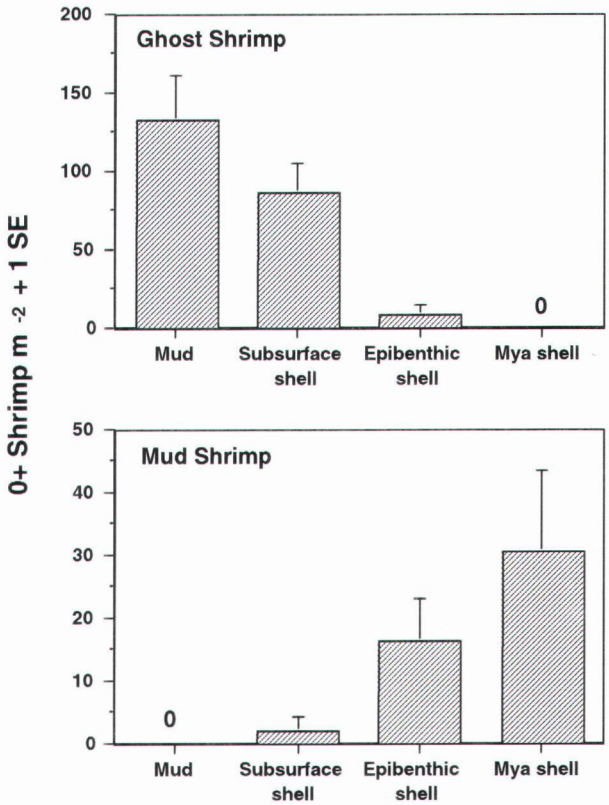

Figure 3.21. Recruitment of thallasinid shrimp. Number of 0+ shrimp recruiting to open mud and various categories of shell cover including empty oyster shell buried 5-10 cm below the sediment surface (subsurface shell), surface deposits of oyster shell forming a thick (10-15 cm) layer (epibenthic shell), and relic surface deposits ("death assemblages") of eastern softshell clam *Mya arenaria* (*Mya* shell). (Source: Dumbauld et al. 1996).

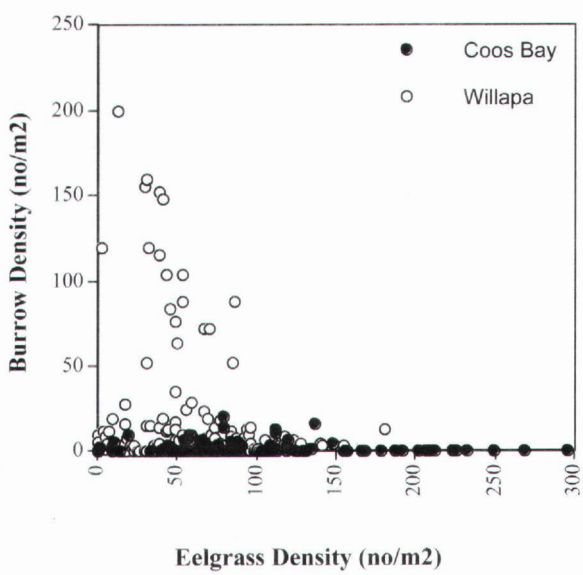

Figure 3.22. Burrow density of thallasinid shrimp in relation to eelgrass density.

Patterns of crab density and abundance suggest that they prefer certain habitat attributes across estuaries, which leads to spatial patterns that may be related to habitat characteristics. To explore possible sets of physio-biological features that define preferred habitats, stations within the original strata were partially regrouped. Each survey site was classified by its spatial location in the estuary as being in the lower main channel (LMC: main channel near mouth, higher salinity, colder summer upwelled water, very low epibenthic material), lower side channel (LSC: small channels bisect tide flats, warmer temperatures, high salinity, extensive epibenthic material), upper main channel (UMC) or upper side channel (USC). Since most survival/production of EBP 0+ is within intertidal habitats, we focused on 1+ analyses with respect to distribution in the four subregions described above. Within all four PNCERS estuaries sampled 1998-2000, highest 1+ density always occurs in LSC in a range of approximately 800-1400 /ha (Figure 3.20). In identical fashion, the data from surveys in 1983-88 within GH and WB also contained highest density (and biomass) in LSC habitats, usually 2-3 times more than all other subregions of the systems, thus implying very different habitat quality to support this age class of crab.

Other examples of animal distribution-substrate relationships are evident from the interactions of two species of burrowing shrimp with various combinations of mud and shell habitat (Figure 3.21). Newly settled 0+ ghost shrimp (*Neotrypaea californiensis*) were most abundant in open mud and subsurface shell, while 0+ mud shrimp (*Upogebia pugettensis*) were most abundant in epibenthic oyster shell and surface deposits of *M. arenaria*. There is also potentially a negative correlation between burrowing shrimp holes and eelgrass density (Figure 3.22).

Eelgrass Habitat

One of the most important habitat types in PNW estuaries is submerged aquatic vegetation (SAV), especially the extensive eelgrass meadows. Eelgrass (*Zostera marina*) is a fringe habitat that provides productive feeding and rearing areas for invertebrates and fish, and supplies organic material to the system. Production and distribution of eelgrass responds to oceanic and watershed inputs, and is influenced by processes such as tidal

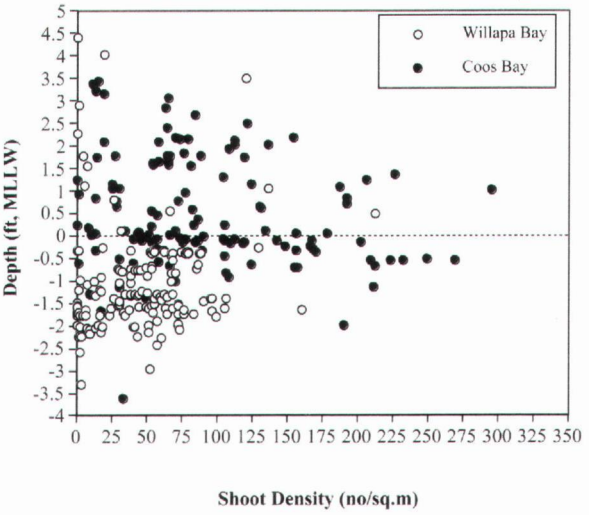

Figure 3.23. Depth distribution of eelgrass in Willapa Bay and Coos Bay.

flushing, which controls temperature, salinity, and turbidity.

Our distribution studies have shown that eelgrass generally occurs in a zone between the depths of ±1.2 m

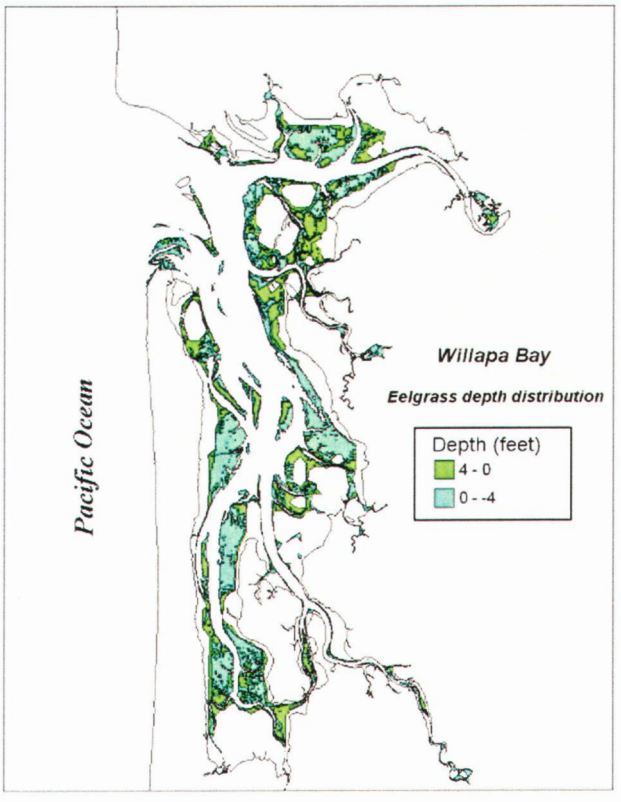

Figure 3.24. Potential eelgrass distribution in Willapa Bay based on field measurements of upper and lower limits and the most recent bathymetry data.

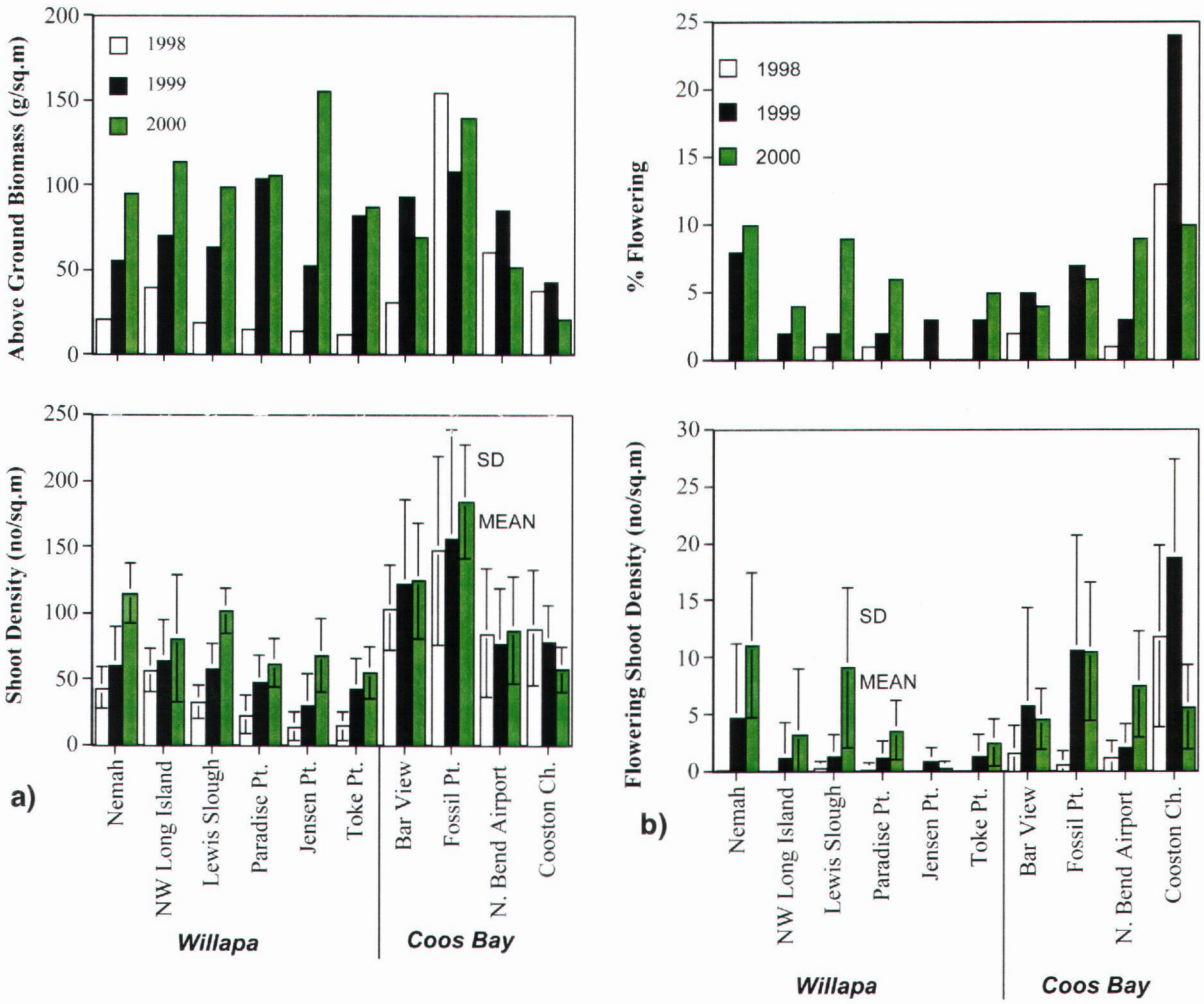

Figure 3.25. (a) Mean eelgrass above ground biomass and shoot density at the 10 sites in 1998, 1999, and 2000. (b) Flowering shoot density at the 10 sites in 1998, 1999, and 2000.

relative to mean lower low water (MLLW) (Figure 3.23). The eelgrass zone is generally defined by the effects of desiccation stress in the intertidal zone and low light in the subtidal zone. Based on the depth range, we estimated the potential distribution of eelgrass in Willapa Bay (Figure 3.24). This area constitutes an important habitat for a variety of organisms, including juvenile salmon and crabs.

There were important interannual differences in eelgrass growth and production (Figure 3.25). Biomass, density, and reproduction were generally curtailed during the el Niño period as seen in 1998, compared to 1999 and 2000, especially in Willapa Bay. In addition, an increase in biomass in Willapa Bay in 2000 might be due to an increase in flowering shoots in 1999, resulting in higher than average seed production and seedling growth. The annual differences in biomass, density, and flowering were not as pronounced in Coos Bay. This may be attributable to the lower temperature variability at most of the sites in Coos Bay (Figure 3.26). Warmer temperatures in spring 2000 might be one explanation for the general increase in biomass, density, and flowering in Willapa Bay.

In addition to interannual variability, our studies also revealed spatial differences within the estuaries. Eelgrass populations tend to increase in biomass and density away from marine dominated sites. (Figure 3.23). The depth distribution of the highest densities of eelgrass shoots differs between Coos Bay and Willapa Bay. Additionally, the lower depth limit appears to be greater in more marine areas than up estuary, which is probably related to turbidity.

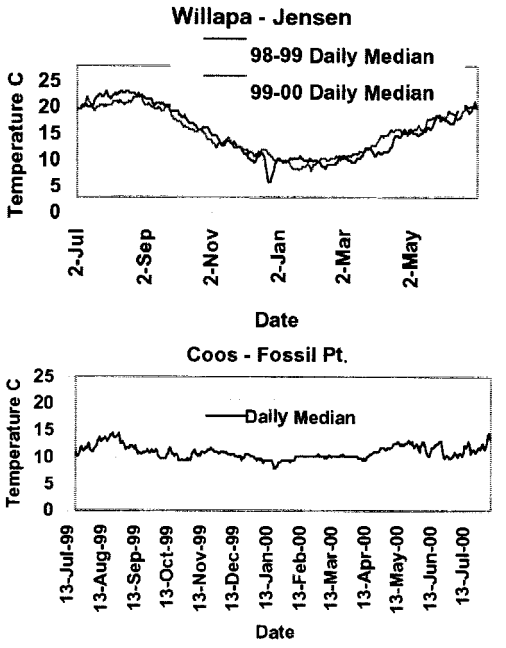

Figure 3.26. Temperature variation between estuarine eelgrass beds. Daily median temperature (C°) at Jensen Point, Willapa Bay (top) and Fossil Point, Coos Bay (bottom) in 1999 and 2000.

Quantitative measurements of light attenuation (decreased photon flux with depth) and light intensity (ambient incident light levels) were obtained in a subtidal eelgrass bed. Low light levels were consistently recorded by light meters at an intermediate 30 cm depth. These depressions in ambient light levels correspond closely with the end of the tidal flood cycle and it is likely that the hydrodynamics of the flooding tidal waters positioned eelgrass blades so that they produced a shading effect at mid-depth strata within the eelgrass canopy. These findings help to define the variation observed within eelgrass beds in both light and eelgrass growth.

Conclusion

Our investigations of PNW estuaries has reveled a remarkable degree of estuarine-nearshore linkage and benthic-pelagic coupling. Physical oceanographic factors strongly influence estuarine circulation patterns in the study systems over a large range of temporal scales. Data analyzed to date has especially shown the importance of wind and tidal forcings on estuarine circulation patterns. Water near the mouth of the estuaries is largely controlled by wind stress, which induces regional changes in coastal upwelling/downwelling and the position of the Columbia River plume. The plume actually enters Washington estuaries but has indirect effects on southern Oregon systems. Tidal advection regulates the import of this nearshore water into estuaries and the subsequent advection and mixing within the system. Wind stress and tidal circulation also control the transport of biogenic material, including invertebrate larvae and coastally-derived phytoplankton, to estuarine sites. Benthic-pelagic coupling between suspension-feeding organisms such as oysters and the imported chlorophyll appears likely and is the subject of new research projects being implemented in 2001. Survival of early benthic stages of crab and sole is regulated by delivery to suitable benthic habitat, such as eelgrass and epibenthic shell material, which affords food and protection from predators. The extent of biogenic habitat like eelgrass is in turn influenced by physical parameters such as temperature, light, and nutrient supply. Much of the tremendous secondary production of these invertebrates and fishes is exported as juveniles exit the estuary (or, in the case of oysters, are harvested). Thus, PNW estuaries import chlorophyll and larvae, which are transformed via interactions with the benthos, and later export secondary production in the form of juvenile organisms. The specific links in this generalized scheme are presently under scrutiny.

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