A HISTORICAL ECOLOGY OF SALISH SEA "RESIDENT" KILLER WHALES (*Orcinus orca*): WITH IMPLICATIONS FOR MANAGEMENT

by

Richard W. Osborne

A Dissertation Submitted in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

in the

Department of Geography, University of Victoria

A HISTORICAL ECOLOGY OF SALISH SEA "RESIDENT" KILLER WHALES (*Orcinus orca*): WITH IMPLICATIONS FOR MANAGEMENT

by

Richard W. Osborne
B.A., The Evergreen State College, 1976
M.A., Western Washington University, 1986

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY

in the
Department of Geography, University of Victoria

We accept this dissertation as conforming to the required standard

Dr. P. Dearden, Supervisor (Department of Geography)

Dr. D.A. Duffus, Departmental Member (Department of Geography)

Dr. M.C.R. Edgell, Departmental Member (Department of Geography)

Dr. B. Maher, Outside Member
(Centre of Geographic Sciences, Lawrencetown, Nova Scotia)

Dr. J. Lien, External Examiner
(Department of Psychology, Memorial University of Newfoundland)

ABSTRACT

The purpose of this study is to explore the implications of the historical perspective when it is linked to the ecological concept of adaptive management. The vehicle for this exploration is a genetically distinct population of killer whales (*Orcinus orca*), whose core coastal habitat includes the inland waters of Georgia Strait, Juan de Fuca Strait and Puget Sound; a geographic region referred to as the "Salish Sea." This stock of killer whales, known as the Southern Resident Community, is unique in having a detailed scientific record that spans over two decades and recently this population was listed as "threatened" by the Committee on the Status of Endangered Wildlife in Canada (April 1999).

The goal of this study is to take account of the specific ecological history of this killer whale population, and provide an assessment of the resiliency of this stock to withstand present levels of human impacts.

In Chapter 1 the academic concepts of historical ecology and adaptive management are reviewed in preparation for their application as theory. Chapter 2 is an inventory of the *ecological domain*, in which the focal population is assessed by temporally measurable indicators of its ecological status: population dynamics, feeding ecology, and habitat use. In Chapter 3 temporally measurable indicators of stress such as predation, disease, food resource depletion, toxic exposure, surface disturbance, and underwater noise are examined for their impact upon the carrying capacity of the environment of the whales. Chapter 4 plots both sets of indicators historically as trends in variation from the Sample Mean at different time scales (months, years, decades, centuries), and indexes them in terms of perturbations from the historical norm.

In Chapter 5 four basic types of historical trends in environmental impacts are identified that are directly relevant to evaluating the resilience of the management unit. These historical indicators of resiliency are:

1) *Relic impacts* - potential impacts that are no longer present, but may account for present conditions.

2) *Adapted impacts* - potential impacts that have been around long enough for the management unit to have adapted to them.

3) *Cumulative impacts*- potential impacts that accumulate slowly in the environment or life history of the management unit before exerting environmental resistance.

4) *New impacts* - potential impacts with which the management unit has not had previous experience.

These four historical criteria allow the manager to identify the most sensitive impacts for present conditions, and identify scales of management for restorative intervention. This resiliency index should have application for most types of ecological systems, or management units, because it describes very generalized types of temporal outcomes, independent of scale and life history pattern of the management unit.

In terms of the focal population of killer whales in this study, the historical assessment suggests that: 1) these whales are presently a remnant population due to killing and capture by European settlers from the turn of the century to the 1970s; 2) they have bio-accumulated toxins during the highest historical periods of environmental pollution in the Salish Sea, and this toxic exposure will continue to increase for the whales over the next few decades; 3) this killer whale population has never previously experienced a lack of salmon, so diminishing salmon stocks are potentially a new stress on them; and 4) these killer whales have adapted to vessel traffic and noise for several decades in relation to vessel-based salmon fishing operations, and that this influence has recently been replaced by record levels of whale watching traffic, which potentially poses more severe impacts than fishing vessels because the boats follow the whales, rather than their prey.

This historical assessment facilitates the application of "adaptive management" strategies for these whales by providing the basis for predicting the current "resiliency" of this population to adapt to environmental conditions.

TABLE OF CONTENTS

Page

Page

LIST OF TABLES:

LIST OF FIGURES:

Page

Chapter 2:

Chapter 3:

Chapter 4:

Page

Appendix I :

* * * * *

ACKNOWLEDGMENTS

The completion of this dissertation would not have been possible without the support and cooperation of numerous people and institutions. For financial assistance the bulk of support was provided by The Whale Museum and its contributors, the Department of Geography, University of Victoria, and by my father and step mother Richard H., and Barbara T. Osborne. Without them this never would have happened.

The scope of information drawn upon in this dissertation spans many sources and disciplines, but without the killer whale photo-identification records initiated by the late Michael A. Bigg, and maintained by Keneth C. Balcomb, III and his colleagues at the Orca Survey, Center for Whale Research, this study would not have been possible. For access to additional observations and unpublished data I would like to specifically acknowledge: David Bain, Robin Baird, Ken Balcomb, Kelley Balcomb-Bartok, Lance Barrett-Lennard, Ron Bates, Mike Bigg, Jim Boran, Graeme Ellis, David Ellifritt, Fred Felleman, John K.B. Ford, Tamara Guenther, Brad Hanson, Sara Heimlich, Bob Otis, Peter Ross, Tom Schroeder, Mark Sears, Jodi Smith, and Pam Stacey.

For critical reviews of the draft manuscripts I'd like to thank Ted Miller, Rowann Tallmon, and my committee members: Phil Dearden, Dave Duffus, Bob Maher, Mike Edgell, and Jon Lien. For their seemingly infinite capacity to "hang in there" I'd especially like to acknowledge the members of my committee and my wife. Finally, for unwavering moral and emotional support my dearest thanks go to my immediate family: my parents, Richard H. Osborne and Barbara W. Osborne, siblings Sue and Dave, my daughter Megan, and especially my wife, Rowann.

Chapter 1

Historical Ecology and Adaptive Management

INTRODUCTION

The modern discipline of "Historical Ecology" (Worster, 1984; 1990; Crumley, 1994; Winterhalder, 1994) is a simple joining of two familiar scholarly pursuits: *history* - the branch of knowledge that systematically analyzes past events (Wells, 1920; White, 1967; McNeil, 1971; Toynbee, 1972; Worster, 1984; Diamond, 1997), and *ecology* - the science that analyzes relationships between organisms and their environments (Odum, 1963; 1969; Bateson, 1979; Ricklefs, 1979; Allen and Hoekstra, 1992; Ulanowicz, 1997). The combination of these two disciplines is nothing new, but the application of historical ecology to management has developed slowly (Leopold, 1949; Holling, 1973; 1978; 1986; Bateson, 1972; Botkin and Sobel, 1975; Walters, 1986; Winterhalder, 1994), and only recently has this perspective started to become standard procedure among some environmental scientists (Beamish and Bouillon, 1993; Francis and Hare, 1994; Bigler *et al*., 1996; Downton and Miller, 1998). The present study is a contribution towards further promoting the use of historical ecology in guiding management practice by applying it to an assessment of a "threatened"* population of killer whales.

The historical ecology of this population (the "Southern Resident Community" after: Bigg *et al*., 1976; 1987; Ford *et al*., 1994 ; Baird 1999) will be constructed by systematically examining trends in available historical records that are deemed ecologically

* Committee on the Status of Endangered Wildlife in Canada (22, April, 1999).

relevant to these whales. Then this historical context will be applied towards the identification of management options for the population. The school of theory associated with "adaptive management" (Holling, 1986; Walters, 1986; Winterhalder, 1994) will serve as the conceptual framework for the recommended management strategies.

In this chapter the modern scope of *historical ecology* and *adaptive management* will be reviewed in preparation for their application as theoretical framework for the study. Following the review of theory, a description of the general methodology employed for the present study will conclude the chapter.

In the chapters that follow, this methodology will be implemented by assembling baseline information and historical indicators for the "Southern Resident" killer whale population (Chapt. 2), identifying indicators for potential human impacts (Chapt. 3), and then plotting these two sets of historical indicators at different time scales and identifying trends (Chapt. 4). In the final chapter the findings from this historical analysis will be applied to the development of a list of management options for these killer whales based upon an assessment of their adaptive resiliency under present conditions.

Historical Ecology

The historical examination of past events in relation to humans and the environment has attributed antecedents dating back to Sumer, Eygpt and Macedonia (White, 1967; Voget, 1975; Hardesty, 1977; Simmons, 1979; Worster, 1984; Johnston 1987; Crumley, 1994; Diamond, 1997), and is a logical conceptual precursor to any sort of a planned society (Service, 1975). The systematic "scientific" investigation of recent historical data on past environmental conditions has been carried out by geographers, archaeologists, biologists, and historians, for well over a century (Marsh, 1864; 1965; Wells, 1920; Barrows, 1923; Sauer, 1925; 1941; Leopold, 1949; Steward, 1963; White, 1967; Voget, 1975; Hardesty, 1977; Simmons, 1979; Worster, 1979; 1984; 1988;

Johnston, 1987; Butzer, 1982; Thomas, 1989; Roberts 1989; Diamond, 1997). However, in the context of present day human impacts on the biosphere, "historical ecology" is no longer an esoteric exploration of past events, it is now the source of critical information necessary to piece together an effective adaptive response to human impacts on planetary resources (White, 1967; Ehrlich *et al.*, 1977; Botkin, 1990; Worster, 1984; 1990; Crumley, 1994). Historical ecology documents the sequence of combined ecological pathways responsible for present conditions, as well as the ecological pathways that now need to be nurtured in order to redirect progress towards more stable conditions (Holling, 1986; 1992; Popper, 1990; Botkin, 1990; Allen and Hoekstra, 1992; Crumley, 1994; Ulanowicz, 1997).

A compelling reason for separately identifying historical ecology as a focused discipline stems from its relevance for understanding the antecedents of current environmental issues (Marsh, 1864; Leopold, 1949; White, 1967; Worster, 1979; 1988a; 1990; Cronon, 1983; Crumley, 1994; Marquardt, 1994). This present trend towards a historical perspective in environmental science has been supported by: 1) the necessity of environmental scientists to document natural conditions prior to impact (Holt and Talbot, 1978; Soule and Kohm, 1989; Botkin, 1990); 2) by the development of new technologies allowing more precise dating methods, computer modeling, and remote sensing in the fields of geography, archaeology and resource management (Holling, 1978; Aronoff, 1989; Mitchel, 1989; Roberts, 1989; Thomas, 1989; Crumley, 1994), and 3) the assimilation of these scientific data sources into the traditional "humanities only" orientation of history departments (White, 1967; Simmons, 1979; Cronon, 1983; Worster, 1984; Ingerson, 1989; 1994; Diamond, 1997).

Dove-tailing with this trend, historical ecology also has a central position as a methodology for the recent "scientific revolutions" in the physical and natural sciences that have emerged during this century (Capra, 1982; Prigogine and Stengers, 1984;

Popper, 1990; Groerner, 1993; Ayres, 1994; Ulanowicz, 1997). This new perspective presents history as cumulative and probabilistic, not as a predictable machine (Gould, 1977; Prigogine and Stengers, 1984; Popper, 1982; 1990; Diamond, 1997). In this view, history is not settling towards some universal equilibrium, but is asymmetrically increasing in complexity over time, and continuously re-setting to new equilibriums (Prigogine and Stengers, 1984; Popper, 1990; Groerner, 1993; Ayres, 1994; Ulanowicz, 1997). Historical ecology is a natural offspring of this new scientific view of cosmology because its focus is explaining the unique web of temporal precursors to present conditions, and it provides the necessary context to understand and predict the unfolding complexity. Now that the universe has been shown to be ultimately ascendant (Ulanowicz, 1986; 1997), historical ecology offers the process by which to intelligently narrow the assessment of possibilities for future outcomes (Popper, 1990; Ulanowicz, 1997).

Adaptive Management

The implications of the current "scientific revolution" in the cosmological sciences (Popper, 1990; Groerner, 1993; Ayers, 1994; Ulanowicz, 1997) has also found application in resource management theory in association with the field of "adaptive management" (Holling, 1973; 1978; 1986; 1992; Botkin and Sobel, 1975; Clark, 1985; Mitchell, 1989; Botkin, 1990; Duffus and Dearden, 1990). Adaptive management has paved the way in finding systematic approaches that recognize the stochasticity and complexity of natural systems*, and incorporates these qualitative characteristics into flexible management strategies, rather than strict management plans (Holling, 1978; 1986; Mitchell, 1989; Winterhalder, 1994).

* The term "system" in this adaptive management scheme refers to any focal ecological system, or *management unit*; such as a specific population, habitat, ecological community, regional energy-matter cycle, regional economy, or ecosystem (Allen and Hoekstra, 1992; Winterhalder, 1994).

In adaptive management the objectives are two-fold: 1) improving the system's resilience for adapting to change, rather than a specifically prescribed stable condition, and 2) maintaining flexible management strategies that are modified depending upon how the system behaves (after: Holling, 1978; 1986; Bateson, 1972; Botkin and Sobel, 1975; Walters, 1986; Duffus and Dearden, 1990; Allen and Hoekstra, 1992; Winterhalder, 1994). To quote some of the prominent proponents of this approach,

> "The [adaptive management] approach ... places emphasis on the dynamics of ecological systems and the need to recognize on the one hand those elements that are sensitive to management and on the other, those that are robust (Holling, 1986, pg. XI)."

> "the most effective management will recognize the manner in which the context is missing, it will identify the services that the context would have offered to the managed unit, and it will subsidize the managed unit to as close to that extent as possible. ... good management will create situations that are sustainable. Sustainable solutions can only be achieved if the manager works with the underlying processes in the system to be managed, not against them (Allen and Hoekstra, 1992, p. 276)."

Stability and Resilience

Two key concepts that have played a role in the adaptive management approach are ecosystem *stability* and *resilience* (Holling, 1973; Botkin and Sobel, 1975; Costanza, 1991; Ulanowicz, 1997). Traditionally in science the concept of stability relates to conditions of systems that are very near measured equilibrium points (Holling, 1973; May, 1973; Botkin & Sobel, 1975; Ricklefs, 1977; Ulanowicz, 1997). The equilibrium is when all the measurable system parameters are at, or near, their mean or average, over time (Botkin and Sobel, 1975; Botkin, 1990; Allen and Hoekstra, 1992; Ulanowicz, 1997). When a system is disturbed it fluctuates away from equilibrium in some of its variables, and then stabilizes back to near equilibrium values after it has adapted to the disturbance. In ecology this classical concept of stable equilibrium has been fundamental for the measurement and description of interacting relationships between variables ranging from biogeochemical cycles, to predator-prey interactions (Ricklefs, 1977; Ehrlich *et al.*, 1979; Botkin, 1990; Allan and Hoekstra, 1992; Ulanowicz, 1997); and it will play a central role in the analysis of trends for this study.

But another form of stability that has also emerged from the study of ecology, is the existence of relatively non-stable complex systems, that exhibit "stability" by not succumbing to extinction over time, despite their tendency at some scales to exist in states far from equilibrium (Holling, 1973; 1986; 1992; Ulanowicz, 1986; 1997; Botkin, 1990; Allen and Hoekstra, 1992). These are ecological systems like some parasite-host and predator prey relationships, and plant communities adapted to a fire ecology, flooding, or agriculture, that persist and remain stable over time, despite the fact that they exhibit fluctuating perturbations away from equilibrium at smaller scales (Holling, 1973; 1986; Botkin, 1990; Allen and Hoekstra, 1992; Ulanowicz, 1997).

From a historical perspective resilient systems remain stable in terms of avoiding extinction, they are persistent in spite of their fluctuations in some conditions, and often increasingly adaptive in a larger context as a result of this complexity (Holling, 1973; 1992; Allen and Hoekstra, 1992; Ulanowicz, 1997). The documentation of behavior over large time-scales is therefore fundamental to any characterization of a management unit's resiliency. In the present study, one of the primary objectives of viewing the data at different time scales is to provide a hierarchy of contexts (Allen and Hoekstra, 1992; Ingerson, 1989; 1994; Ulanowicz, 1997) from which to identify any potential human impacts that stress the resiliency of this killer whale population.

When applying this concept of resiliency to the actual management strategy, the logical prescription for how to manage the system distinctly changes from imposing a stable equilibrium according to design, to one that first must distinguish natural instabilities from anthropogenic ones, and then manage flexibly towards self-maintained stability of the system. To quote C.F. Holling (1973) once again:

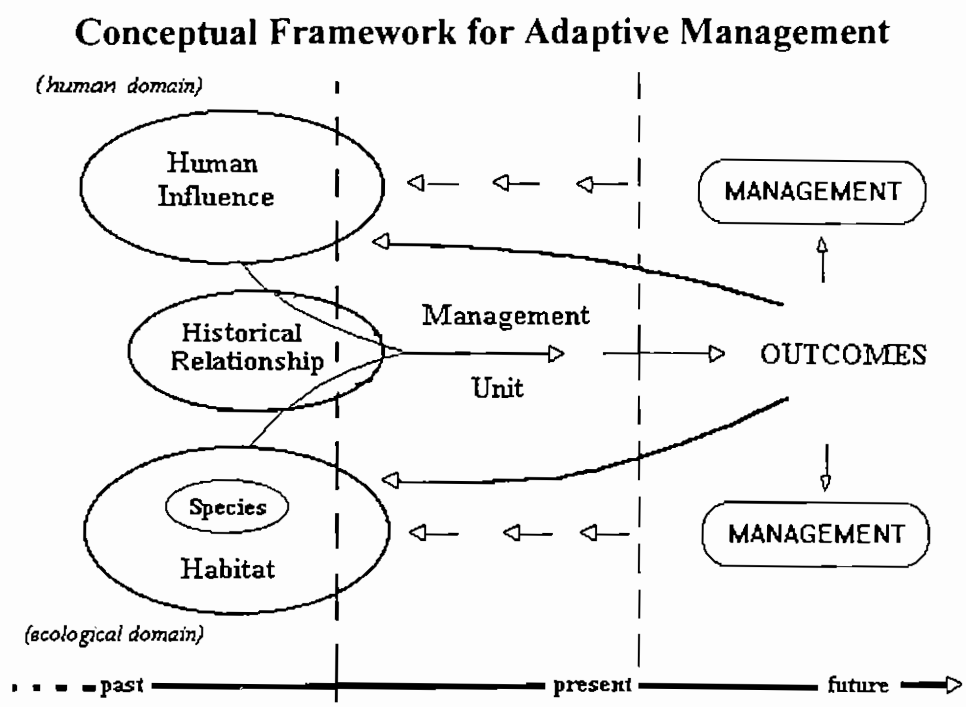
> A management approach based on resilience, ... would emphasize the need to keep options open, the need to view events in a regional rather than a local context, and the need to emphasize heterogeneity. Flowing from this would be not the presumption of sufficient knowledge, but the recognition of our ignorance; not the assumption that future events are expected, but that they will be unexpected. The resilience framework can accommodate this shift of perspective, for it does not require a precise capacity to predict the future, but only a qualitative capacity to devise systems that can absorb and accommodate future events in whatever unexpected form they may take (Holling, 1973; pg.21)."

The Conceptual Framework

To place this approach in a conceptual framework for wildlife management, Duffus and Dearden (1990) presented the model depicted in Figure 1, for application in a recreational-use context. In this wildlife-use scenario the interaction between humans and wildlife begins with the historical relationship and evolves in a series of phases where interspecific interactions are adjusted through management, modifying both the human users and the host ecosystem (Duffus, 1988). As illustrated in Figure 1, the management nodes are positioned as two related feedback loops, one in the strictly human domain and the other in the ecological domain, illustrating how management strategies are adjusted as the result of interaction outcomes. The adaptive flexibility in both domains is critical to achieving a sustainably balanced relationship in which both species continue to meet their habitat requirements over time (Duffus and Dearden, 1993).

In this study, the diagram in Figure 1 will be followed like a map (Figure 2): Chapter 2 will be the inventory of the *ecological domain*, in which the focal population will be indexed in terms of temporally measurable indicators of its ecological status; in Chapter 3, the *human domain* will be inventoried and indexed in terms of temporally measurable indicators of stress upon the theoretical carrying capacity of the focal

Figure 1



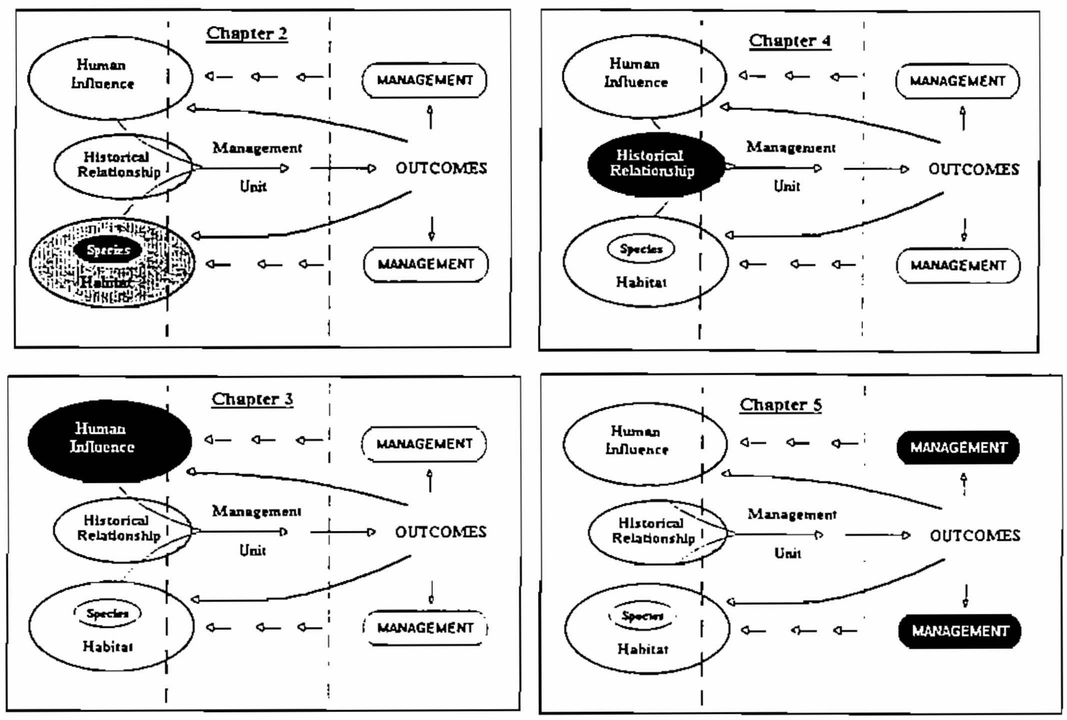
(After Duffus, 1988; Duffus and Dearden, 1990)

population, and in Chapter 4, both sets of indicators will be traced historically at different time scales, and indexed in terms of perturbations from the historical norm. These findings will provide a basis for the historical relationship described in Figure 1, and thus the benchmark for evaluating management practices. In Chapter 5 this information is then presented as a table of management options derived from the historical assessment.

As indicated in Figure 1, the historical perspective is the critical starting point in an adaptive management approach, but in most management situations it is distinctly missing, leaving managers working with indicators that are blind outside the present

Figure 2

Conceptual Blueprint for the Study



(Shaded area in each diagram represents the topic for the corresponding chapter.)

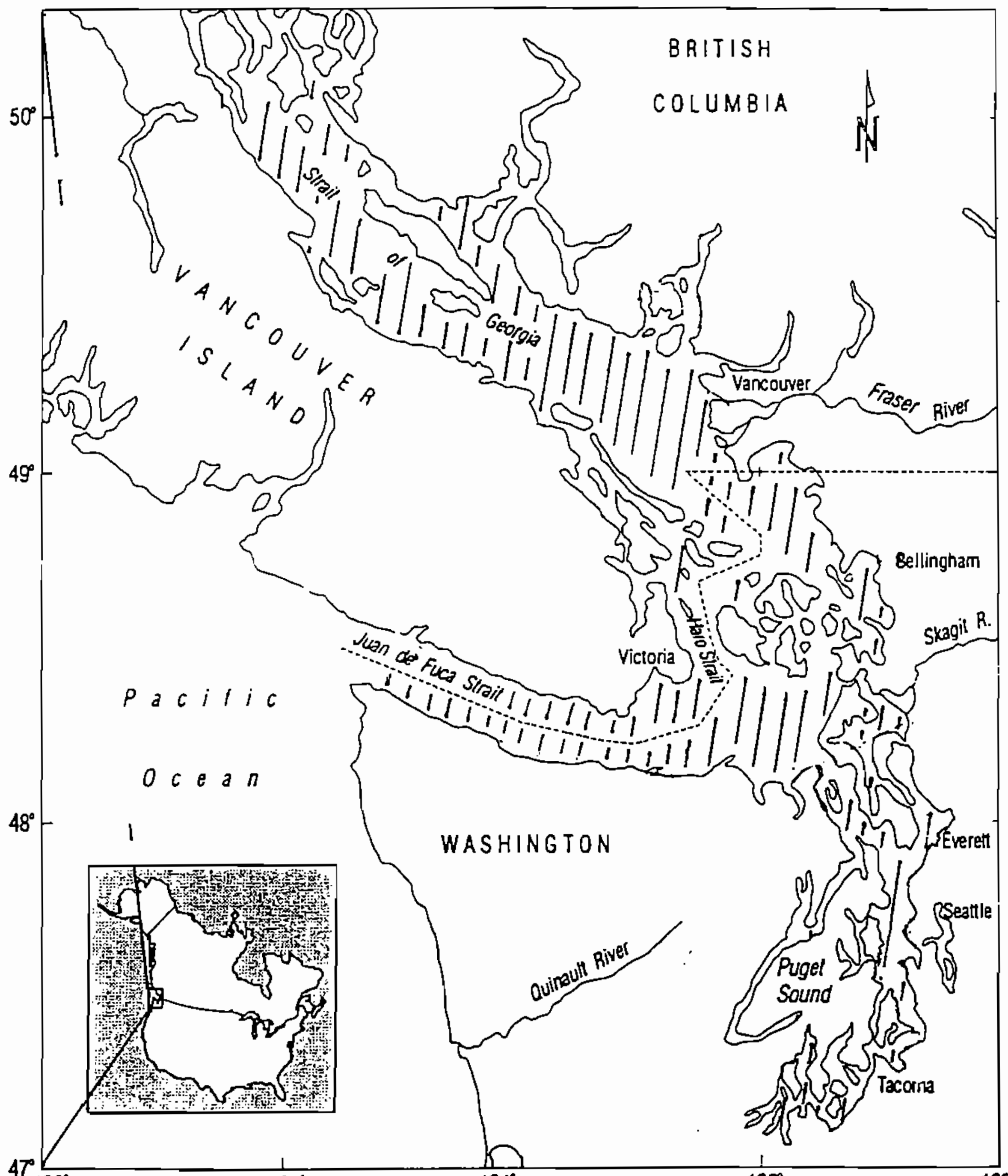
context. Under circumstances where the history of the system is unknown, present indicators may be misleading because they are being influenced by a larger context that is not being accounted for (Allen and Hoekstra, 1992). Historical influences can also override or counteract the management regime, or enhance some undesired variable. To avoid these pitfalls the present study is an attempt to systematically reconstruct the history of the management unit, and its human influences, before the management strategy is devised or implemented.

The Management Unit - Southern Resident Community (J,K and L-Pods)

The management unit for this study is a geographically and genetically distinct population of killer whales, or orcas (*Orcinus orca*), known as the "Southern Resident Community" (after: M.A. Bigg *et al.*, 1976; 1987; 1990). This population is currently declining, and has just been listed as a federally "threatened stock" by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC, 1999; Baird, 1999). This killer whale population presently consists of four interbreeding maternal family lines (4 Pods) totaling 84 members (Ford *et al.*, 1994; Balcomb, 1997; Ginneken and Ellifritt, 1999). Geographically their core coastal habitat includes the various inland waters of Southern Vancouver Island and Washington State, an area recently referred to as the "Salish Sea" by some authors (Yates, 1992; Garrett, 1995; Figure 3).

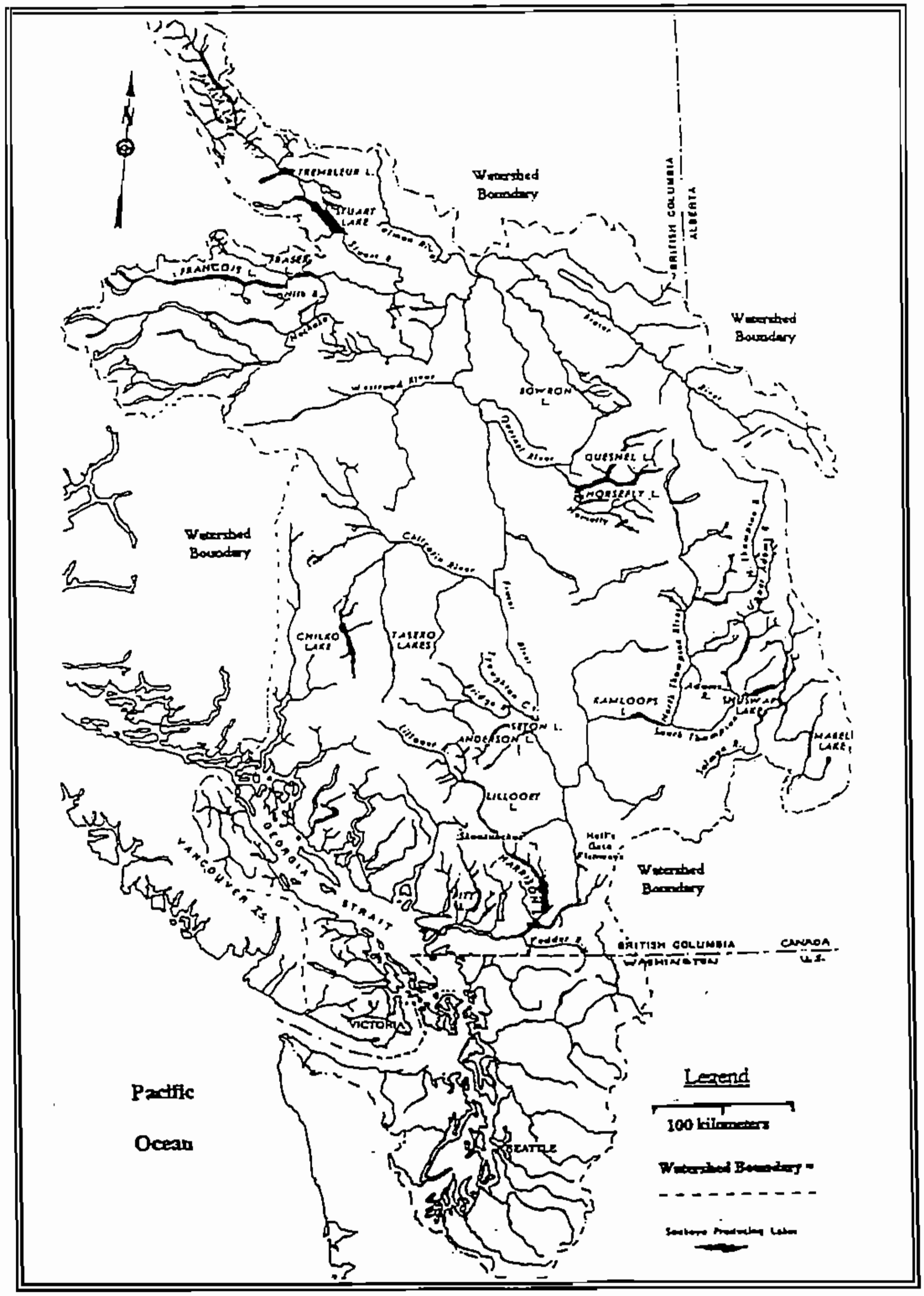
The geographic name "Salish Sea" (Yates, 1992; Garrett, 1995; Figure 3), recognizes both the culturally distinct native bands that traditionally inhabited this region for millennia prior to European contact (Drucker, 1965; McMillan, 1988), and the fact that the Salish Sea is physiographically an identifiable unit bounded by tidal exchange and a finite watershed (Thomson, 1981; Figures 3 and 4). Beyond these existing physical and ethnic boundaries, human development patterns over the last 100 years have also contributed spatial uniformity to this region (Vance, 1990; Turner, 1990; Schwantes, 1996; Fleming, 1997). The Georgia and Puget Sound basins represent a single urban/industrial realm, with similar patterns of coastal population density and resource use centered upon the primary urban centers and coastal ports for western Canada (Vancouver/ Nanaimo/Victoria B.C) and the northwestern United States (Seattle/ Everette/Tacoma, WA). Outside of the Salish Sea the surrounding coastal areas can be clearly demarcated as "hinterland" in all directions. The single term "Salish Sea" avoids the myriad names for this region that have resulted in part from its geographic status as two different nations (Figure 3).

Figure 3 **The Salish Sea***



* Cross hatching on the map illustrates the region of the Canadian/U.S. inland marine waters that are popularly referred to as the "Salish Sea" (after Yates, 1992).

Figure 4 **The Salish Sea Watershed***



*Composite map of the Salish Sea watershed constructed from maps in McKervill, 1967; Thomson, 1981; Kruckeberg, 1991, and from the map, *The Northwest Coast, South Portion*, an A. Sobay Co., Publication, Gibson's, B.C., Coast Smallworks, 1984.

In addition to being listed as "threatened" in Canada under COSEWIC, the Southern Resident Community of killer whales is unique from other killer whale populations because their history can be readily reconstructed: 1) they have shared these same inland waters with humans for millennia, 2) there is an existing 20 year data base on many aspects of their biology and ecology, and 3) their core habitat is presently the most densely populated by humans of any other killer whales in the world. This allows the recorded history of humans in the region to be directly tied to these whales, providing a more complete record of their environmental history than would be possible for any other population.

A Methodology for a Historical Ecology

If historical ecology is to be taken as "the multi-scalar and multi-temporal study of the dynamics between (a management unit) and the physical environment (Marquardt, 1994, p. 204)", then at its very foundations it will be necessary to: 1) assemble a suite of relevant measurements over long time periods, and 2) develop a systematic approach to comparing temporal trends of these different types of data at different time scales (Sheail, 1980; Reinhold, 1987; Worster, 1988;Marquardt, 1994; Hassan, 1994). The process by which this has been undertaken for the present study will be reviewed in this section.

Identifying Relevant Variables

The first step in assembling data for a historical ecology is identifying what might be relevant to the ecological system being studied; the ecological sphere of Figure 1. This requires a thorough review of data on the present status of the management unit being investigated in order to identify the best possible data, and the features of the system that can be represented by longitudinal indicators.

Only after this process of identifying the ecological qualities of the management unit, should the specific types of historical records that might serve as indicators be identified. Obviously, these qualitative categories are ultimately subjective and arbitrary, but if they are logical in terms of present measurable conditions, and clearly defined, then they can serve as an effective basis upon which to focus the search for existing historical data, and after that, the focus for management.

The historical records utilized in the study therefore, should ideally be dictated by how well they represent the ecological relationships being assessed, and not chosen just because they exist. In practice, however, unless managers are willing to wait for the results of their own longitudinal research, they are faced with a limited choice of available historical records, and must make do (Sheail, 1980; Worster, 1988; Crumley, 1994; Hassan, 1994). The objective is not to compile the ultimate historical archive, but to obtain an assessment of historical factors based upon relevant trends; and from those trends, distinguish resiliency from acute impacts.

Assembling Historical Data

Perhaps the biggest challenge for the construction of a historical ecology is obtaining long-term data sets (Sheail, 1980; Reinhold, 1987; Worster, 1988; Crumley, 1994; Hassan, 1994). The value of the information being compiled is obviously limited by the quality and continuity of available records. If a variable contains a discrete quantitative measurement that is reliable over a long time series, then it is obviously more valuable than anecdotal references, but anecdotal records should rarely be ignored. Anecdotes at the very least provide a point of reference for further investigation (Sheail, 1980; Worster, 1988; Hassan, 1994), and often provide information about extreme events that are more likely to be associated with an environmental impact.

The focus here is on environmental indicators for the marine environment. Sea surface temperature is one fundamental variable that should be sought in such a study (Roberts, 1989; Newton, 1995), and in some regions there are data bases that go back over 100 years for this variable (Newton, 1995; Downton and Miller, 1998). Other data sets of oceanographic variables covering the last 50 years are regionally available for measurements such as sub-surface temperature, salinity, and dissolved oxygen, and atmospheric measures such as precipitation and air temperature (Newton, 1995). Climatic indices like the El Nino Southern Oscillation Index (ENSO; Philander, 1990; Newton, 1995) and the Pacific Interdecadal Oscillation (PDO; Mantua *et al.*, 1997; Downton and Miller, 1998) are also available. These latter indices have been constructed from a combination of oceanographic variables assembled from the 1950s to the present (Philander, 1990).

Records on the commercial exploitation of living resources can also provide very valuable long-term data sets on the marine environment (Holt, 1969; Holt and Talbot, 1978; Roos, 1990; Groot and Margolis, 1991). In the present study salmon catch statistics and governmental salmon abundance estimates are utilized as historical variables to track the primary food resource of the study population of killer whales (Roos, 1990; Pacific Salmon Commission, 1985-1998; WDFW, 1996). Additional environmental data sets that are available to historical ecologists looking at the marine environment, include marine sediment cores and coastal archaeological sites (Siemans, 1966; Levings and Thom, 1994; Crumley, 1994; Marquardt, 1994). These data sources have the potential to yield huge amounts of information ranging from sequences of marine floral and faunal remains (Roberts, 1989) to sedimentation patterns of toxic wastes (Macdonald and Crecelius, 1994).

The best data sets are terrestrial, and have been collected by historically-minded natural scientists in physical geography, archaeology, geology, climatology, forestry, landscape ecology, and limnology (Kormondy, 1969; Sheail, 1980; Reinhold, 1987; Worster, 1988; Roberts, 1989; Crumley, 1994; Hassan, 1994; Newton, 1995). When these scientific records are then combined with less accurate governmental statistics on human activities, and the historical print media, there is a potential abundance of material from which to build corroborating historical evidence. In this study the objective is to gain an initial assessment of basic historical trends that can be immediately applied to management.

Besides finding appropriate variables to track for the specific ecological history being constructed, another common problem in the methodology of historical ecology is dealing with data sets that are either incomplete in some fashion, or have large breaks in their sequence (Roberts, 1989; Hassan, 1994; Crumley, 1994). In almost all cases there will be gaps in the temporal sequence. Yet, when trying to extrapolate trends over different time scales (diurnal, seasonal, annual, decadal, centennial, millennial, ...), these gaps are unavoidable. Under these circumstances the investigator is faced with either rejecting the data, systematically bridging the gaps, or creating estimates (Sheail, 1980; Worster, 1984; 1988; Hassan, 1994). So instead of rejecting the data in all cases, a systematic way of estimating needs to be employed.

In dealing with gaps in a data series, the most obvious procedure is to insert the calculated mean for the series, or to bridge the difference between the points at either end of the gap with a simple stepwise function (Box and Jenkins, 1976; Zar, 1996). In this study both of these procedures are utilized depending on the nature of the gap. However, particularly when extrapolating to the larger time scales, outright estimates are really the only recourse, which has also been employed in this study where it was deemed necessary. However, in all these procedures, as long as the gap-function or the estimate is explicitly described, then the findings are easily traced to their original values and available to modification with the advent of new information.

Once the data sets are assembled they are potentially available for a multitude of different analytical procedures, depending upon their sampling accuracy (Sheail, 1980; Worster, 1988; Crumley, 1994; Hassan, 1994; Marquardt, 1994). However, the chief problem with historical data, particularly human records, is that there is almost always no measurement of data collection effort, and so by its nature, the homogeneity of the data is invalid for most statistical analyses (Zar, 1996). Exceptions to this problem can be found in scientific data sets where uniform data collection is satisfied, such as the annual photo-identification data for population composition of killer whales used in this study (Olesiuk *et al.*, 1990; Brault and Caswell, 1993; Ginneken and Ellifritt, 1999) or when measuring extant empirical environmental variables such as radio-active isotopes (Stuiver and

Pearson, 1986), tree rings (Pierson and Turner, 1998), sediment cores (Crecelius *et al.*, 1995), and material stratification in archaeological sites (Borden, 1968; Thomas, 1989; Crumley, 1994; Marquardt, 1994). Other potentially valuable data sets, such as government records of vessel traffic, park visitors, recreational salmon catch, and even human population and sea surface temperature, are all unlikely to satisfy statistical homogeneity, especially when they span several human lifetimes. This then, presents a problem for doing analysis once the longitudinal data sets are finally assembled, and is one reason multi-scaler and multi-temporal systematic scientific studies of history are so rare (Cronon, 1983; Worster, 1984; 1988; Crumley, 1994).

Comparing Trends at Different Time Scales

One of the primary reasons for constructing a historical ecology is to gain insights on the focal ecological system, or management unit, by comparing its behavior from the perspective of different time scales (Allen and Hoekstra, 1992, Ingerson, 1989; 1994). This provides a mechanism for evaluating resiliency as the relationship between lower level chaotic behavior relative to stabilities operating at larger scales (Margalef, 1969; Botkin and Sobel, 1975; Allen and Starr, 1982; Holling, 1973; 1986; 1992; Prigogine and Stengers, 1984; Allen and Hoekstra, 1992). As mentioned in the previous section, the methodological problem is that the data these comparisons are to be based upon are almost always imperfect to the point that they are invalid for most statistical analysis (Box and Jenkins, 1976; Sheail, 1980; Reinhold, 1987; Worster, 1988).

The solution employed here is to stay quantitatively very close to the data and to only statistically compare it with itself, by using a measure of variation around the sample mean (Zar, 1996). The sample mean is a measure that can be calculated on any data series, so the behavior of the series around its mean provides a basis for comparison between data sets at the same time scale. The simplest measure of variation around this mean is its standard deviation (SD) (Box and Jenkins, 1976; Zar, 1996). Although the likelihood of having a data series exhibit behavior that is statistically significant to the 95% level in terms of standard deviations (> 2 SD) is low, it does provide a uniform translation of almost any data series to almost any scale, and so satisfies the ability to qualitatively compare and contrast trends.

In the more empirical forms of history, such as geology, climatology, and archaeology, some type of variance around the mean of the series is usually the basis upon which statistically valid data sets are analyzed (Thomas, 1976; 1989; Reinhold, 1987; Parker and Folland, 1989; Roberts, 1989). A classic example is the El Nino/Southern Oscillation Index, which is expressed as cumulative variance from the mean for several variables (Philander, 1990).

In this study a measurement of standard deviations around the sample mean has been chosen as the basis to compare all historical indices among themselves and across time scales. This allows the comparison of high variance incidents between indicators in order to identify long-term trends, sequences, and potential interactions.

Evaluating Historical Trends in Terms of Management

When long-term trends in ecological variables are compared, four basic types of historical trends in environmental impacts can be identified that are directly relevant to evaluating the resilience of the management unit. These historical indicators of resiliency are:

1) *Relic impacts* - potential impacts that are no longer present, but may account for present conditions.

2) *Adapted impacts* - potential impacts that have been around long enough for the management unit to have adapted to them.

3) *Cumulative impacts*- potential impacts that accumulate slowly in the environment or life history of the management unit before exerting environmental resistance.

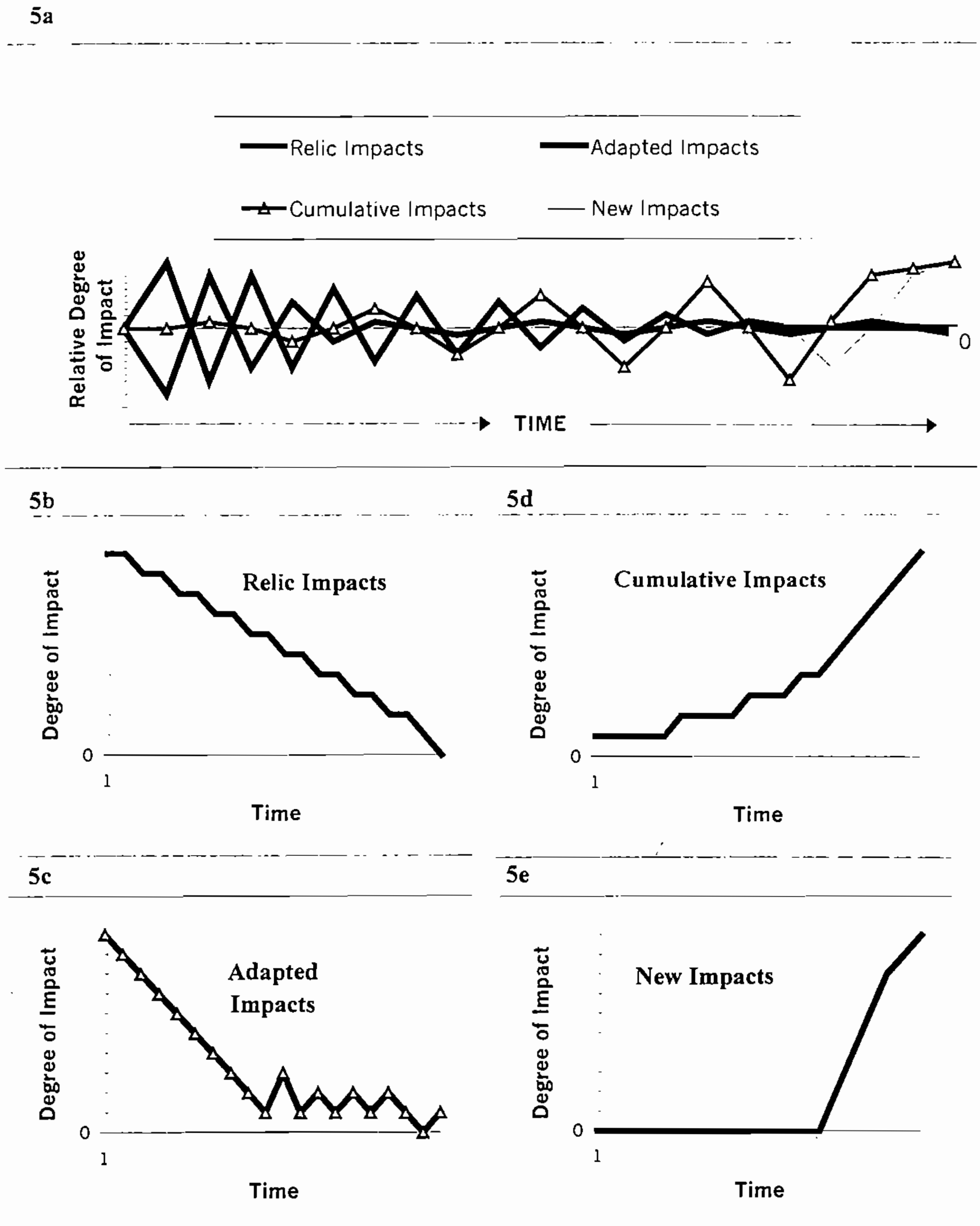
4) *New impacts* - potential impacts with which the management unit has not had previous experience.

These four historical criteria allow the manager to identify the most sensitive impacts for present conditions, and more effectively identify scales of management for restorative intervention. To illustrate this further, in Figure 5 the predicted patterns of influence for each of these general types of impact are depicted as plots of the relative degree of impact over time.

Relic impacts exhibit an initial strong influence and then slowly dissipate over time (Figure 5b). *Adapted impacts* should, by definition, disappear rather rapidly or be maintained at fairly low levels of influence after their initial introduction (Figure 5c). The influences of adapted impacts could be quite variable however, depending on the nature of the impact and the adaptive mechanism(s) utilized to respond to it. *Cumulative impacts* would be expected to build slowly over time, and to not exhibit their influence until after very long periods of exposure (Figure 5d). *New impacts* are unknown outside of the present, so in a management scheme they would likely be prioritized for more detailed research and/or precautionary management (Figure 5e).

Figure 5

Idealized Patterns of Historical Impacts on Ecological Management Units



This resiliency index should have application for most types of ecological systems, or management units, because it describes very generalized types of temporal outcomes, independent of scale and life history pattern of the management unit. In the present study this scheme will provide the basis for interpreting the historical trends relative to management options for the study population. It will allow potential impacts to be prioritized on the basis of whether they are new or old impacts, whether they are still exerting an influence, and whether they are impacts with sources that are presently available for manipulation through management.

Summary

Historical ecology and adaptive management have been reviewed in preparation for their application as the theoretical basis for developing management options for a threatened population of killer whales. Following the review of theory, a description of the general methodology employed for the present study has been outlined. From this overview it is concluded that a historical assessment of the ecology of a management unit provides essential information necessary for adequately explaining current conditions and developing effective management strategies that account for the resiliency of the management unit.

The diachronic method in ecological management contributes meaning and context to otherwise temporally one dimensional data. Historical ecology provides a record of the ultimate outcomes from past experiments played upon specific ecological relationships, and provides context for determining if current trends are natural, resilient, or acutely anthropogenic.

Chapter 2

Identifying Ecological Indicators for Salish Sea Resident Killer Whales

INTRODUCTION

The "ecology" part of a study in *historical ecology* requires a well-rounded understanding of the ecological variables most prominently affecting the management unit under investigation (Crumley, 1994; Winterhalder, 1994). Depending upon the characteristics of the ecosystem being examined the most important variables will differ significantly between components, but at the organism/population level they will usually fall into three major categories for each population (Kormondy, 1969; Holling, 1973; 1992; Ricklefs, 1979; Eisenberg, 1981; Allen and Starr, 1982; Allen and Hoekstra, 1992): 1) population biology (recruitment and reproductive life history pattern), 2) food resources (energy requirements), and 3) spatial habitat requirements (behavioral ecology).

In the present study the management unit is a geographically distinct population of killer whales, or orcas (*Orcinus orca*), known in the literature as the "Southern Resident Community" (after Bigg *et al.*, 1987; 1990a; Ford *et al.*, 1994; Center for Whale Research, 1998), and also referred to in this study as the "Salish Sea Resident Community." The objective is to describe this population so that measurable indicators of their ecology and environment can be identified and traced historically. The first step is to assemble what is currently known about the population and develop some measures of long-term trends in their ecology. This is the focus of the present chapter. Photo-identification records and public sightings are developed as indicators of the ecological condition of this population in terms of spatial habitat requirements, population biology, and food resources.

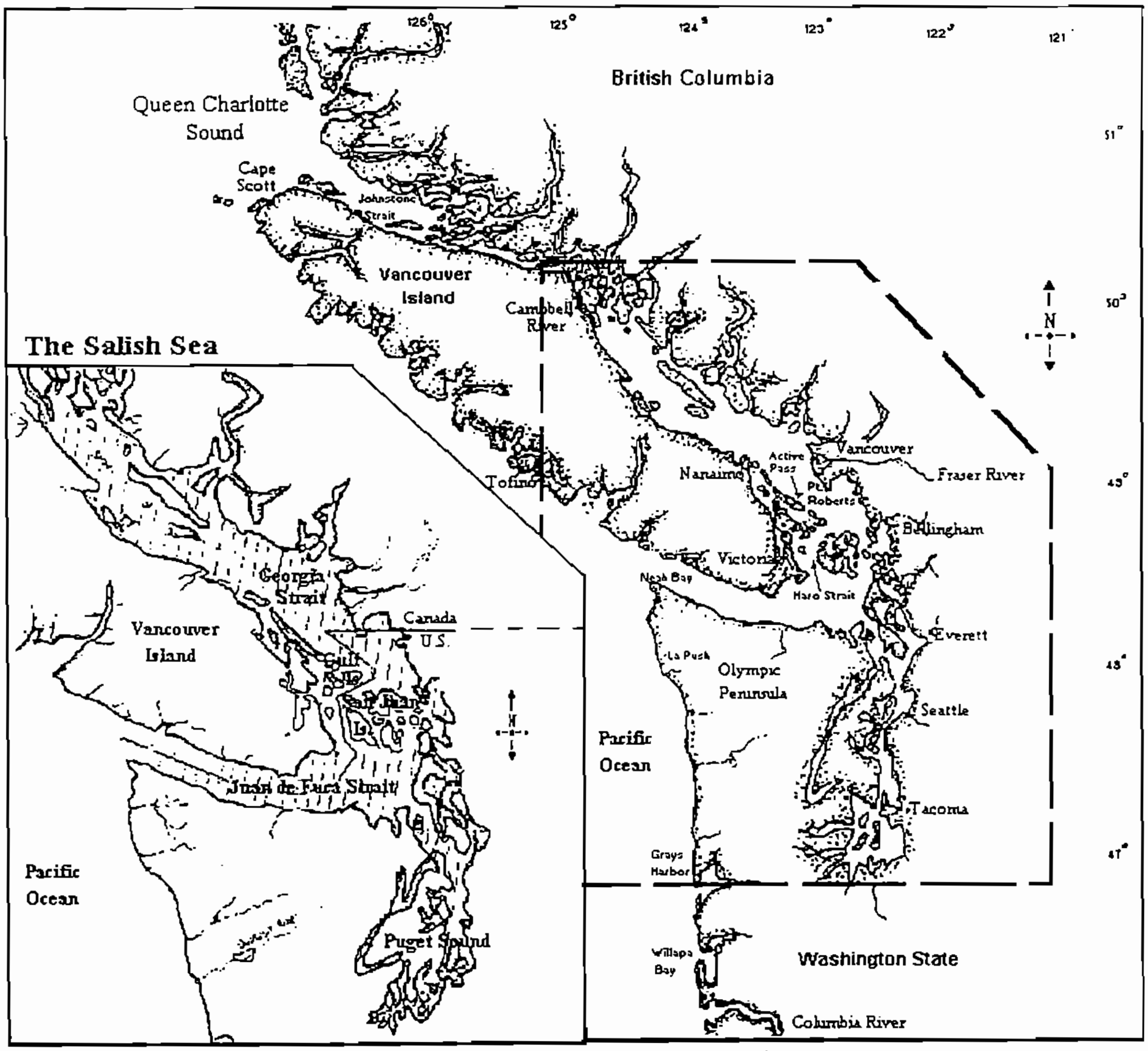
In the next chapter this assessment will be used to construct an interaction matrix of potentially limiting environmental variables for these killer whales, and to enumerate vectors of human impact. In the final chapters, historical plots of all these variables at different time scales are presented in support of a discussion on adaptive resiliency in these killer whales, and concludes with a discussion on management options for this "threatened" population (COSEWIC, 1999).

The Salish Sea

The geographic core area for the "Southern Resident" killer whale population has recently been referred to in aggregate as the "Salish Sea" (Yates, 1992; Garrett, 1995; Figures 1, 6 and 7). This geographic name recognizes the distinct native culture that uniformly inhabited this region for most of human history (Drucker, 1965; McMillan, 1988), and the fact that the Salish Sea can be identified as a single marine region that is bounded by tidal exchange, salinity gradient, temperature gradient, and a finite watershed (Thomson, 1981; 1994; Figures 4 and 6).

The Georgia and Puget Sound basins also represent an identifiable urban/industrial realm in terms of population density and resource use that are centered around coastal ports as the primary urban centers (Vance, 1990; Turner, 1990; PSWQA, 1994; Schwantes, 1996). Finally, the single term "Salish Sea" avoids the artificial political boundaries that have evolved for this international region, and instead, rarefies its physical and ecological characteristics, as well as its ethnohistory.

Figure 6 **Map of Geographic Place Names**



Species Characteristics

At the species level, killer whales are large brained (Osborne and Sundsten, 1981; Ridgway, 1986; Jerison, 1986), intelligent (DeFran and Pryor, 1980; Herman, 1986; Hoyt, 1990; 1992b), social predators (Heyning and Dahlheim, 1988; Felleman *et al.*, 1991;

Hoelzel, 1993), with a life history pattern of ontological development that is closer to humans than any other species (Olesiuk *et al.*, 1990; Osborne, 1990; Heimlich-Boran and Heimlich-Boran, 1999). Killer whales are globally cosmopolitan in their distribution (Matkin and Leatherwood, 1986; Heyning and Dahlheim, 1988; Hoelzel, 1993; Jefferson *et al.*, 1991), culturally distinct by population and/or region (Osborne, 1986; 1990; Ford, 1989; Morton, 1990; Jefferson *et al.*, 1991; Heimlich-Boran and Heimlich-Boran, 1999; Whitehead, 1998), and feed upon a variety of organisms throughout the upper trophic levels of marine food webs (Bigg *et al.*, 1990a; 1990b; Felleman *et al.*, 1991; Jefferson *et al.*, 1991; Baird *et al.*, 1992). They are one of the top predators of all oceans, with no history of being preyed upon by another vertebrate species, except very recently by humans in a few instances (Jefferson *et al.*, 1991; Hoyt, 1990). Their social organization appears to vary by breeding population (Osborne, 1990; Baird, 1994; Heimlich-Boran and Heimlich-Boran, 1999; Baird and Whitehead, in prep..), with a basic species-wide pattern of matrilineal family units called pods, that vary in size from the minimum of mother and offspring, to extended family units of up to 50 individuals (Bigg *et al.*, 1987; 1990a). In the eastern North Pacific killer whale pods appear to consistently affiliate in communities of related family groups, and communities are believed to represent semi-closed breeding populations (Bigg *et al.*, 1987; 1990a; Hoelzel and Dover, 1991; Hoelzel *et al.*, 1998).

Cultural Characteristics

Recent evidence from studies in several different areas of investigation on killer whales have bolstered the case for killer whales being a species of long-lived social mammals that possess culture* (Osborne, 1986; 1990; Ford, 1990; Morton, 1990; Whitehead, 1998; Heimlich-Boran and Heimlich-Boran, 1999). Cultural transmission in killer whales is suggested by: 1) their long life-span and extended childhood learning

* "culture" in this context is defined in accordance with J.T. Bonner's definition: "*the transfer of information by behavioral means, most particularly by the process of teaching and learning* (Bonner, 1980, pg. 10)."

periods (Olesiuk *et al.*, 1990) relative to other mammals that possess culture (Moss, 1988; Caro and Hauser, 1992; Boesch, 1996; Tomasello and Call, 1997), 2) their advanced central nervous system relative to other mammals that possess culture (Jerison, 1973; 1986; Osborne and Sundsten, 1981; Ridgway; 1986) and 3) their complex learned communication system (Singleton and Poulter, 1971; Hoelzel and Osborne, 1986; Bain, 1986; 1989; Ford, 1989; 1990; Janik and Slater, 1997).

An additional way that killer whales appear to demonstrate cultural attributes is by exhibiting low diversity in their mitochondrial DNA (Whitehead, 1998). The reasoning is that females pass on behavioral traits to their offspring, such as specific feeding techniques or communication repertoires, and that these behaviors impart a significant reproductive advantage on their daughters, resulting in neutral mitichondrial DNA "hitchhiking" on the success of these behaviors passed from older females (Whitehead, 1998). The well known result of this in humans is low diversity of mitochondrial DNA (Cavalli-Sforza and Feldman, 1981). Whitehead's findings on this phenomena in matrilineal odontocetes is the first non-human example of this cultural characteristic, and strengthens the case that cultural adaptation should be given consideration as an influence upon the killer whale population in this study.

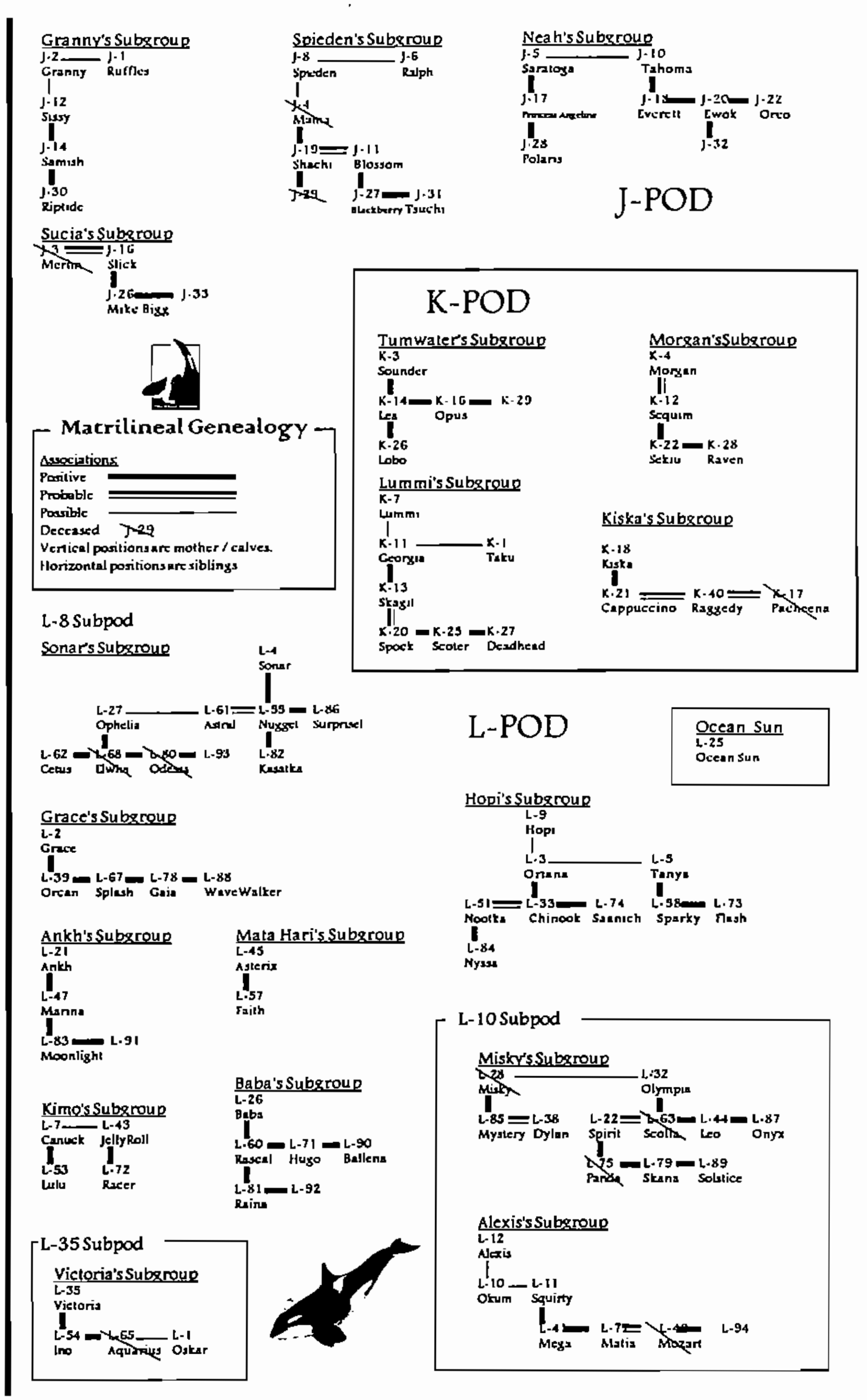
The Study Population

The "Southern Resident Community" of killer whale pods (Bigg *et al.*, 1976; 1987; 1990a), currently consists of four primary interbreeding maternal family lines (4 Pods) totaling about 90 members (Ford *et al.*, 1994; Ginneken and Ellifrit, 1999; Figure 8). This population of whales has been the subject of intensive study for over twenty years, allowing the accumulation of a long-term records on some aspects of their ecology

(Bigg *et al.*, 1987; 1990; Felleman *et al.*, 1991; Osborne, 1991; Barid *et al.*, 1992; Hoelzel, 1993; Brault and Caswell, 1993; Ford *et al.*, 1994; Center for Whale Research, 1998; Baird, 1999). A large part of their year-round home range includes the international inland waters of Puget Sound, Juan de Fuca, and Georgia Straits (the "Salish Sea"; Figures 3, 4 and 6). The unknown component of their home range comprises regions off the Pacific coasts of Washington State and British Columbia outside the entrance to Juan de Fuca Strait, to as far south as the Columbia River, and as far north as Cape Scott on Vancouver Island (Ford *et al.*, 1994; Ford and Ellis, 1999; Baird, 1999; Figure 6).

Based on the documented site fidelity of the Southern Resident killer whale population over the last 30 years (Ford *et al.*, 1994; Center for Whale Research, 1998; Baird, 1999), and in respect to recent findings on genetic relatedness between these killer whales and the surrounding Eastern North Pacific killer whale stocks (Hoelzel *et al.*, 1998; Barrett-Lennard, pers.com.), it is likely that the present Salish Sea community is the same ancestral line of killer whales that are first described in the human record. The human record of these killer whales begins with the art and folklore of Coast Salish peoples (Drucker, 1965; Borden 1979; McMillan, 1988) and later, European settlers of the region (Stenzel, 1975; Scheffer and Slipp, 1948; Griffin, 1982; Hoyt, 1990; Yates, 1992; Olesiuk *et al.*, 1990). Existing information will now be reviewed in more detail in an attempt to characterize the general ecological requirements for this killer whale population.

Figure 7 1994-1996 Southern Resident Killer Whale Genealogy



(Based on Center for Whale Research published and unpublished data, reprinted with permission of The Whale Museum, Orca Adoption Program, 1996, layout by Albert Shepard).

Overlapping and Adjacent Killer Whale Populations

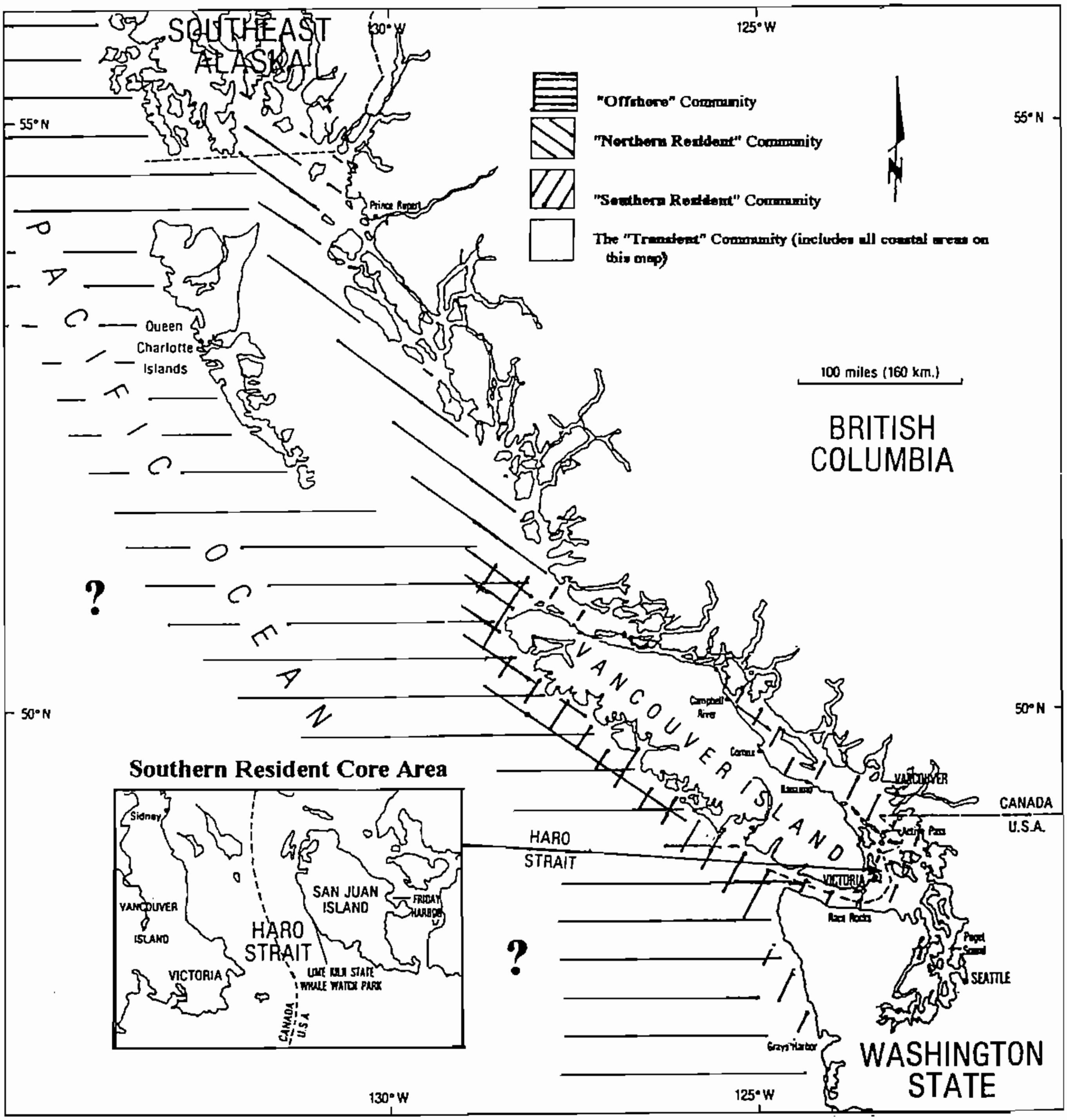
Overlapping with the "Southern Resident Community" are three other communities of killer whale pods (Figure 8): two other fish-eating populations (the *Northern Resident Community* and the *Offshore Community*) that are sympatric at the borders of the Southern Resident's range, and the mammal-eating *Transient Community,* which is sympatric throughout the coastal range of both the Southern Resident and Northern Resident Communities (Ford *et al.*, 1994; Baird, 1999; Ford and Ellis, 1999).

Transient Community

The most distinguishing characteristic of Transient killer whales (after Bigg, 1982) is that they primarily prey on other marine mammals, unlike the fish-eating communities (Morton, 1990; Ford and Morton, 1990; Felleman *et al.*, 1991; Ford *et al.*, 1994; 1995; Baird, 1994; Baird and Dill, 1996; Ford and Ellis, 1999). Other differences between transients and residents include measurable differences in morphology (Baird and Stacey, 1988; Bain, 1989), behavioral differences in group size and social organization (Baird, 1994; Baird and Whitehead, in prep.), and acoustic repertoire (Ford, 1981; 1987; Ford and Ellis, 1999). The northern limit for this Transient community appears to be the Icy Strait and Glacier Bay region of southeast Alaska, and their southern boundary is believed to be Puget Sound and along the outer Washington coast (Bigg *et al.*, 1987; Baird 1994; Ford *et al.*, 1994; Ford and Ellis, 1999).

The Transient Community pods that have been regularly documented within the Salish Sea represent a subset of the population of approximately 174 Transient individuals that have been photo-documented for the entire community (Ford and Ellis, 1999). The pods frequenting the Salish Sea represent about 22 individuals in 8 pods (Baird, 1994; Ginneken *et al.*, 1998; Ford and Ellis, 1999). These Transients are completely sympatric with the Southern Residents, but there is no genetic evidence to suggest that they

Figure 8 Geographic Range of the Southern Resident Killer Whale Community Relative to Neighboring Killer Whale Communities
(Map after Bigg *et al.*, 1987 and Ford *et al.*, 1994)

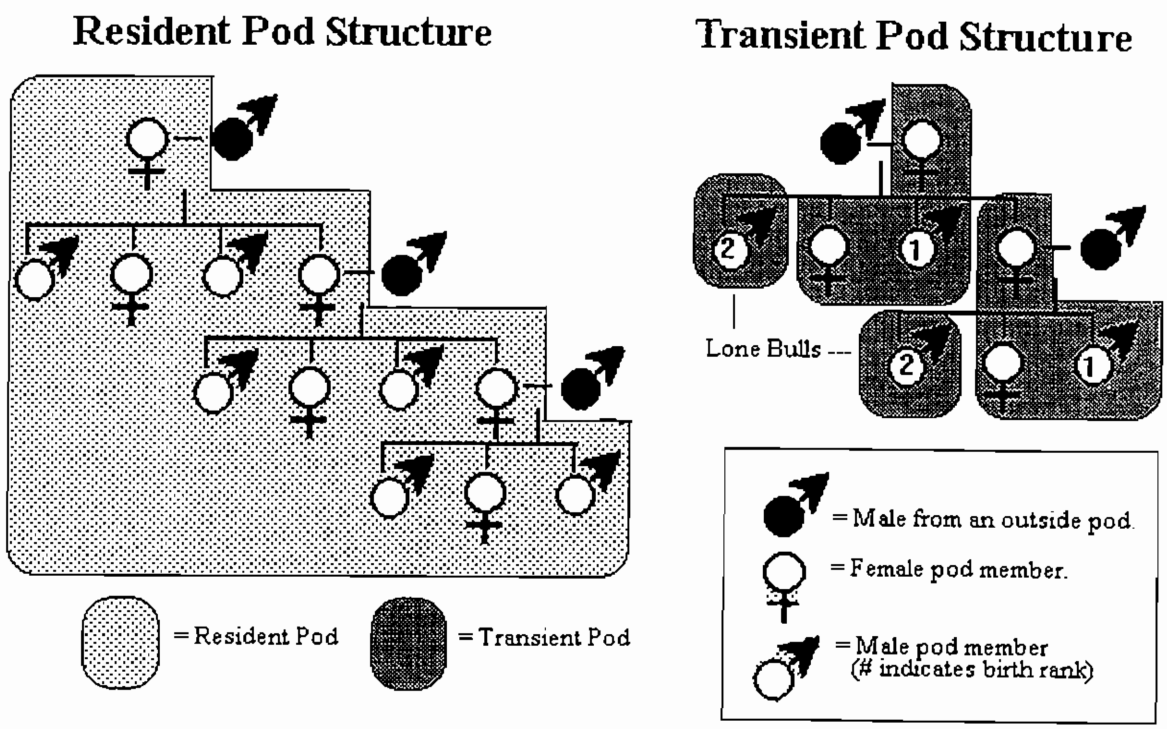


interbreed other than on an evolutionary time scale (Bigg *et al.*, 1987; 1990a; Hoelzel and Dover, 1992; Hoelzel *et al.*, 1998; Baird, 1994). All behavioral evidence in fact suggests that Transients actively avoid the resident pods (Felleman *et al.*, 1991; Ford and Morton, 1995; Baird, 1994; Ford and Ellis, 1999), and on at least one occasion where a clear interaction between residents and transients was observed, the small group of transients was documented being chased and harassed by the much larger Southern Resident group, J-Pod (Morton, 1990; Baird and Dill, 1996; Ford and Ellis, 1999; Baird, in press).

From a recruitment perspective the major difference between residents and transients is in their group size (Felleman *et al.*, 1991; Baird *et al.*, 1992; Baird, 1994; Baird and Dill, 1996). In long-lived, social predators like killer whales, social structure is going to be the primary factor maintaining group size (Eisenberg, 1981; Baird and Dill, 1996; Baird and Whitehead, in prep.). Social structure in the Northern and Southern Resident pods has been thoroughly described (Bigg, 1982; S.L. Heimlich-Boran, 1986; Bigg *et al.*, 1987; 1990a; Waite, 1988; Bain, 1989; Jacobson, 1990; Rose, 1992; Ford *et al.*, 1994; Figure 9). Unfortunately, the photo-identification record on Transients has only recently reached a size and consistency that allows it to be analyzed to the same extent as the Northern and Southern Resident pods (Baird and Whitehead, in prep.).

These recent findings on Transient social organization confirm the structure proposed by Baird in his doctoral dissertation (Baird, 1994). In Figure 9 a kinship schematic contrasting these two matrilineal social structures is presented. The "Resident" pod structure is characterized by the absence of offspring dispersal, so pods continue to grow, initially limited only by mortality and fertility (Bain, 1989). The "Transient" social structure involves offspring dispersal in both sexes (Baird, 1994; Baird and Whitehead, in prep.). Females disperse from the maternal pod with their first offspring and form a new pod. First born males stay in the maternal pod for life, and all subsequent male offspring disperse upon adulthood (Baird, 1994; Baird and Whitehead, in prep.).

Figure 9 Differences in Social Structure Between Resident and Transient Killer Whales (after Baird, 1994)



Northern Resident Community:

The Northern Residents represent approximately 200 individuals in 15 pods that range from Northern Georgia Strait along the B.C. coast into Southeast Alaska (Ford *et al.*, 1994; Figure 8). The Northern Residents are fish-eaters, and like the Southern Residents have been the subjects of continuous photo-identification cataloging (Bigg *et al.*, 1987; 1990a; Ford *et al.*, 1994; Dahlheim *et al.*, 1997), and numerous short-term studies of behavior, acoustics, genetics, and management (Spong *et al.*, 1970; Kirkevold and Lockard,

1986; Ford, 1984; 1989; 1991; Duffus, 1988; Waite, 1988; Bain, 1989; Morton, 1990; Nichol and Shackleton, 1996; Jacobson, 1990; Kruse, 1991; Rose, 1992; Barrett-Leonard *et al.*, 1996; Duffus and Dearden, 1992; 1993). Of all the pod communities that have overlapping ranges with the Southern Resident Community, the Northern Residents are considered to be the most similar to the Southern Residents in terms of behavior and ecology (Bigg *et al.*, 1987; 1990a; Felleman *et al.*, 1991; Ford *et al.*, 1994; Baird, 1999), and logically provide the best model for comparison with the Southern Residents in terms of historical ecology.

Offshore Community:

The Offshore Community is not as well understood as the other two fish-eating populations, due to their recent discovery (late 1980s), and the still incomplete photo-identification catalog of all individuals (Walters *et al.*, 1992; Ford *et al.*, 1992; 1994; Dahlheim *et al.*, 1997). They apparently live in the coastal and open ocean in the Eastern North Pacific (Figure 8), hence, almost all that is known about the Offshore Community comes from opportunistic encounters when they have ventured into coastal areas. Recent systematic work by researchers in the Queen Charlotte Islands (Ford *et al.*, 1992; 1994), Southeast Alaska (Dahlheim *et al.*, 1997), and California (Black *et al.*, 1996) is yielding some intriguing information about the Offshores.

The Offshore Community isbelieved to total between 200 and 250 individuals that are assembled into an unknown number of large "Resident-like" pods that have been documented feeding on fish (Ford *et al.*; 1994; 1998; Ford and Ellis, 1999). From the little that is known, it is thought that they spend most of their time in open ocean habitat that includes areas beyond the continental shelf. Photo-identification matches currently have their range stretching from Southeast Alaska to California (Black *et al.*, 1996; Dahlheim *et al.*, 1997). Genetic analysis of skin biopsies collected from the Offshore Community, and compared with the other communities, indicates that they exhibit high amounts of genetic similarity with the other fish-eaters in the region, and are more closely related to the Southern Residents than the Northern Residents (Hoelzel *et al.*, 1998).

Characterizing Indicators for the Southern Resident Community

As mentioned in the introduction to this chapter, descriptions of the ecology of a population of organisms are usually organized into several broad functional categories for heuristic purposes (Kormondy, 1969; Holling, 1973; 1992; Ricklefs, 1979; Eisenberg, 1981; Allen and Hoekstra, 1992). In the present study three classes of ecological requirements are utilized: 1) spatial requirements, 2) reproductive requirements, and 3) food requirements. Available information on the Southern Resident population of killer whales will be reviewed in respect to these three categories in order to provide a context for evaluating year-round sighting data, photo-identification data, and salmon catch data as longitudinal indicators for the ecology of these whales.

Spatial Requirements

Descriptions of spatial requirements for killer whales should include both geographic habitat range and three dimensional use of space above and below the surface of the ocean (Norris and Dohl, 1980; Hoelzel and Osborne, 1986; Baird, 1994). The geographic distribution of the Southern Resident killer whale population within the inland waters of the Salish Sea has been well documented except in the northern half of Georgia Strait (Bigg *et al.*, 1987; Osborne *et al.*, 1988; Ford *et al.*, 1994; Olson, 1998). In Northern Georgia Strait human population density and public participation in sighting networks is the lowest, and distances between shorelines are the greatest (Figure 8; Osborne, 1991; Olson, 1998). Outside of the Salish Sea, information on resident killer whale distribution along the coasts north and south of Juan de Fuca Strait is sketchy (Figure 8; Ford *et al.*, 1994). The information that does exist, however, is the most complete distribution record available for any population of killer whales in the world.

The geographic distribution of the Southern Resident killer whale population appears to be year-round in the adjoining waters of Puget Sound, Georgia Strait, Juan de Fuca Strait, and the outer coastal waters of the continental shelf (Figure 8). On a 24 hour cycle these resident killer whales are constantly traveling, with an average speed of 4 Knots (Osborne, 1986), and they have been tracked covering between 75 and 100 miles/day (Balcomb *et al.*, 1980; Heimlich-Boran, 1988). The extreme edges of their range encompasses most of the Washington Coast to unknown distances off shore, and all of Vancouver Island (Ford *et al.*, 1994). Seasonal distribution has been described in numerous publications, but has not been subjected to very thorough analysis (Bigg *et al.*, 1987; 1990a; Felleman *et al.*, 1991; Osborne, 1991; Ford *et al.*, 1994). This is primarily because the lack of information on their distribution outside the inland waters, severely restricts the potential for a valid seasonal analysis of habitat use.

In the present study an attempt is being made to examine seasonal patterns more thoroughly, by considering long-term records of killer whale occurrence in two sub-regions of the population's habitat where sampling efforts have been the highest (J.R. Heimlich-Boran, 1986a; 1988; Osborne, 1991).

Seasonal Geographic Cycle

The published literature on the basic seasonal pattern of the Southern Resident killer whales (Balcomb *et al.*, 1980; J.R. Heimlich-Boran, 1986a; 1988; Bigg *et al.*, 1987; 1990a; Felleman *et al.*, 1991; Osborne, 1991; Ford *et al.*, 1994; Olson, 1998), is for the majority of the population to be distributed in the core waters of northern Juan de Fuca Strait, Haro Strait and southern Georgia Strait during summer months (Figures 6, 8). In fall, a part of the population makes regular forays into Puget Sound (primarily J-Pod), while the rest of the population (primarily L-Pod) makes increasingly extended trips west out Juan de Fuca Strait, until they essentially disappear from the inland waters by December. After December, with few exceptions, K- and L- Pods (about 75% of the population) are consistently undetected in the Salish Sea region until May or June (J.R. Heimlich-Boran, 1986a; Felleman *et al.*, 1991; Osborne, 1991); when these two pods regularly return within a week or so of each other (Center for Whale Research, unpublished data; Osborne unpublished data).

One extended family unit, J-Pod (currently 22 individuals), is consistently detected in the inland waters during all months of the year, and has never been documented further west than Barkeley Sound, along the west coast of Vancouver Island (Felleman *et al.*, 1991; Ford *et al.*, 1994). It is assumed by most local investigators that J-Pod's year-round habitat is essentially restricted to the waters of the Salish Sea, but in the winter months they spend less time in the Haro Strait region and more time in Puget Sound, northern Georgia Strait, and other peripheral reaches of the inland waters (Heimlich-Boran 1988; Felleman *et al.*, 1991; Osborne, 1991; Balcomb, 1995).

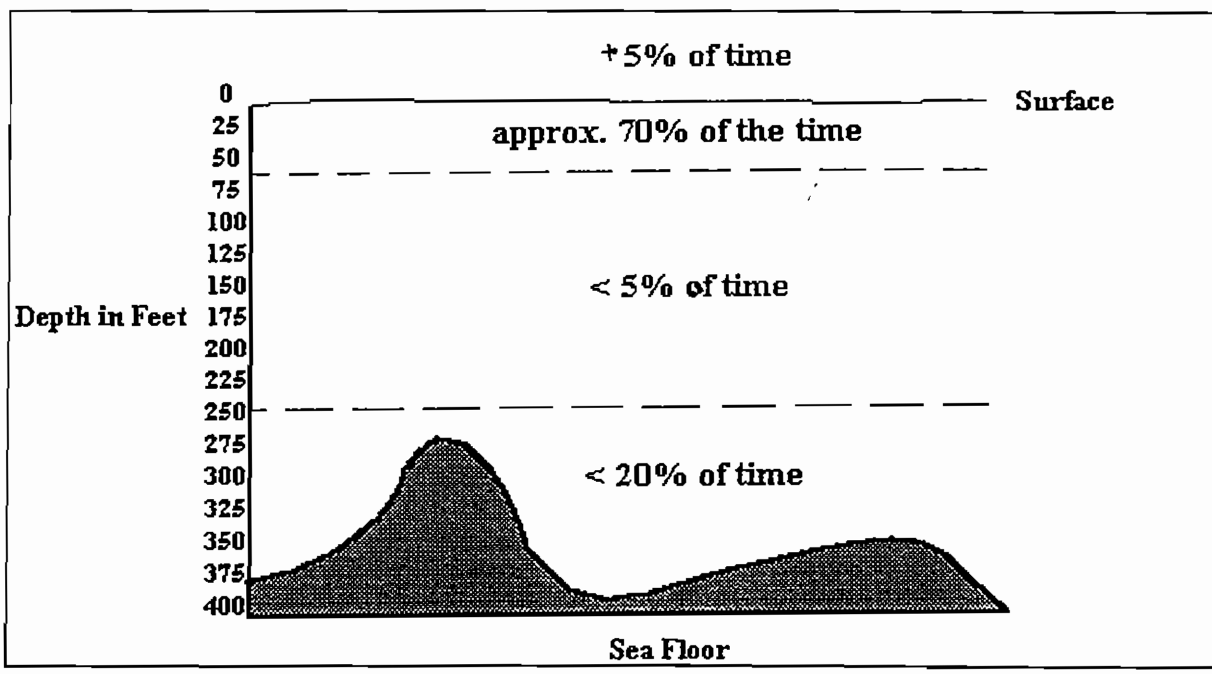
Three Dimensional Habitat-Use

Three dimensionally, killer whales have a dependence on regularly reaching the ocean surface to breath (Bateson, 1974; Herman, 1991), though they are underwater close to 95% of the time (Baird, 1994; Baird *et al.*, 1998). Breathing, resting, percussive behavior, and aerial displays are the primary things killer whales do at or above the ocean surface. These are the behaviors that almost all scientific observations of killer whale behavior are based upon, and they have been described thoroughly in the literature (Martinez and Klinghammer; 1970; 1978; Salden, 1979; Jacobson, 1986; 1990; Osborne, 1986; Hoelzel and Osborne, 1986; Heimlich-Boran, 1988; Waite, 1988; Ford, 1989; Morton, 1990; Felleman *et al.*, 1991; Kruse, 1991; Rose, 1992; Hoelzel, 1993). Yet the majority of killer whale behavior; including feeding, reproduction, socialization, and acoustics (both echolocation and social communication), takes place below the surface. This inability to directly monitor killer whale behavior underwater has severely restricted any real understanding about how they use their three-dimensional habitat until recently (Baird, 1994; Baird *et al.*, 1998) .

Using suction cup tags with time-depth recorders, R.W. Baird and his colleagues have been conducting field studies on the underwater behavior of Southern Resident and Transient killer whales since 1991. The initial findings indicate that resident killer whales spend about 60-70% of their time between the surface and a depth of 20 meters, and they regularly make deep dives of over 200 meters (Baird, 1994; Baird *et al.*, 1998). The deep dives consistently involve a direct trip to the bottom, often to the upper reaches of underwater sea mounts. Further research using this technology is on-going, and providing a host of additional insights into the underwater behavior and ecology of both resident and transient killer whales (Baird *et al.*, 1998).

The preliminary findings indicate a contrast between the diving patterns of residents and transients. Transient killer whales rarely dive deep, and appear to spend the majority of their time within 5 meters of the surface (Baird, 1994; Baird *et al.*, 1998). Resident killer whales primarily use the upper 20 meters of the water column, secondarily use deep bottom habitat, and are not spending very much of their daily lives in the water column between these two zones (Baird, 1994; Baird *et al.*, 1998; depicted in Figure 10).

Figure 10 **Southern Resident Killer Whale Underwater Zones** (after Baird, 1994).



Reproductive Requirements

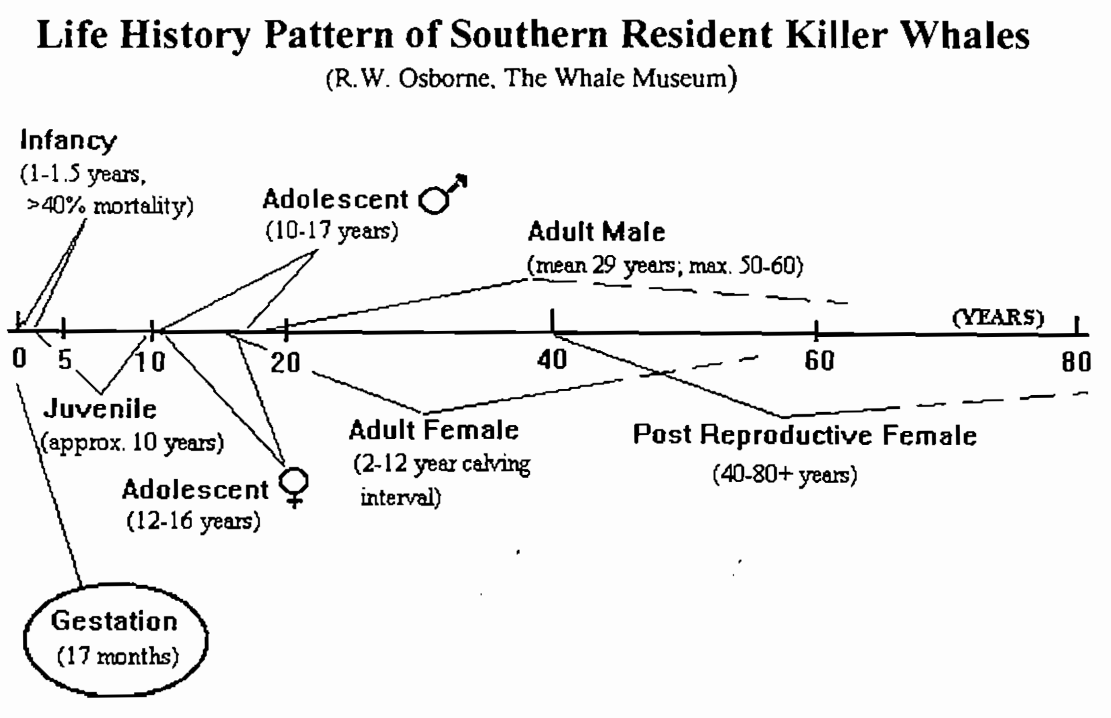
The continuous photographic record on individual killer whales in the Southern Resident population dates back to matches with "capture photographs" from the mid-1960s (Bigg *et al.*, 1990a; Hoyt 1990; Olesiuk *et al.*, 1990; Balcomb, 1995; 1997) to essentially all individual whales alive after 1974 (Ford *et al.*, 1994; Ginneken and Ellifrit, 1999), when systematic individual photo-identification was first initiated by Michael Bigg, Graeme Ellis, and Ian MacAskie (1976). Thus, the demographic history of this population has been completely documented for over two decades, and has allowed their life history patterns and social structure to be described in detail (S.L. Heimlich-Boran, 1986; Haenel, 1986; Bigg *et al.*, 1990; Olesiuk *et al.*, 1990; Ford *et al.*, 1994; Ginneken *et al.*, in prep.; Baird and Whitehead, in prep.).

Life History Pattern

The photo-identification records show that killer whales exhibit a life history pattern closer to humans than any other species (Figure 11). Average life expectancy for the Northern and Southern Resident Communities has been calculated as 29.2 years for males and 50.2 years for females, with expected maximum longevity of 50-60 years, and 80-90 years respectively (Olesiuk *et al.*, 1990). The basic killer whale life cycle begins with 17 months of gestation (Walker *et al.*, 1988), and then a perilous first year of infancy, with a mortality rate approaching 50% (Olesiuk *et al.*, 1990). Nursing is believed to last a minimum of 1-2 years in the Southern Residents based on surface observations of behavior (Haenel, 1986; Waite, 1988; Baird, pers. comm.; Ellifritt, pers.comm.). Stomach contents of a dead calf suggests that they may begin eating some solid food shortly after parturition (Heyning, 1988).

A long juvenile period of up to 10 years follows infancy, and extends into an adolescent period of 3-5 years (Haenel, 1986; Olesiuk *et al.*, 1990). In their comprehensive assessment of life history patterns in the Vancouver Island resident pods, Olesiuk *et al.* (1990) defined sexual maturity as the age when a female first gives birth to a viable offspring (12-16 years, mean = 14.9), and male sexual maturity as the time when a male's dorsal fin shape can be photogrametrically distinguished from that of a female (10-17.5 years, mean = 15). Sexually dimorphic dorsal fin growth in males is believed to indicate the onset of increased testosterone levels indicative of adolescence, and appears to last at least six years (J.R. Heimlich-Boran, 1986b; Olesiuk *et al.*, 1990). Physical maturity is thought to occur at the end of this dorsal fin growth period, in the individual's late teens or early twenties (Olesiuk *et al.*, 1990).

Figure 11



(Schematic diagram summarizing information presented in the text)

Mean reproductive life span for females has been calculated by Olesiuk *et al.* (1990) to be from 14.9 to 40.1 years, with some individuals appearing to stay reproductive into their 60th year. Reproductive life span of males is unknown. Calving intervals have been calculated to vary from 2 to 12 years in the Northern and Southern Resident pods, with a mean calving interval of 5.3 years (Olesiuk *et al.*, 1990). This provides a mean female reproductive life span of 25.2 years resulting in the average production of 4.75 calves. Infant mortality rates suggest that about half those calves will die in their first year, but during the rest of their life span, the surviving juveniles will experience mortality rates ranging from 20% to less than 5% for most of the rest of their lives until senescence (Olesiuk *et al.*, 1990).

Causes of mortality in this population are sketchy, since very few carcasses have ever been recovered (18 carcasses out of 70 deaths since 1976; Table 1). In only one case was the cause of death even remotely suggested (L-8, September, 1977); which was a stranding of an adult male who had possible net marks on the decomposed carcass, that corresponded with a rumor among fishers about a whale getting caught in a gillnet around the estimated time of the death (Balcomb *et al.*, 1980; author's records). The majority of other strandings are neonates (78%), and of the 14 neonates that have historically been recovered in the region, 86% are male (Table 1). The lack of recovered adult carcasses is likely due to the fact that adult carcasses have a greater tendency to sink in deep water and never make it back to the surface where they can be deposited as a terrestrial stranding. However, the predominance of male neonate strandings raises the specter of male infanticide (Lockard, 1986; Bigg *et al.*, 1990a).

There are no records of killer whales being attacked by any marine predators (Jefferson *et al.*, 1991; Baird *et al.*, 1992). It is possible, however, that wandering infants, or sick or injured individuals have been taken by sharks or other killer whales (Jefferson *et al.*, 1991; Baird *et al.*, 1992). Parasitism and disease have been recorded for killer whales

Table 1 Dead Stranded Killer Whales Attributable to the Southern Resident Community

Age Class	Date	Location	Sex	Length (cm)	Suspected Pod	Lungs Inflated	Source
Neonate	Sep. 28th,1944	Cherry Point, WA	female	246 cm	Unknown if Res./Trans.	No ?	Carl (1946) in Olesiuk, et al. 1990
Neonate	Feb. 1967	Yukon Harbor, WA	unknown	257 cm	K-Pod	Yes	Olesiuk, et al, 1990
Neonate	May 9th, 1976	Long Beach, B.C.	male	250 cm	K or L-Pods	No ?	Olesiuk, et al, 1990
Neonate	Nov. 5th, 1976	Radar Beach	male	226 cm	K or L-Pods	Unknown	Olesiuk, et al, 1990
Adult	Sep., 1977	San Juan Is., WA	male		L-Pod	N.A.	The Whale Museum
Neonate	Mar. 31st, 1978	Oyster Bay	male	225 cm	Southern Resident	Yes	Olesiuk, et al, 1990
Neonate	Oct 4th, 1978	Victoria, B.C.	male	221 cm	Southern Resident	Unknown	Olesiuk, et al, 1990
Juvenile	Aug. 14th, 1981	Lummi Is., WA	unknown	580 cm	Unknown if Res./Trans.	N.A.	U.S. Nat. Mar. Fish. Serv..
Neonate	Nov. 15th 1983	Seattle, WA	female	218 cm	J or K-Pods	Yes	Olesiuk, et al, 1990
Neonate	Oct. 7th, 1986	Tsawassen, B.C.	male	226 cm	Southern Resident	Yes	Olesiuk, et al, 1990
Neonate	Nov. 13th, 1987	Ucluelet, B.C.	male	245 cm	K or L-Pods	Yes	Olesiuk, et al, 1990
Neonate	Jan. 5th, 1989	Stuart Is., WA	male	230 cm	J-Pod	Yes	The Whale Museum
Adolescent	Apr., 24th, 1989	Long Beach, B.C.	male		L-Pod (L-14)	N.A.	D.F.O., Pac. Biol. Station
Neonate	May 15th, 1991	Esquimalt, B.C.	unknown	unknown	Southern Resident	Unknown	Marine Mammal Research Group
Neonate	May 26th, 1991	Clallam Bay, WA	unknown	unknown	Unknown if Res./Trans.	Unknown	U.S. Nat. Mar. Fish. Serv..
Adult	Dec. 13th, 1995	Texada Is., B.C.	female		J-Pod (J-4)	N.A.	D.F.O., Pac. Biol. Station
Neonate	November, 1998	B.C.	male	unknown	J-Pod	Unknown	U.S. Nat. Mar. Fish. Serv..
Neonate	February, 1999	Whidbey Island, WA	male		J-Pod	Unknown	D.F.O., Pac. Biol. Station

N.A. = Not Applicable **Infant** = 1 mth. to 3 yr **Adolescent** = 12-17 yrs
Neonate = Still-born to 1 mth. **Juvenile** = 3 to 11 yrs **Adult** = 18 yrs +

from the region, but not as severe infestations or epidemics (Calambokidis and Baird, 1994; Baird,1999). Human predation has likely been a significant factor in mortality for this population, ranging from random shootings, to military target practice, and captures for the entertainment industry (Hoyt, 1990; Olesiuk *et al.*, 1990; Baird, 1999). Indirect human impacts from toxic chemicals, hazardous waste, and other forms of habitat deterioration would be expected to be contributing sources of mortality, but at the present time these impacts are poorly understood. A primary objective of the present study is to increase our understanding of these potential impacts by examining their historical context.

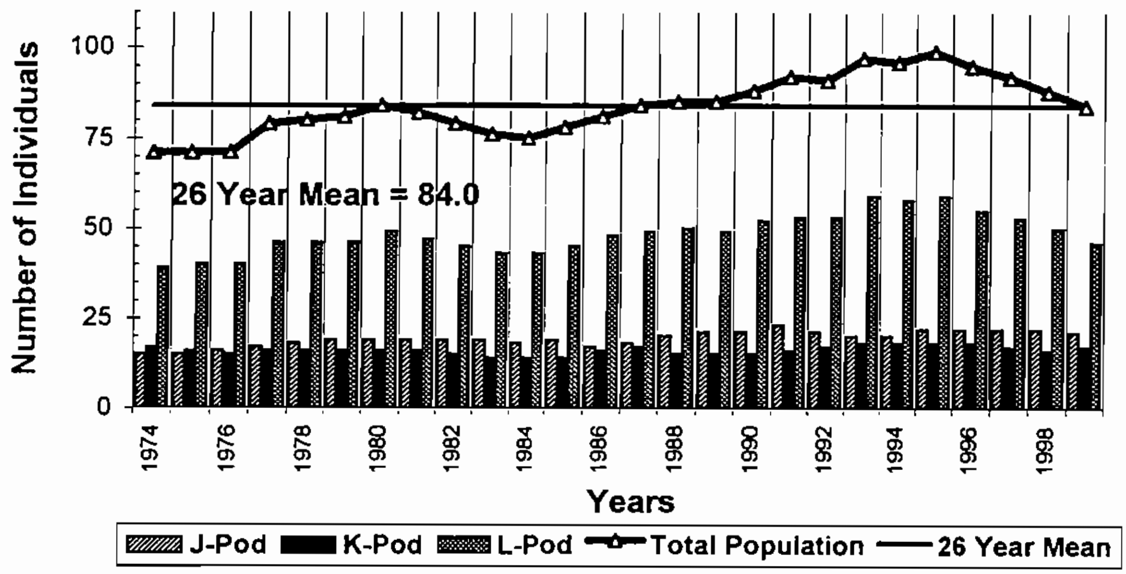
Population Growth

The growth rate for this population during the first 15 years of photographic data has been calculated between 2.5% (Brault and Caswell, 1993) and 2.9% per year (Olesiuk *et al.*, 1990) using independent methods. Both of these studies describe the Northern and

Southern Resident Communities as similarly stable breeding populations that show an over all positive increase that suggests they are presently below carrying capacity (Olesiuk *et al.*, 1990; Brault and Caswell, 1993). However, due to the very long reproductive response times for these populations in terms of gestation, female sexual maturity, and calving intervals, and the relatively small sizes of the breeding populations, any perturbations of adult survivorship or fertility rates could strongly affect their sustainability (Brault and Caswell, 1993). This is particularly true for the Southern Residents with their much smaller breeding population (unless a portion of them are actively breeding with Offshores). As a population of less than 90 individuals these killer whales would not be in a strong position to recover from a random mass mortality event (Baird, 1999).

In Figure 12 the most recent historical compilation of annual population size published by the Center for Whale Research (Ginneken and Ellifrit, 1999; Ginneken *et al.*, In Prep.) is plotted relative to pod size and the 25 year mean for the Southern Resident Community. The 2-3% growth rate predicted by Olesiuk *et al.* (1990) and Brault and Caswell (1993), seems to have basically held true over the first 22 years; but due to a recent downward trend, as of 1999 the 26 year growth rate is below its sample mean for the first time in the history of the data set (Figure 12). In their original analyses, both of the above studies included the slump in the population that occurred from 1980 to 1984 (Figure 12); suggesting that the current downward trend could still be within the natural stochastic fluctuations of a long-term 2-3% growth rate; though in 1999 this trend did not level off like it did in 1984. In summary, this population has been relatively stable over the last 26 years, not exhibiting the degree of growth that would be expected for a population below carrying capacity (Brault and Caswell, 1993), and presently it is on a downward trend that is longer than any that have been previously documented.

Figure 12 Southern Resident Killer Whale Community Annual Population Relative to the Population Mean (1974-1999)



(Data from Olesiuk et al., 1990; Ginneken and Ellifrit, 1999)

Food Requirements

The Southern Resident Community of killer whales have consistently been reported to have a strong specialization upon salmon as their primary food resource (Balcomb *et al.*, 1980; J.R. Heimlich-Boran, 1986a; Bigg *et al.*, 1987; 1990a; 1990b; Felleman *et al.*, 1991; Ford *et al.*, 1995; 1998). An inventory on the diet of these whales has been summarized most recently by Ford, Ellis, Morton (1995; and Ford *et al.*, 1998), using 161 records of feeding events pooled from the Northern and "Southern Resident" populations (Table 1). Their findings show a large variety of fish and marine mammal species as occasional prey for these communities of killer whale pods, but the sample is small, and sampling bias in terms of season and geography is high (Ford *et al.*, 1998). Given these cautions, the study shows a 93% preference for salmon, and among the five

Table 2 Diet of Northern and "Southern Resident" Killer Whales Based Upon 161 Feeding Events

(after Ford, Ellis and Morton, 1995; Ford *et al.*, 1998)

Prey Species	Sample Size	% of Diet
Chinook salmon (*Oncorhynchus tshawytscha*)	62	38.0
Pink Salmon (*O. gorbuscha*)	16	10.0
Coho salmon (*O. kisutch*)	6	4.0
Chum salmon (*O. keta*)	6	4.0
Sockeye salmon (*O. nerka*)	4	3.5
Steelhead salmon (*O. mykiss*)	2	2.5
Unidentified salmon (*Oncorhynchus spp.*)	50	31.0
Total Salmon		93.0
Other fish species	6	4.0
Harbor Seal (*Phoca vitulina*)	1	
Harbor porpoise (*Phocoena phocoena*)	4	
Dall's porpoise (*Phocoenoides dalli*)	4	3.0
TOTAL:	**161**	**100%**

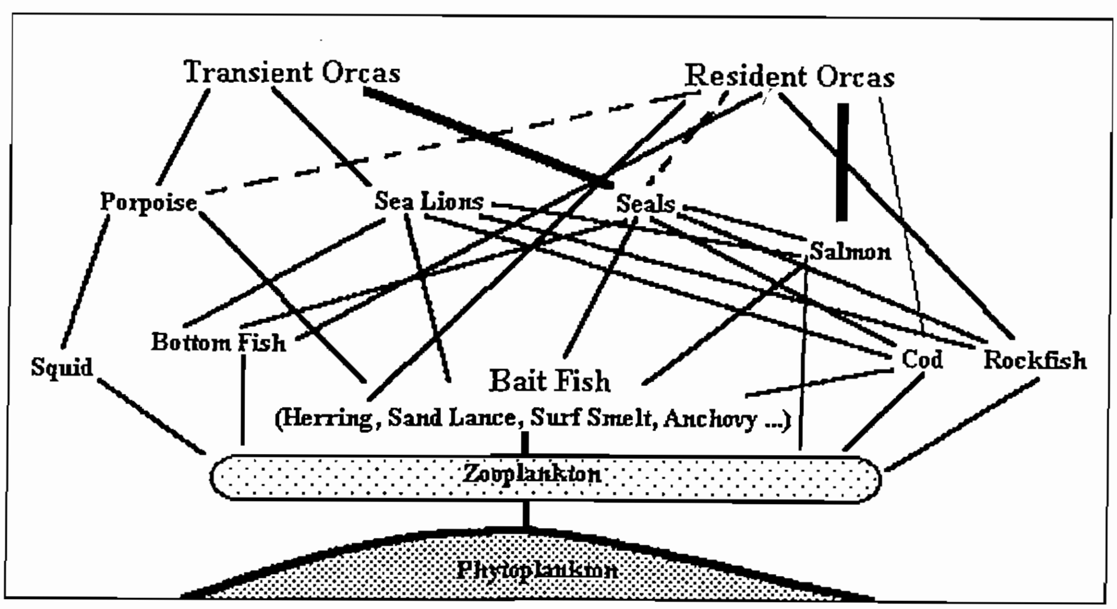
species of salmonids identified in the study, 63% were Chinook salmon (*Oncorhynchus tshawytscha*).

The other species of fish prey identified in this study include Pacific herring (*Clupea harengus*), Yelloweye rockfish (*Sebastes ruberrimus*), halibut, and other unidentified flatfish, *Pleuronecties sp.* (Ford *et al.*, 1998). The marine mammal predations represent sporadic attacks on pups or calves of the most common species of seal (*Phoca vitulina*) and porpoises (*Phocoena phocoena* and *Phocoenoides dalli*), and do not indicate that marine mammals are a very significant part of the resident killer whale diet (Bigg *et al.*, 1990b; Ford *et al.*, 1998).

Although salmon dominate this inventory of prey species (Table 2), and undoubtedly dominate the feeding strategies of these whales, the importance of the other species of fish in their diet should not be overlooked. Baird's findings on repeated deep dives by Southern Residents, indicates that these killer whales regularly direct their effort(Baird, 1994; Baird *et al.*, 1998). These other prey resources could be providing essential nutrients that are absent from a pure salmon diet, and may prove to be critical as supplementary or replacement resources if year-round salmon continue their current downward trend in abundance (Schmitt *et al.*, 1994; Appleby and Doty, 1995; Pacific Salmon Commission, 1999).

The emphasis on the importance of salmon for these killer whales must also be placed in the larger ecological context of the regional food web that underlies it all (Figure 13). Killer whales are at the pinnacle of this food web and as such, are dependent upon the stability of the entire system (Simenstad *et al.*, 1979). They also directly consume resources from many of the other upper trophic levels (Figure 13). The primary prey of to be in habitat zones where salmon are absent and these other prey species are abundant resident killer whales, adult salmon, are themselves upper trophic level feeders; but in the

Figure 13 **A Simplified Food Web for Salish Sea Killer Whales**
(simplified from Simenstad *et al.*, 1979)



context of the salmon's entire life cycle, they probably span more trophic levels (phytoplankton, zooplankton, insect larvae, bait fish, con-specific smolt and fry), and habitats (freshwater streams, lakes, rivers, estuaries, coastal upwelling areas, open ocean) than any other species in the Salish Sea bioregion (Groot and Margolis, 1991). For the killer whales to be dependent upon a species that is itself so vulnerable to habitat interference, makes the killer whales themselves equally vulnerable if they are unable to adapt to different food resources.

Salmon Prey

From all the available evidence salmon may be the single best indicator of food resource conditions for this killer whale population (Balcomb *et al.*, 1980; J.R. Heimlich-Boran, 1986a; Bigg *et al.*, 1987; 1990a; 1990b; Felleman *et al.*, 1991; Ford *et al.*, 1995; 1998). To thoroughly assess this ecological relationship the ideal data would provide prey identification and predation counts for each age and sex class of killer whale in the population, and at representative locations, times of day, and season (Brown and Downhower, 1988). Unfortunately the capture of fish by killer whales is virtually invisible with present technology (Thomas and Felleman, 1988; Baird, 1994), so indirect methods must be used.

The types of salmonids that Salish Sea killer whales have been documented to feed on include ocean-going adult fish from all five local species, as well as the closely related steelhead salmon (*Oncorhynchus mykiss*) (Table 2; Bigg *et al.*, 1990b; Ford *et al.*, 1998). Ages of salmon prey for these killer whales range from 2nd year Chinook juveniles (personal observation: January 1978 w/J-Pod in Haro Strait; Balcomb *et al.*, 1980), to nearly senescent chum salmon at the estuarine mouth of their spawning stream (personal observation: November 1997 w/L-Pod in Dyes Inlet; Smith *et al.*, in prep.).

The availability of this range of salmon prey at any one time or location is controlled by many factors. Each salmon run varies according to genetic characteristics of their stock's unique life cycle. Each run also varies annually due to the environmental history of the particular year-class (Groot and Margolis, 1991; Schmitt *et al.*, 1994). For Puget Sound alone there are currently 208 stocks of salmon officially identified (Schmitt *et al.*, 1994; Wash. State, 1999). An estimate of the total number of salmon stocks that produce fish available to Salish Sea killer whales has yet to be calculated, but it would have to include all the runs associated with the entire Salish Sea watershed (Figure 4). Conservatively this represents a minimum of 500 salmon runs and each of these runs will produce adult salmon that are available to the killer whales in different locations depending on their unique genetic and historical set of characteristics.

In most cases the adult fish that the killer whales are feeding on are fish returning to their natal stream to spawn after spending 2-6 years feeding in the Eastern North Pacific (Groot and Margolis, 1991). These are exactly the same size and age of salmon maximally sought after by humans for commercial and recreational fisheries.

As migrating salmon enter the inland waters on the journey to their natal stream they become more concentrated by the geography of the inland waters and begin schooling up with their cohorts (Groot and Margolis, 1991). It is these concentrated schools of salmon that the resident killer whales are likely seeking (Hoelzel and Osborne, 1986; Felleman *et al.*, 1991; Baird, 1994; Nichol and Shackleton, 1996). Depending on the salmon run, a school can remain for days, weeks, or months in the inland waters before traveling to the mouth of their natal river or stream (Simenstad *et al.*, 1982; Schmitt *et al.*, 1994). Since each run is usually made up of several consecutive schools that pass through the inland waters in pulses, any given run has several pulses of schools spread along the inland route at the same time (Heard, 1991; Salo, 1991; Sandercock, 1991; Healey, 1991).

Since humans and killer whales both exploit the same size and age of salmon, at essentially the same time and in the same places, records of salmon predation by humans in the Salish Sea should be good indicators of salmon availability for killer whales

(J.R.Heimlich-Boran, 1986a; Nichol and Shackleton, 1996). The types of salmon data available include commercial harvest data, recreational harvest data, tribal fisheries harvest data, hatchery release and return data, and freshwater production and return data. Of these data sets, the commercial, tribal and recreational harvest data are the closest to sampling salmon at the same time and place as the killer whales. However, the commercial harvest data is usually highly skewed by management for specific runs of salmon, and does a poor job of sampling salmon outside the highly regulated commercial fishing openings. Only recreational sport fishing data samples the salmon 365 days a year.

Sport fishing data are based either on crile surveys, or the collection of salmon punch cards, which are probably the least reliable sampling methods used in salmon management (Applby and Doty, 1995). Also, of the local species of salmon, only chinook, coho and pink salmon can be predictably caught by sport fishers. Sockeye and chum salmon are much more difficult to sample using a hook and line, and are severely under-represented by recreational fishing data (Roos, 1990). However, because sport data is collected all year round, it is the most useful data set for describing the year-round availability of salmon as prey for the killer whales (Figure 14).

Seasonal salmon sport catch data represents monthly totals of the number of salmon caught by sport fishers in different geographic zones of the inland waters of Washington State for each species of salmon from 1967-1994 (Washington State Dept. Fish & Wildlife 1993; 1994; Schmitt *et al.*, 1994). Calculating the percentage of the salmon caught by month over a 15-25 year sample gives a fairly accurate picture of the relative seasonal abundance for each species of salmon. This seasonal plot also allows Sockeye (Figure 14a) and chum (Figures 14a - 14c) to be plotted even though they are consistently under represented in the sample.

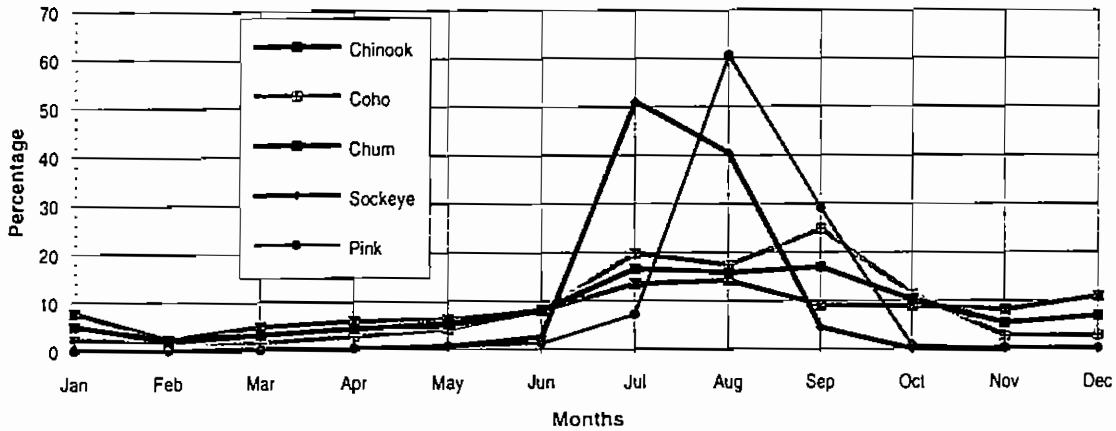
As can be seen in Figure 14, all salmon species, except chum, have their highest abundance in the inland waters during the summer and early fall, with chum reaching a maximum in October and November in Puget Sound and the San Juan Islands (Figures 14b and 14c). Thus, the bulk of the Salish Sea salmon runs are available to the killer whales in the inland waters summer and fall, which corresponds exactly with published findings on the seasons when both Northern and Southern Resident killer whale populations are maximally found in the inland waters of Washington State and British Columbia (Ford *et al.*, 1994; J.R.Heimlich-Boran, 1986a; Nichol and Shackleton, 1996; Felleman *et al.*, 1991). From January to May chinook salmon are most consistently caught by sport fishers, indicating that they are available to killer whales in the inland waters during this 4-5 month period (Figure 15).

The seasonal availability of chinook salmon, and to some extent coho salmon , is unique relative to the other salmonids, because some species naturally spend their entire adult life in the coastal and inland marine waters, and do not go out into the Eastern North Pacific to mature (Simenstad *et al.*, 1988; Healy, 1991; Sandercock, 1991; Appleby and Doty, 1995). Fisheries managers have taken advantage of this characteristic of chinook and coho with their hatcheries for these species. This is accomplished by implementing "extended rearing programs" that theoretically increase the number of fish that stay in the inland waters so they are more available to year-round sport fishers (Appleby and Doty, 1995). This also results in a significant number of these salmon, at all adult sizes, being available as killer whale food in the inland and coastal waters year-round (Figure 14). These resident chinook and coho stocks would be particularly important to the resident killer whale pods that stay in the inland waters through the winter and early spring months (i.e. J-Pod), when other adult salmon stocks are oceanic in their distribution (Simenstad *et al.*, 1982; Appleby and Doty, 1995). Interestingly, chinook was the one species of salmon that clearly dominated the year-round sample of 161 feeding events compiled by Ford *et al.* (1998) for the Northern and Southern resident killer whales.

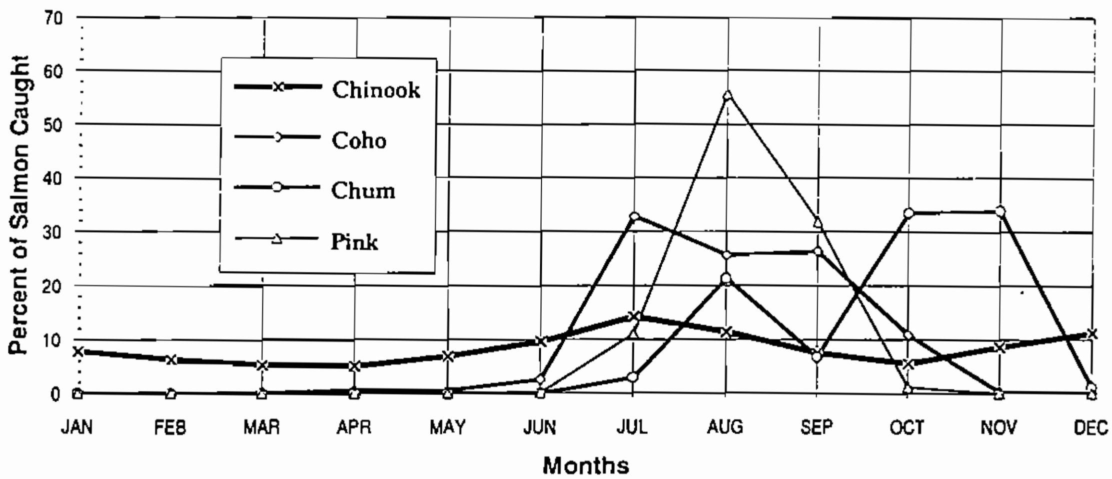
Figure 14

14a: **Seasonality of Washington State Salmon Sport Catch All Inland Marine Waters (1978-94)**

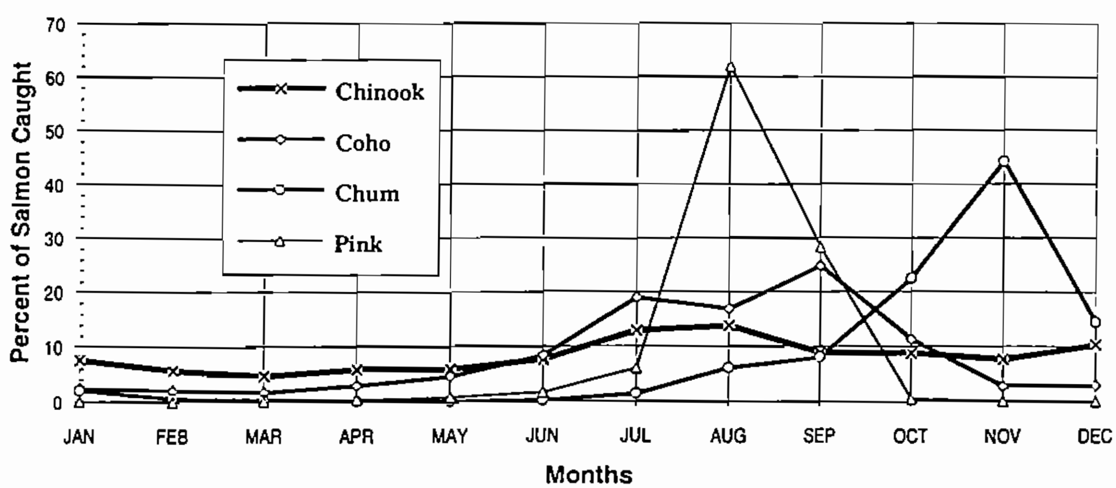
(Data: Wash. St. Dept. Fish & Wildlife)



14b: **Seasonal Salmon Sport Catch in the San Juan Islands**



14c: **Seasonal Salmon Sport Catch in Puget Sound**



Now, within the context of the published findings on this population that have just been presented, the status of the Southern Resident killer whale population will be characterized through the use of: 1) photo-identification as a measure of population size and stability, 2) population size to estimate food resource requirements, and 3) public sighting data as a measure of habitat-use.

METHODS

For over two decades the "Southern Resident Community" of killer whales have been inventoried through individual photo-identification (Bigg *et al.*, 1987; Balcomb, 1997; Ginneken and Ellifrit, 1999). These killer whales have also had their seasonal movements tracked through public sighting records (Balcomb *et al.*, 1980; J.R.Heimlich-Boran, 1986a; 1988; Osborne, 1991; Olson, 1998), and have been the subjects of numerous short-term studies (see Kirkevold and Lockard, 1986; Hoelzel, 1993; Felleman *et al.*, 1991; Osborne, 1991; Baird, 1994; Kriete, 1995; Burgen and Otis, 1995). These data sets are able to provide quantitative indicators of some of the basic ecological variables characteristic of the status of this population of killer whales, and their stability over time. The three proposed ecological indicators are: 1) photo-identification as a measure of population size and structure, 2) population size and composition to estimate food resource requirements, and 3) public sighting data as a measure of spatial habitat-use. The methods for deriving these quantitative indicators will now be presented.

Study Area

For some discussions the geographic context will expand to the entire known range of the Southern Resident killer whale pods (Figure 8): from Grays Harbor and Willapa Bay in the south, to Queen Charlotte Sound in the north, and unknown distances off the coast into the Pacific (Ford *et al.*, 1994). However, the core study area only includes the adjoining waters of Juan de Fuca Strait between Race Rocks and the San Juan

Islands, Haro and Rosario Straits, Southern Georgia Strait to Point Roberts, and Puget Sound. This region is then divided into two sampling zones for the purposes of analysis (Figure 15). The southern zone corresponds to Admiralty Inlet and Puget Sound proper (Wash. State Fishery Reporting Areas 8-13), and the other is the straits convergence zone around the San Juan and Gulf Islands (Wash. State Fishery Reporting Areas 6-7 and DFO Reporting Areas 18-20). The objective is to measure the number of days per month killer whales occur in these two zones as an indicator of trends in habitat use.

Photo-identification

Long-term photo-identification of all the individuals in a population provides a highly accurate measure of annual population size and composition (Bigg, 1982; Olesiuk *et al.*, 1990; Brault and Caswell, 1993; Balcomb, 1997). This allows mortality, natality, dispersal, and other population measures to be assessed for any and all years a complete photo-inventory is compiled (Olesiuk *et al.*, 1990; Brault and Caswell, 1993).

The focal population of killer whales in this study have had complete photographic inventories compiled on them for every year since 1973 (Bigg *et al.*, 1976; 1987; 1990a; Ford *et al.*, 1994; Balcomb, 1997; Ginneken and Ellifrit, 1999). The classification system utilized by these investigators is alpha-numeric, where a letter (A, B, C, ...) is used to designate the group, or pod (extended matrilineal family), and a number (1,2,3, ...) is used to signify each individual within the pod (A-1, A-2, A-3 ...). Beyond this level of classification, pods that associate with each other are referred to as "communities" (Bigg *et al.*, 1987; 1990), and pods that share the same acoustic dialects are referred to as "clans" (Ford, 1990; Ford *et al.*, 1994).

Figure 15:

Killer Whale Study Quadrants and Killer Whale Sighting Effort (1976-1996)

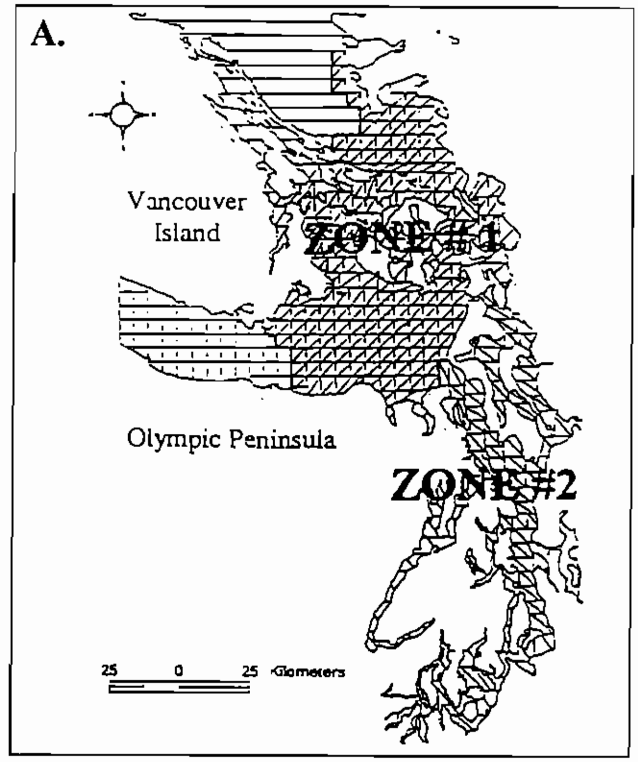
Map A: Statistical study area showing the two
primary zones used in analysis:

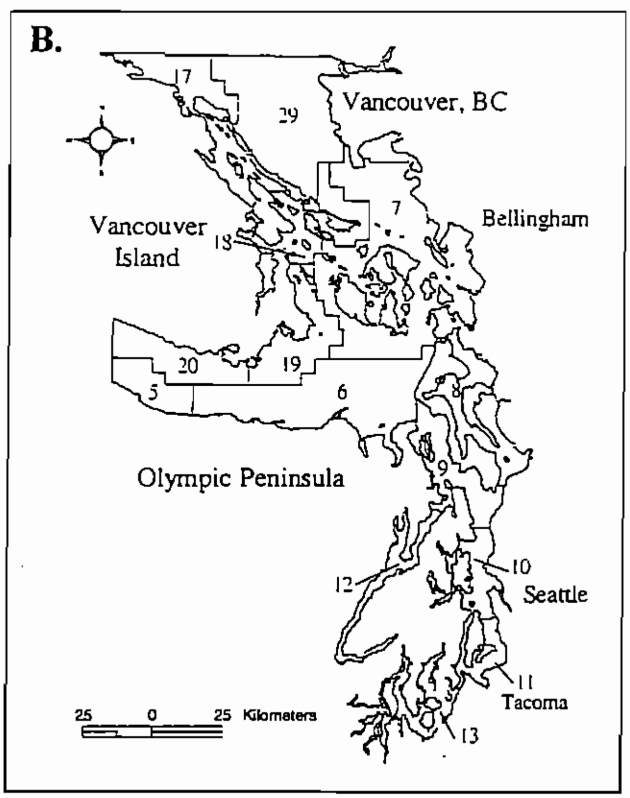
Zone 1 = San Juan & Gulf Islands Between Pt. Roberts and Race Rocks.

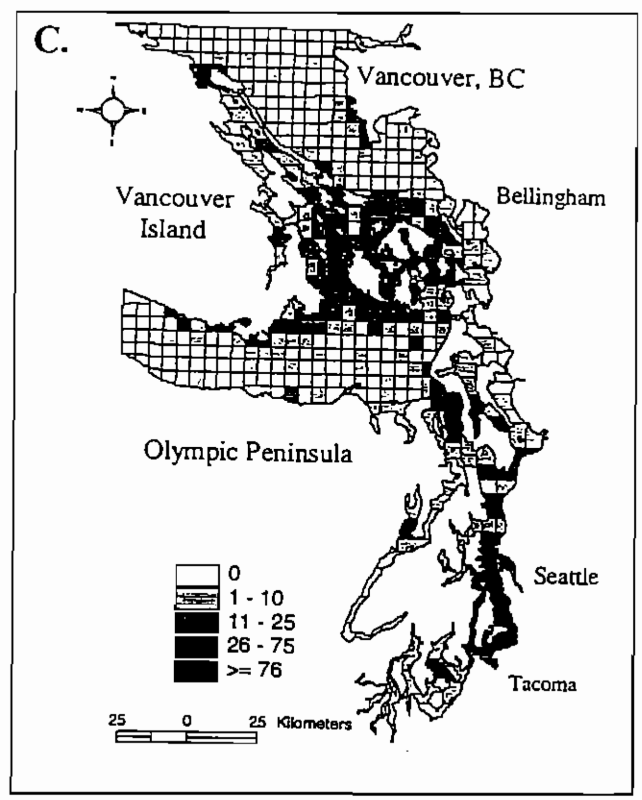
Zone 2 = Puget Sound.

Map B: Statistical Study Area showing U.S. and Canadian Salmon Reporting areas.

Map C: Statistical Study Area showing small scale quadrants plotting sighting distributions 1976-96 (after J.R. Heimlich-Boran, 1988; J.M.Olson, 1998).







The "Southern Resident Community" are designated as J-Pod, K-Pod, L-2 Sub-Pod, L-12 Sub-pod and L-35 Sub-pod (Figure 7). In 1982 a few modifications were made to the designations of the "Southern Resident Community" (Bigg, 1982; Bigg *et al.*, 1987): a maternal sub-group originally designated in L-Pod was switched to K-Pod (K-17, 18, 21 & 40) due to a reinterpretation of their association patterns, and L-Pod was sub-divided into three "sub-pods" (L-12s, L-25s & L-35s). In the present study, records on annual population composition from 1974 to 1999 as published by the Center for Whale Research (Ginneken and Ellifrit, 1999) are utilized to show annual recruitment and total population count (Figure 12). These numbers will also provide the basis for calculating the second indicator for this population: food resource requirements.

Food Resource Requirements

The energetic requirements of both captive and wild killer whales has been the subject of several studies over the last decade (Innes *et al.*, 1987; Kastelein and Vaughan, 1989; Kriete, 1995). The assessment completed by Kriete (1995) employed a combination of techniques (respiration rate, respiratory gas analysis, urine analysis) with both captive and wild killer whales of different sex and age categories, and under different activity states. The animals in her study included captive North Atlantic fish-eaters and Northern Residents, and her wild data came from killer whales in the Northern and Southern Resident Communities (Kriete, 1995).

Kriete's findings provide the basis for an assessment of energy requirements for any group of killer whales where age (or length), sex, and reproductive condition of females is known (Kriete, 1995). For the purposes of the present study a quantitative "indicator" of food requirements for this population is needed, that is usable at scales where precise information about age and sex composition of the population is not available. This is accomplished by taking conservative mid-range estimates from Kriete's energetic estimates and rounding to the nearest 1,000 calories/kilogram/day (Kcal/Day).

Using Kriete's published values tables were constructed (Tables 3 and 4) utilizing her four age/sex categories (immature, juvenile, adult female and adult male), each assigned with the mean value rounded to the nearest 1,000 Kcals/Day (Kriete, 1995). These values were then combined with the number of salmon/day it would take to equal the daily food requirement with each of the five local species of salmon (Table 3). Caloric values for each of the five local species of salmon were derived from published values (NWAFC, NOAA, 1977) and divided by the estimated average size of the fish for that species (Table 3).

Table 3 Food Values for Selected Salmon Species

(100 gram portions)					(1 kg. portions)		
Species	% Water	Calories	Protein	Fat	Kcal/kg	kg/Fish	Kcal/Fish
Chinook	64.2	222	19.1	15.6	2,220	4.5	9,990
Chum	70.8	139	21.5	5.2	1,390	4	5,560
Coho	69.3	153	20.8	7.1	1,530	4	6,120
Pink	76	119	20	3.7	1,190	3	3,570
Sockeye	67.2	171	20.3	9.3	1,710	4	6,840

Caloric values for fish = Dept. of Food Science, NWAFC, NMFS, NOAA, 1977.

Table 4 Daily Number of Salmon Needed to Sustain a Killer Whale

Species	Immature (1-6 yrs.) 85,000 kcal/day	Juvinile (7-12 yrs.) 100,000 kcal/day	Female (+ 12 yrs.) 160,000 kcal/day	Male (+12 yrs.) 200,000 kcal/day
Chinook	8	10	16	20
Chum	15	18	29	34
Coho	14	16	26	33
Pink	24	28	45	56
Sockeye	13	15	23	29

RULE OF THUMB = 25 SALMON / D *(23.6 = the mean for all species of salmon and all age classes of orca)*

Orca values derived from Bigg and Wolman, 1975; Innes et al, 1987; Kastelein and Vaughan, 1989; Kriete, 1995)

This information was then used to derive an estimate that included the mean of all species of salmon, with the mean of all age/sex categories of killer whales (23.6 generic salmon/generic killer whale/day: Table 4). That number was then rounded up 1.4 fish for mathematical convenience, and to err on the side of over estimating their salmon requirements. This value of 25 salmon/killer whale/day was then utilized as the energetic indicator for most comparisons. The next section will attempt to find a reliable quantitative measure of the third indicator for this killer whale population: habitat use.

Sighting Records

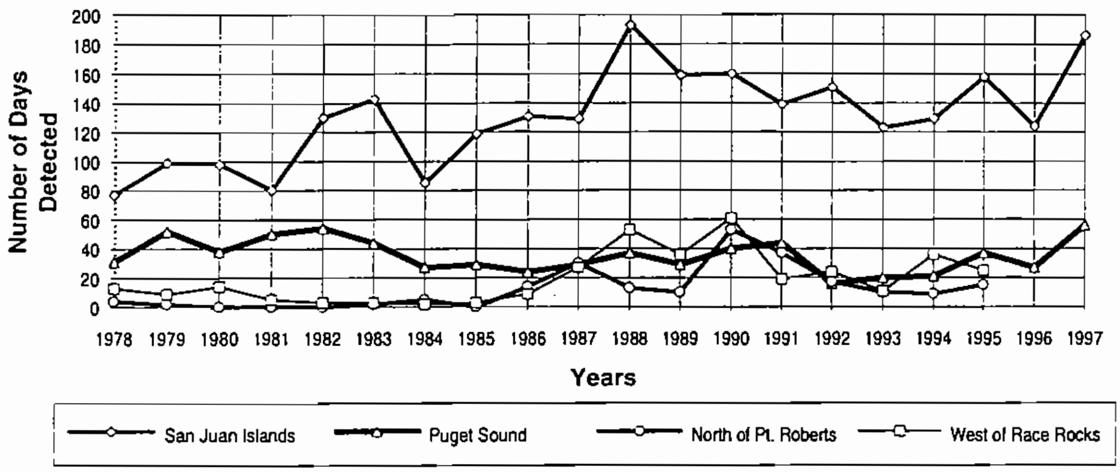
The data that forms the foundation for a measure of habitat use by these killer whales is calculated as the number of days per month resident whales were detected in two geographic zones (Figure 15a): 1) the Strait of Juan de Fuca east of Race Rocks and Port Angeles to Southern Georgia Strait south of Pt. Roberts (Zone 1), or 2) Whidbey Island to Puget Sound (Zone 2). It was assumed that if the whales were not detected in one of these two zones in a 24 hour period, then they were somewhere else using another area of their range, and did not enter those zones during the 24 hour period.

A total of 10,642 sightings were used in the study (Figure 15c). However, the total sample in the analysis was based on the number of days/month the killer whales were or were not detected by 1 or more of those sightings (January 1978-December 1997 = 7,300 sighting days). Outside of the two study zones, sightings were classified as either north or west of Zone 1. These sightings were also plotted as sighting days, but were deemed too small a sample size, and too irregular to include in the analysis (Figure 16). Days where whales were not detected were classified as days not in the two study zones.

Sighting data was collected in a fashion that is not possible to subject to a uniform test of reliability due to the large variety of sighting platforms, observers, and the variation in their qualifications (after Balcomb *et al.*, 1980; J.R.Heimlich-Boran, 1986a; 1988; Felleman *et al.*, 1991; Osborne, 1991; Olson, 1998). The data also violates the

Figure 16

Annual Number of Days Killer Whales Were Detected in Four Different Zones of the Salish Sea (1978-97)



assumption of homogeneity because the range of variance is exceeded by a factor of 10 in many places, and there is no measure of temporal or spatial effort, so it is not a statistically valid sample of the population (Box and Jenkins, 1976; Zar, 1996).

For the purposes of the present study, despite its unverifiability, the assumption will be that since the year 1985, 95% of the time the resident killer whales have entered these zones, they have been detected by humans at least once during a 24 hour sampling period, and reported to one of several sources: 1) the Whale Museum's Whale Hotline (which has been in place since 1976), 2) the B.C. Whale Hotline (in place since 1985), 3) the Center for Whale Research's Orca Survey project (in place since 1976), or 4) commercial whale watch operators with a daily summertime schedule (in place since 1983, intensively since 1990). For the years 1978-1984 sightings are Whale Museum Whale Hotline and Orca Survey sightings only. For this earlier period reliability will not even be attempted to be estimated, though it is probably reasonably complete for summer months. The observers contributing to the data base range from the untrained general public, to highly reliable long time shoreline residents, to trained naturalists, to cetologists with photo-identification records. Observations of the untrained general public were not included in the data base unless they were either: 1) Verified through interview, or 2) had a convincing description of the species that could be corroborated with at least one other sighting.

For any given daily detection of the killer whales in the data base, anywhere from one to over 25 sightings might have been collected for a single 24 hour sample. Seasonally there are extreme sampling biases in terms of: 1) number of observers, 2) number of observers actively searching for whales, 3) period of daylight, and 4) visibility in terms of sea surface and atmospheric conditions. For summer data (June-August) the bias of all these variables have been minimized close to zero in recent years (since 1992) as a result of the huge increase in (commercial) observer effort, coupled with the consistently ideal environmental conditions for detecting killer whales during those months. Outside of the summer months all the variables of potential bias become problematic.

The only reliability tests of this data have been opportunistic. Since 1991 the spring through Fall season has been thoroughly tested for reliability due to the effort applied to tracking killer whales with the paid subscription sighting networks for commercial whale watch operators. The commercial networks use aerial surveys, vessel surveys, as well as dedicated cliff observers to track the killer whales. The other opportunistic reliability test has been the use of 24 hour hydrophone surveillance through the winters of 1978-80, 1986-88, 1991, and 1995-98, but with inconsistant effort. However, in none of these instances did the periods of increased winter sighting effort increase the overall number of sighting days.

Bias in sighting effort is then further controlled by scoring killer whale presence as days/month and then coding the data as a percentage for each month separately over the entire 240 month study period (1978-97). These 20 year means by month, serve as the basis for deriving the seasonal pattern of habitat use in the study sites, and as the central tendency upon which to compare variations characteristic of specific years.

RESULTS

Southern Resident Killer Whale Ecological Indicators

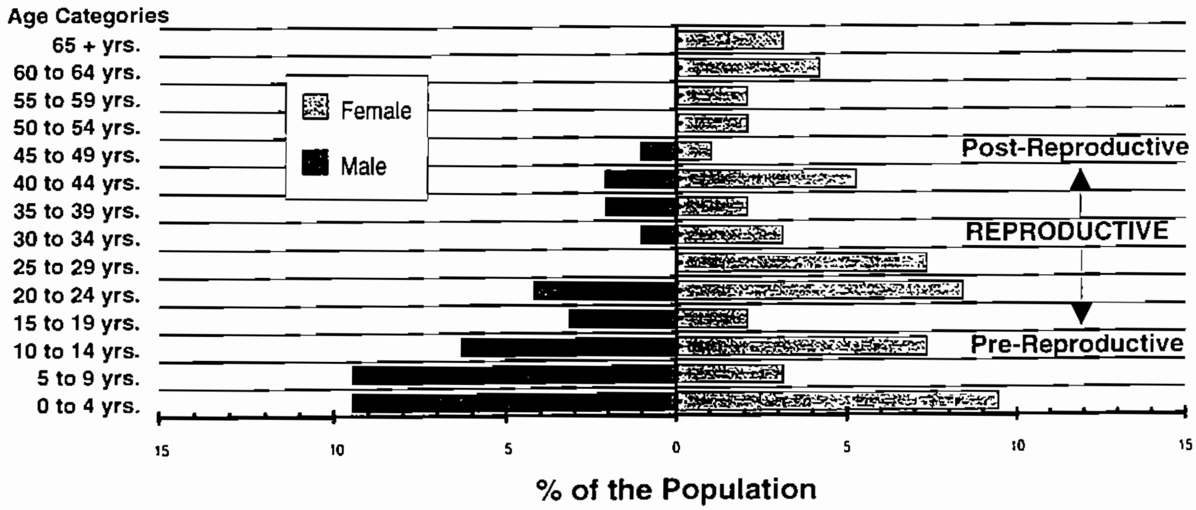
The ecological status of the Southern Resident Community of killer whales in terms of *reproductive requirements*, *food resource requirements*, and *habitat-use patterns*, can be roughly monitored using a combination of an annual individual photo-inventory of the population, and maintenance of a year-round public sighting network to uniformly detect them in portions of their range.

Recruitment Status

Long-term assessment of the recruitment status of this killer whale population through photo-identification has been thoroughly demonstrated (Balcomb and Bigg, 1986; Olesiuk *et al.*, 1990; Brault and Caswell, 1993), and already serves as an important management tool and monitor of their ecological health (Calambokidis and Baird, 1994; Balcomb, 1997; Baird, 1999; Ross *et al.*, in press). This record provides the basis for assessing the population in terms of the standard analytical procedures available to demographers (Olesiuk *et al.*, 1990; Brault and Caswell, 1993; Baird and Whitehead, in prep.; Figures 7, 12 and 17), and therefore serves as a longitudinal measure of the recruitment status of this population.

In Figure 17 this is demonstrated graphically as an age distribution pyramid, where the reproductive potential of the population into the immediate future can be seen as the percentage of breeding age females. For this age structure information, reconstructions on the estimated birth-year of each individual prior to 1974 were used, as published by Bigg *et al.*, (1987; 1990); Ford *et al.*, (1994); and the Center for Whale Research (Balcomb, 1997; Ginneken and Ellifrit, 1999). The Salish Sea Resident Killer Whale Community presently has a large percentage of breeding age females in the early years of their reproductive life span, suggesting a strong potential for population growth in

Figure 17 **Southern Resident Killer Whale Community Age Distribution Pyramid 1997**



the absence of any decreases in survivorship of these females (Brault and Caswell, 1993). Additionally, age distribution pyramids can serve as historical markers of generational mortality and fertility events, potentially allowing associations with historical environmental conditions (Chapter 4).

Food Requirements

The amount of food required to maintain the Salish Sea Resident Community of killer whales is going to be a function of the number of individuals in the population (Figure 12), their age/sex composition (Figure 17), the basic energetic requirements for killer whales of those age and sex categories (Kriete, 1995; Table 4), and the energetic value of their food species (Table 3). In Table 5 the results of such an assessment are presented for the population as a whole based upon their composition in 1997 (Center for Whale Research, 1998), and the unlikely assumption that they eat nothing but salmon. This results in an estimate that the whole population needed to consume 817,673 salmon in 1997. Using the even more conservative "rule of thumb estimate" the number is

857,750 salmon. Since it is known that some percentage of their diet also includes other species, this is explicitly a high estimate; a salmon diet of 90% would be 735,906 and 771,975, respectively.

In Table 6 consumption estimates based upon the composition of only J-pod, and just for the period from December through April are presented. Published evidence suggests they are the only portion of the Salish Sea resident population exploiting salmon resources from the inland waters of the Salish Sea during this time of year (J.R.Heimlich-Boran, 1986a; 1988; Felleman *et al.*, 1991; Ford *et al.*, 1994). These findings indicate that J-Pod needed to consume 70 to 80,000 salmon over that five month period in 1997.

Table 5 Southern Resident Community Salmon Consumption Estimates for 1997

Age/Sex Class	Daily Calories	Daily Mean # of Salmon	Number of Individuals	Annual # of Salmon
Immature (1-6 yrs.)	85,000 kcal/day	14.8	19	102,638
Juvinile (7-12 yrs.)	100,000 kcal/day	17.4	21	133,371
Female (+ 12 yrs.)	160,000 kcal/day	27.8	40	405,880
Male (+12 yrs.)	200,000 kcal/day	34.4	14	175,784
	TOTALS:	23.6	94	817,673
Generic Killer Whale Rule of Thumb: 25 salmon x 94 individuals x 365 days =				857,750

(Killer whale energetic values derrived from Kriete, 1995; salmon from NWAFC, NMFS, NOAA, 1977)

Table 6 J-Pod Salmon Consumption Estimates for December - April 1997-98

Age/Sex Class	Daily Calories	Daily Mean # of Salmon	Number Of Individuals	Number of Winter Salmon
Immature (1-6 yrs.)	85,000 kcal/day	14.8	7	15,644
Juvinile (7-12 yrs.)	100,000 kcal/day	17.4	3	7,882
Female (+ 12 yrs.)	160,000 kcal/day	27.8	9	37,780
Male (+12 yrs.)	200,000 kcal/day	34.4	3	15,583
	TOTALS:	23.6	22	76,889
Generic Killer Whale Rule of Thumb: almon x 22 individuals x 151 days =				83,050

(Killer Whale energetic values derrived from Kriete, 1995; salmon from NWAFC, NMFS, NOAA, 1977)

This method of calculating food requirements from population composition, and energetic values for killer whales and their food resources, appears to satisfy the criteria of a longitudinal indicator of the ecological status of this population relative to salmon food resources. This allows an assessment of the salmon resources necessary to sustain this population, or portions of the population, over specified time scales by utilizing annual population estimates. However, it does not account for food requirements relative to non-salmonid prey.

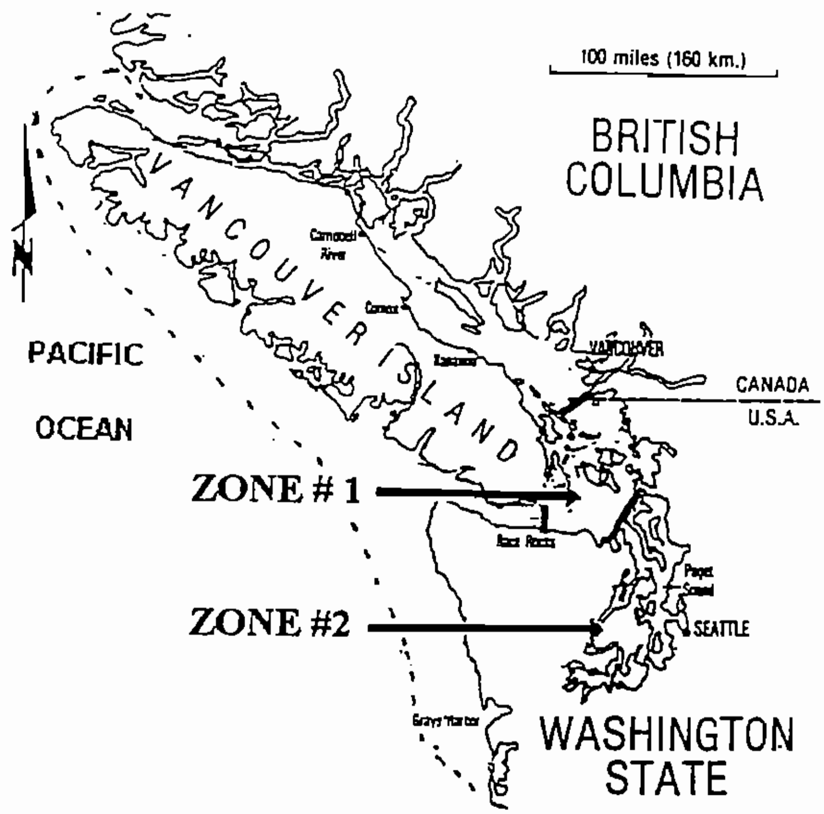
Habitat Use

The degree to which a population of organisms utilizes different parts of their range will vary according to the benefits and costs of utilizing those parts of their habitat (Cox and Moore, 1985, Brown and Downhower, 1988). In this study the number of days/month the killer whales are detected by humans reporting to a sighting data base, is used as an indicator of the benefits and costs the killer whales receive from entering these two zones. The comparisons are annual values relative to the mean values of 15 to 20 year samples. In this fashion the average seasonal habitat use pattern of the entire 15 to 20 year sample can be used as a baseline indicator of stable ecological conditions. This then allows extreme variant years to be identified and later compared diachronically with other variables (Chapter 4).

The two zones in the habitat of the Southern Resident Community of killer whales being sampled are the San Juan & Gulf Islands (Zone 1) and Puget Sound (Zone 2). These zones each have similarities and differences in how often and at what season the Southern Resident killer whales use them. But the main difference between the two zones is their geographic position relative to the entire range of these whales (Figure 18).

Figure 18

Study Zones Relative to the Entire Habitat Range of the Southern Resident Killer Whale Community



Zone 1 (the San Juan & Gulf Islands) encompasses the central node connecting the travel routes of the whales between the Salish Sea and the Outer Coast; and within the Salish Sea, between Puget Sound and Georgia Strait. This central location in the travel network makes Zone 1 a good indicator of killer whale habitat-use of the Salish Sea as a whole.

Zone 2 (Puget Sound) is off the central travel routes and encompasses the southern extreme of their distribution within the Salish Sea (Figure 18). Zone 2 is also the most densely human populated portion of their habitat, and so the most likely place to see changes in habitat-use in response to human impacts.

Site Fidelity and Habitat Partitioning

The Southern Resident Killer Whale Community's site fidelity to specific habitat regions over time has been documented using photo-identification records of where and when pods were identified (Balcomb *et al.*, 1980; J.R. Heimlich-Boran, 1986a; 1988; Felleman *et al.*, 1991; Osborne, 1991; Hoelzel, 1993; Ford *et al.*, 1994). When photo-identification is combined with sighting data, seasonal partitioning of the habitat between pods can be inferred more completely for all months of the year (Figure 19).

Photo-identification serves to verify the actual pods that are associated with sequences of public sightings, and to directly sample the range and seasonality of each pod over time. It has also been demonstrated that acoustic identification of pod vocalization dialects can similarly be used to document pod range and seasonality over time (Ford, 1989; 1990; Bain, 1989), but acoustic identification was rarely applied in this study (Two identifications in the data set).

In the present study 1,392 out of 3,310 sighting days (42%) included pod identification information. In Zone 1, 49% of the sighting days included pod identification, Zone 2 had only 14%. Zone 1 exhibited a regular mix of all three pods in the summer, and then primarily only J-Pod from December until April. Zone 2 was dominated by J-Pod (70%), with K and L-Pods visiting Zone 2 primarily in the fall. This pattern supports previous findings on seasonal patterns of habitat partitioning among this community of killer whales (J.R.Heimlich-Boran, 1986a;1988; Felleman *et al.*, 1991).

In Figure 19 apparent habitat partitioning by the pods is depicted spatially in the map, and as a matrix that shows the arrival and departure months for K & L-Pods from the Salish Sea over the last 22 years. Variations in this longitudinal pattern can clearly be utilized as indicators of potential shifts in use of these zones, such as K-Pod's sporadic spring appearances in 1976, 1978, 1981 and 1989, and the four years when all three pods stayed around Zones 1 & 2 into December (1977, 1987, 1989, and 1992; Figure 20).

Seasonal Habitat Use

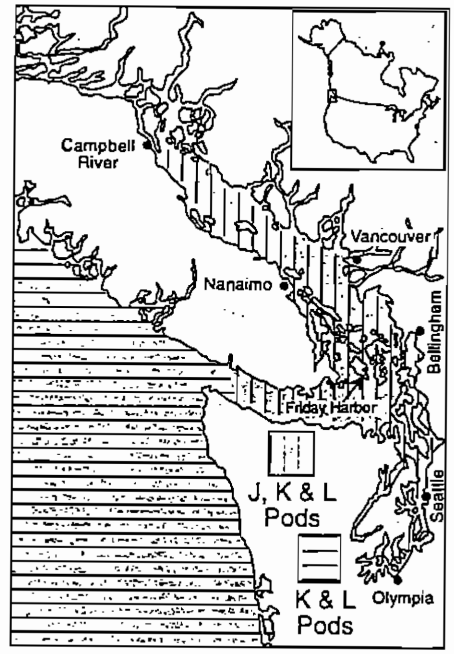
Seasonal habitat use can be shown by calculating the mean number of sighting days/month that killer whales are detected in each geographic sub-area over the entire data set. In figure 20, Zone 1 and Zone 2 are plotted along with the mean number of sighting days/month they were not detected in those two zones. The assumption is that when the whales are not in Zones 1 or 2 they are using other parts of their habitat. This serves as a potential indicator of their seasonal interest in these other parts of their habitat.

As depicted by the site fidelity and habitat partitioning data (Figure 19), on average the resident killer whales are in the inland waters of the Salish Sea most often during the summer months. This finding is well known in the literature (Bigg *et al.*, 1976, 1981; 1990; Balcomb *et al.*, 1980; Baird *et al.*, 1992; Ford *et al.*, 1994) and has been clearly linked with seasonal peaks of most salmon species (J.R.Heimlich-Boran, 1986a; Felleman *et al.*, 1991; Figure 15). Over the whole sample resident killer whales were detected in Zone 1 (San Juan/Gulf Islands) for over half the days of the month for May through August, with a peak in June and July; and on average, continue to be detected regularly in Zone 1 during the boundary months at either end of this period (Figure 20). This represents 5 months out of the year where the daily presence of the killer whales in this component of their habitat can annually be accounted for 50 to 80% of the time. However, as can also be seen in Figure 19, J-Pod is being detected in either Zone 1 or Zone 2 during every month of the year (see also Figure 20).

Figure 19

Spatial and Temporal Habitat Partitioning in Salish Sea Resident Killer Whales (Year-Round 1976-1997)

Based upon 1,392 pod identification days. Pod identifications are primarily from investigators associated with the Orca Survey, Center for Whale Research or verified records supplied to The Whale Museum's Whale Hotline sighting network. The map depicts spatial partitioning between J-Pod and the rest of the community. The matrix shows temporal and seasonal partitioning.



J, K & L-PODs Annual Monthly Arrivals & Departures from the Salish Sea Habitat

(J-Pod spends some of their time in the Salish Sea every month of the year)

<table>
<tr><th>Year</th><th>JAN</th><th>FEB</th><th>MAR</th><th>APR</th><th>MAY</th><th>JUN</th><th>JUL</th><th>AUG</th><th>SEP</th><th>OCT</th><th>NOV</th><th>DEC</th></tr>
<tr><td>1976</td><td>?</td><td>?</td><td>?</td><td>J&K</td><td>J</td><td colspan="5">J,K&L</td><td>?</td><td>J</td></tr>
<tr><td>1977</td><td>?</td><td>?</td><td>?</td><td>?</td><td>?</td><td>?</td><td colspan="6">J,K&L</td></tr>
<tr><td>1978</td><td>J</td><td>J</td><td>J&K</td><td>J</td><td>J</td><td>J</td><td colspan="4">J,K&L</td><td>J</td><td>J</td></tr>
<tr><td>1979</td><td>J</td><td>J</td><td>J</td><td>J</td><td>J</td><td colspan="5">J,K&L</td><td>J&K</td><td>J</td></tr>
<tr><td>1980</td><td>J</td><td>J</td><td>J</td><td>J</td><td>J</td><td colspan="5">J,K&L</td><td>J</td><td>J</td></tr>
<tr><td>1981</td><td>J</td><td>J</td><td>J</td><td>J&K</td><td>J</td><td colspan="6">J,K&L</td><td>J</td></tr>
<tr><td>1982</td><td>J</td><td>J</td><td>J</td><td>J</td><td>J</td><td>J&K</td><td colspan="3">J,K&L</td><td>J&K</td><td>J</td><td>J</td></tr>
<tr><td>1983</td><td>J</td><td>J</td><td>J</td><td>J</td><td>J</td><td colspan="4">J,K&L</td><td colspan="2">J&K</td><td>J</td></tr>
<tr><td>1984</td><td>J</td><td>J</td><td>J</td><td>J</td><td>J</td><td>J&K</td><td colspan="3">J,K&L</td><td>J</td><td>J</td><td>J</td></tr>
<tr><td>1985</td><td>J</td><td>J</td><td>J</td><td>J</td><td>J</td><td>J&K</td><td colspan="4">J,K&L</td><td>J</td><td>J</td></tr>
<tr><td>1986</td><td>J</td><td>J</td><td>J</td><td>J</td><td>J&K</td><td colspan="4">J,K&L</td><td>J</td><td>J</td><td>J</td></tr>
<tr><td>1987</td><td>J</td><td>J</td><td>J</td><td>J</td><td>J</td><td colspan="4">J,K&L</td><td colspan="3">J&K</td></tr>
<tr><td>1988</td><td>J</td><td>J</td><td>J</td><td>J</td><td>J&K</td><td colspan="5">J,K&L</td><td>J</td><td>J</td></tr>
<tr><td>1989</td><td>J</td><td>J</td><td>J&K</td><td>J</td><td colspan="5">J,K&L</td><td colspan="3">J&K</td></tr>
<tr><td>1990</td><td>J</td><td>J</td><td>J</td><td>J</td><td colspan="6">J,K&L</td><td>J</td><td>J</td></tr>
<tr><td>1991</td><td>J</td><td>J</td><td>J</td><td>J</td><td>J&K</td><td colspan="4">J,K&L</td><td>J&K</td><td>J</td><td>J</td></tr>
<tr><td>1992</td><td>J</td><td>J</td><td>J</td><td>J</td><td colspan="8">J,K&L</td></tr>
<tr><td>1993</td><td>J</td><td>J</td><td>J</td><td>J</td><td>J&K</td><td colspan="4">J,K&L</td><td>J</td><td>J</td><td>J</td></tr>
<tr><td>1994</td><td>J</td><td>J</td><td>J</td><td>J</td><td>J</td><td colspan="4">J,K&L</td><td>J&L</td><td>J</td><td>J</td></tr>
<tr><td>1995</td><td>J</td><td>J</td><td>J</td><td>J</td><td colspan="5">J,K&L</td><td>J</td><td>J</td><td>J</td></tr>
<tr><td>1996</td><td>J</td><td>J</td><td>J</td><td>J</td><td>J</td><td colspan="4">J,K&L</td><td colspan="2">J&K</td><td>J</td></tr>
<tr><td>1997</td><td>J</td><td>J</td><td>J</td><td>J</td><td colspan="6">J,K&L</td><td>J&L</td><td>J</td></tr>
</table>

(Data compiled by R. Osborne from records maintained by Orca Survey, Center for Whale Research, The Whale Museum's Whale Hotline, and the Marine Mammal Research Group's Whale Hotline)

J-Pod= J   J&K-Pod=   J&L-Pod=   J,K & L-Pods=

Zone 2 shows a low overall year-round presence of a couple of days per month, with a slight peak October through January. This peak appears to roughly correspond with the chum and chinook salmon peaks in the sports catch data presented in Figure 14. The difference in the level of activity in Zone 2, as compared to Zone 1, seems attributable to the fact that the whales do not use Zone 2 as often. Sighting effort in Zone 2 has always been consistant due to the elevated human density and narrow channels. (see Figure 15).

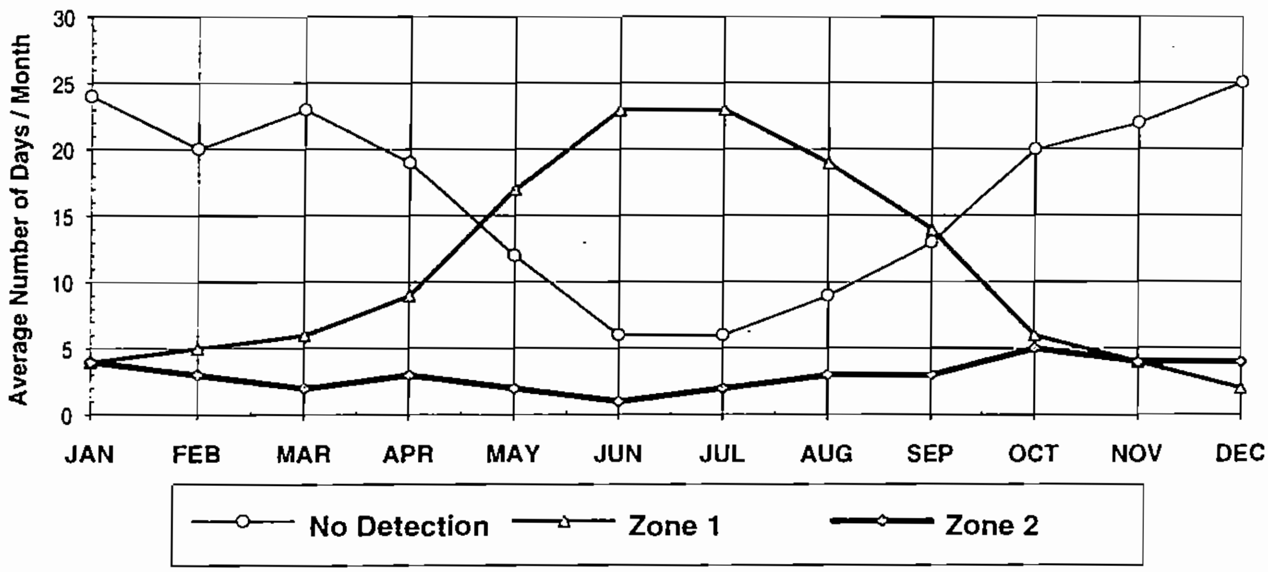
As previously mentioned, photo-identification indicates that most of Zone 2 activity can be attributed to J-Pod (70%) and appears to be exclusively J-Pod for November through May. The only exception to this was in 1997 when a sub-group of L-Pod stayed in Dyes Inlet in Puget Sound for 30 days in October and November (Osborne, 1998; Smith *et al.*, in prep.). The unusualness of this event becomes quite clear when placed in the context of this longitudinal photo-ID and sighting data, and illustrates how this data base can be used as an "indicator" of changes in the environmental conditions for the population.

Longitudinal Habitat Use

The longitudinal record of sighting days/month in these two zones provides a continuous sequence of monthly activity for 240 months. When this data is plotted with the 20 year mean (Figure 20), it allows extremes in variation from the mean to be examined in the context of preceding and following trends (Figures 21 and 22).

The twenty year plot of sighting days/month for Zone 1 (Figure 21) shows an overall lower level of activity in the earlier years (white space below the mean), which is probably attributable to the lower sighting effort during this period. Correspondingly, later years show a tendency to be above the mean probably because sighting effort has improved with time. Between these obvious trends of bias are, mostly, chaotic fluctuations around the mean; and these are relatively minor when considered in terms of

Figure 20 **20 Year Monthly Averages for the Seasonal Detection of Resident Killer Whales in the Salish Sea (1978-97)**



their values as days per month. However, in some places there are extreme perturbations in the data set either above or below the mean (i.e. 1984, 1988 and 1997 in Figure 21), that can potentially be used as indicators of ecologically significant events. In this respect, extreme perturbations showing an increase in sighting days are more reliable as indicators of ecological events, than perturbations that suggest the killer whales were not present in the habitat zone, due to the latter's greater sensitivity to a sighting effort bias.

Zone 2 displays a relatively lower level of overall activity indicating its status as an outlying habitat area for these whales (Figure 22). This lower level of sighting days means extreme perturbations below the mean are even more dubious as indicators of ecological conditions than in the case of Zone 1. However, it also makes perturbations of high sighting days even clearer indicators of potential ecological events.

In Figure 22 the early spring of 1979, the summer of 1981, December of 1995 and fall of 1997, all show very large increases in sighting days that strongly suggest some

Figure 21

Number of Days/Month Resident Killer Whales were Detected in the San Juan / Gulf Islands relative to the Mean (1978-97)

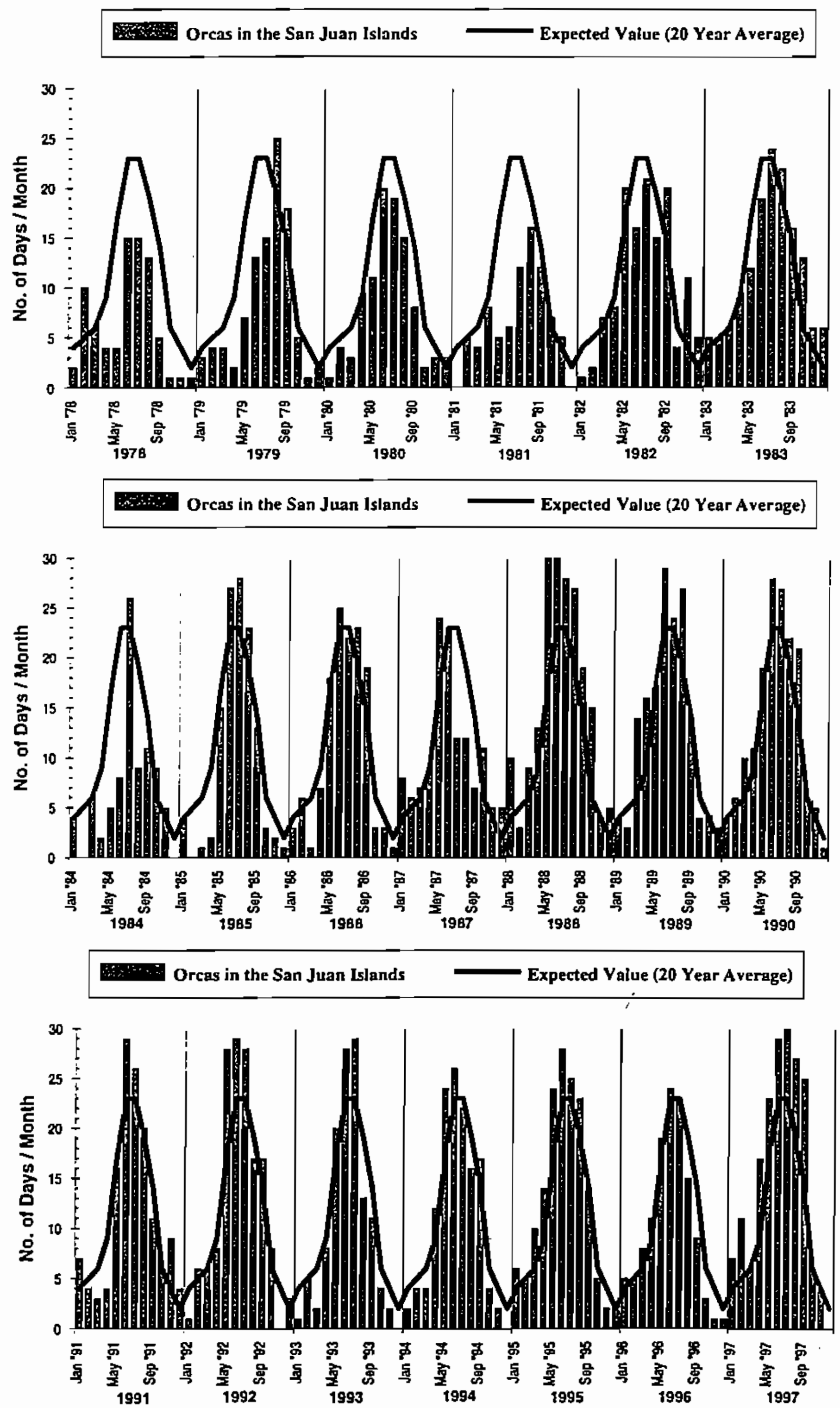
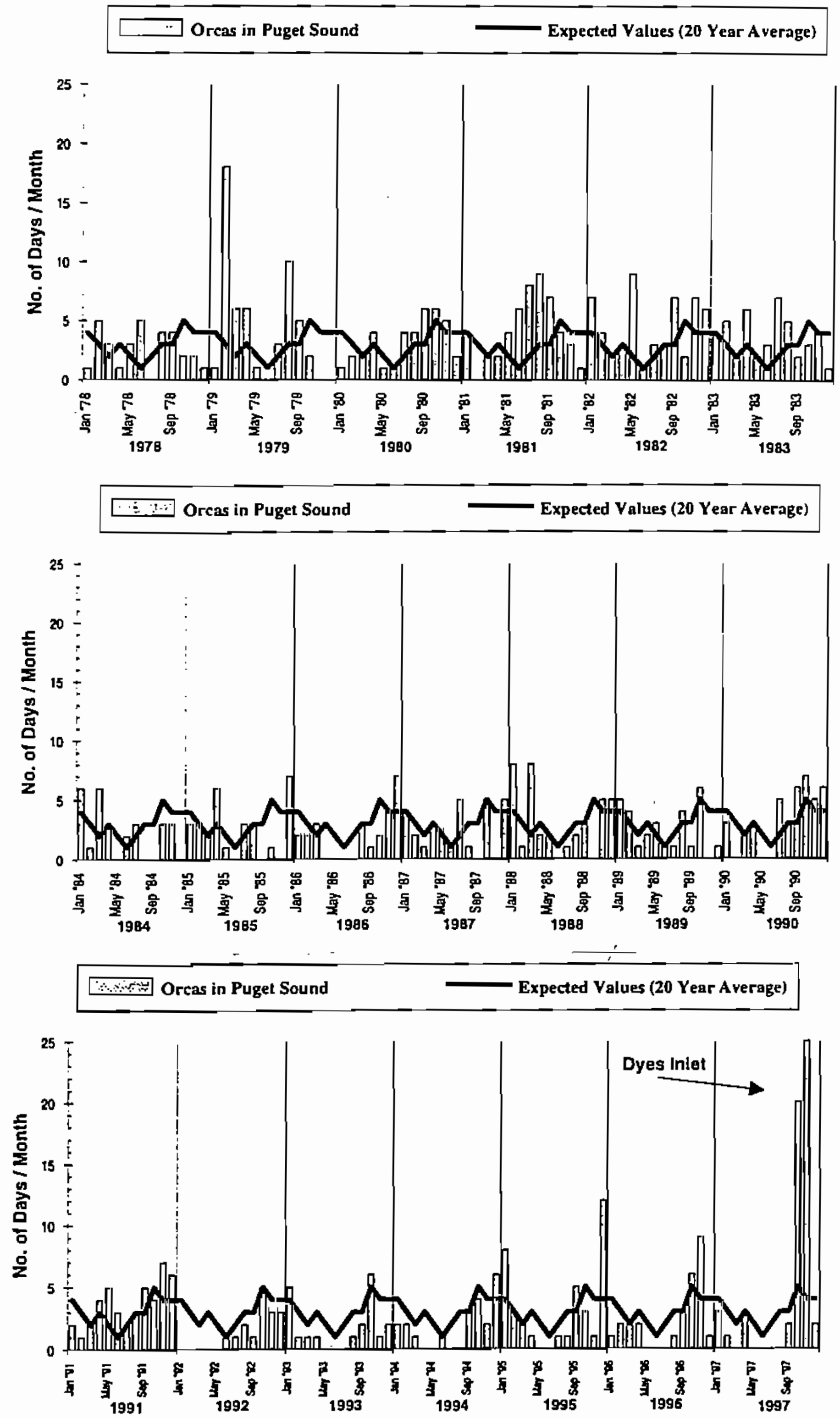


Figure 22

Number of Days/Month Resident Killer Whales were Detected in Puget Sound Relative to the Mean (1978-97)



significant ecological event must have occurred. In the case of the autumn of 1997, the perturbation is clearly attributable to L-Pod's extended stay in Dyes Inlet (a significant ecological event; Osborne, 1997; Smith *et al.*, in prep.). The other perturbations require further investigation (Chapter 4), but they demonstrate that assessing habitat-use with public sighting data and photo-identification can provide a useful indicator of ecological fluctuations in this population in some instances.

Another way of assessing these longitudinal variations in habitat-use is presented in Figures 23 and 24. This is the same data as Figures 21 and 22, except: 1) it only samples the last 15 years as a further precaution against including unequal sighting effort, 2) it is grouped into three-month seasons (Dec-Jan-Feb, Mar-Apr-May, Jun-Jul-Aug, Sep-Oct-Nov), and 3) it is plotted in relation to standard deviations above or below the seasonal 15 year mean. Similar to figures 21 and 22, these plots also serve to identify extreme variations of habitat-use that can be used as historical markers of potentially important ecological events.

Starting with the winter in Zone 1 (Figure 23), we do not see any variation that is far enough away from the mean to suggest an effect. The spring in Zone 1 however, does have one notable trend from a low in 1984, that consistently shifted to a high over the next 5 years. It serves as an indicator that something may have changed in the whale's habitat which caused an increase of their use of Zone 1 during the spring. From Figure 19 it can be seen that during this period, only J-Pod was present during the spring months, until 1986 when K-Pod began showing up in May, and by 1989 so was L-Pod. The summer and fall annual variation plots for Zone 1 (Figure 23) do not show any indications of extreme ecological events. All variation is close to the mean.

In Figure 24, the Zone 2 winter plot shows a lot of variability around the mean, with a notable shift to an increase for the years 1995 and 1996. The spring and summer plots for Zone 2, show a significantly high detection rate for the killer whales in 1982 and

Figure 23
Seasonal Variations in Habitat-Use of Zone 1 from 1982-1997

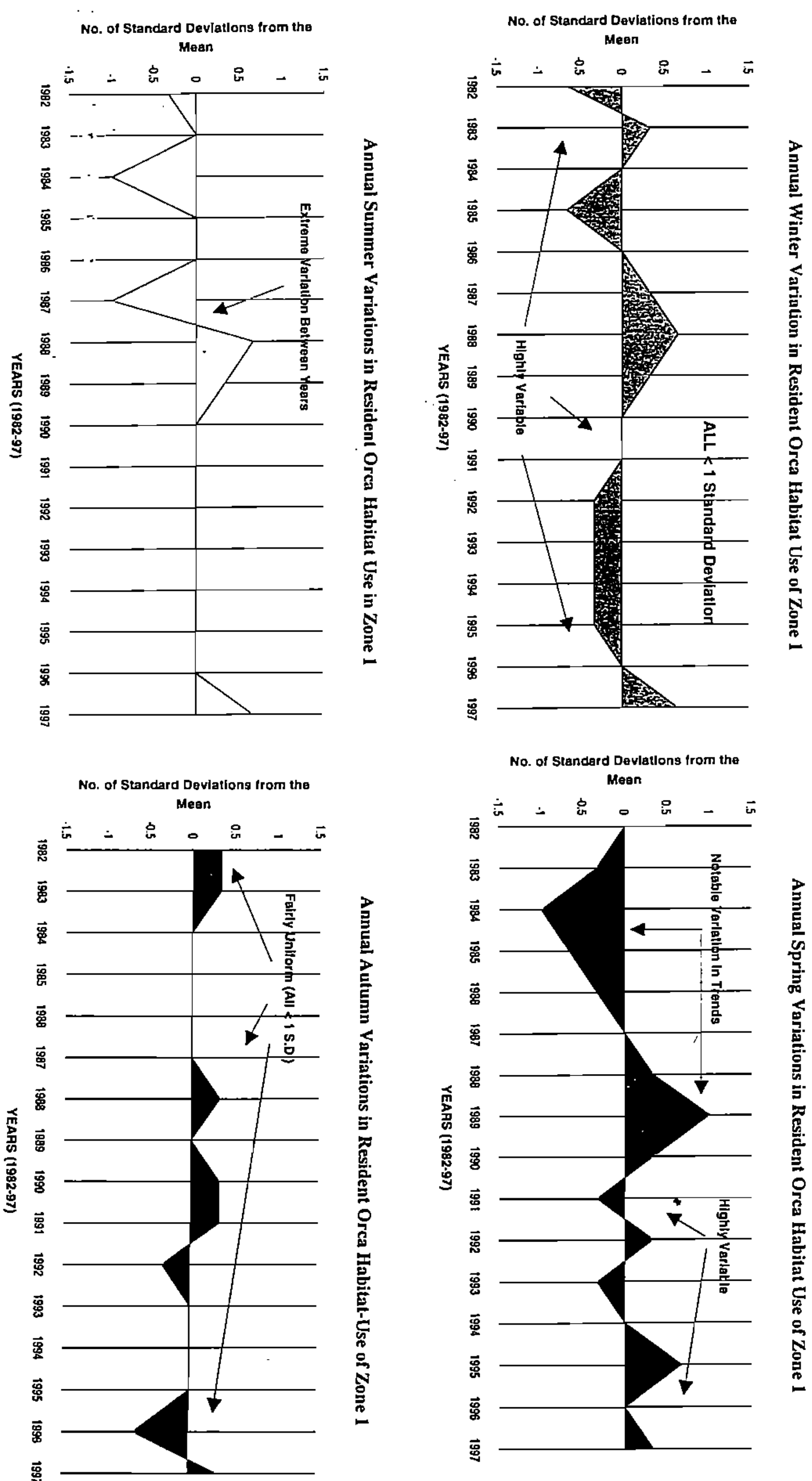
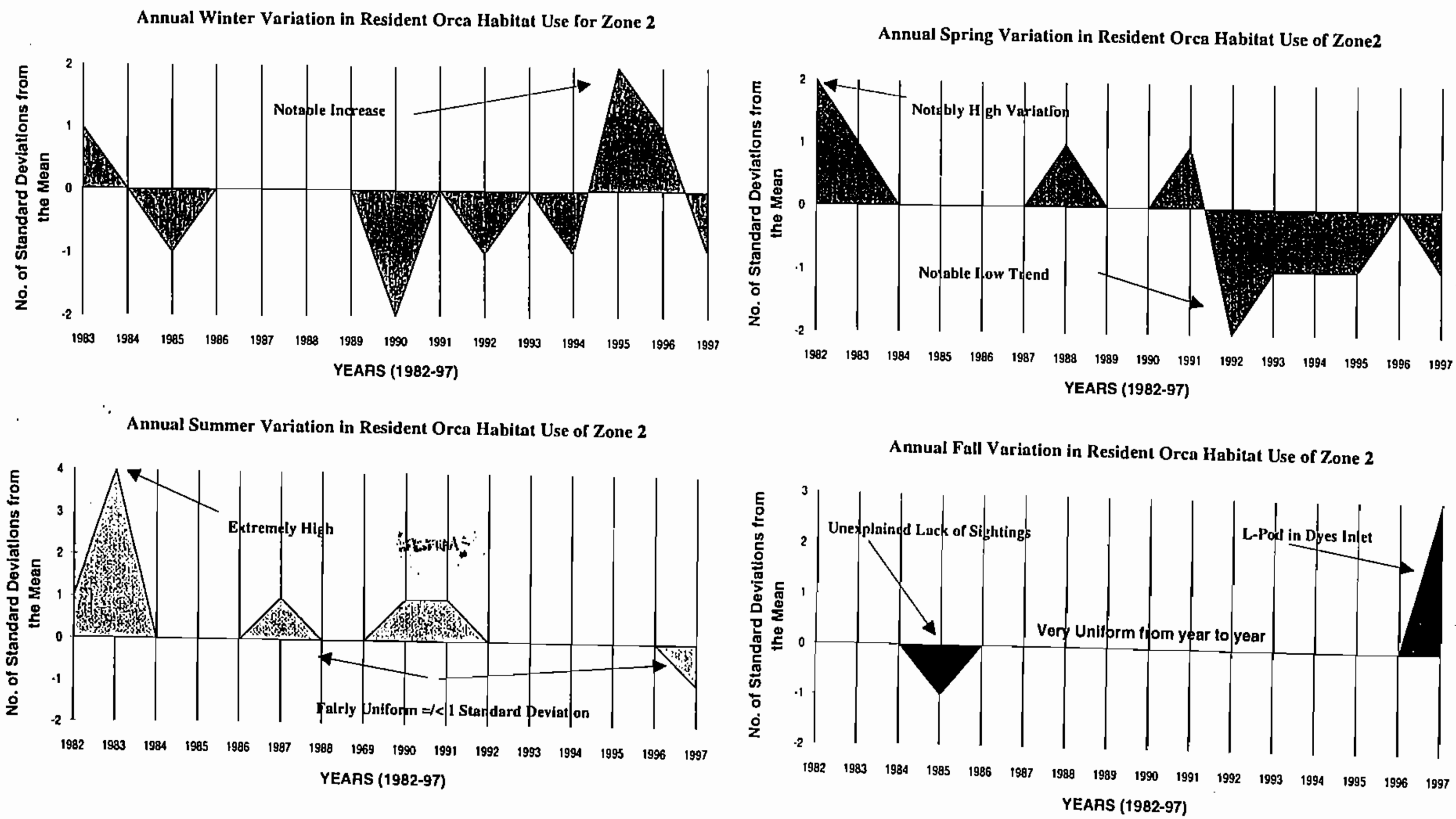


Figure 24

Seasonal Variations in Habitat-Use of Zone 2 from 1982-1997



1983 and then there is a shift to an extended period of lower detection rates in the spring since 1992. The autumn variations in habitat use in Zone 2 are very uniform,except for the Dyes Inlet incident mentioned earlier, which clearly demonstrates its severity as a habitat-use event.

In summary, habitat use of these two zones by the Southern Resident Community over the last 20 years indicates that annual seasonal variations can be detected using this method, and in at least one extreme case (i.e. Dyes Inlet) a specific environmental event can be linked with the variation. But in Zone 1, where the data is the most reliable, annual and seasonal variations in detection do not vary much beyond one standard deviation above or below the mean over the last 15 years (Figure 24), suggesting that recent habitat use patterns of this population are fairly stable overall.

Conclusions

The objective of this chapter was to describe the ecology of this resident killer whale population according to current findings, and to develop measurable baseline indicators of their ecological status that could be traced historically. The first step was to assemble what is currently known about the population, and then three indicators of their ecological status were developed based upon individual photo-identification records and public sighting records as the measurements.

These three indicators of the ecological status of this population represent three of the most basic ecological requirements of any population of organisms: *recruitment*, *food resources* and *spatial habitat-use*. Annual photo-identification of every individual in a population allows fluctuations in population ecology to be monitored directly (Figures 7, 12, and 17), and serves as the ultimate measure of ecological stability on an evolutionary time scale. Utilizing recent findings on the energetics of killer whales and their prey, allows annual and seasonal food resource requirements to be calculated directly from the photo-identification data (Tables 4, 5, and 6) and serves as a nearly direct indicator of food resource needs at different population levels. Finally, public sighting data, when collected over decades, allows fluctuations of spatial activity to be identified relative to average patterns, thus serving as an indicator of habitat-use in selected zones Figures 19 to 24).

In assessing the present ecological status of this threatened population of killer whales in the absence of a historical perspective (Chapter 4), the three indicators suggest:

1) Recruitment is on a downward trend since 1995 (presently 0.6% annual growth rate), but the population is still theoretically within the range of fluctuations for a stable population at or just below carrying capacity (Figure 12), and there is an up-coming increase in the number of breeding females that could counter the current increase in mortalities (Figure 17).

2) The population as a whole requires an annual salmon resource of around 800,00 fish (Table 5), and J-Pod alone requires about 80,000 salmon during the winter months of December through April (Table 6).

3) Habitat-use by these killer whales can be quite variable from month to month, but appears stable overall relative to the seasonal sample means over the last 15 years. However, 1997 was an unusual year for the killer whales, with record highs in the number of days they were detected during the fall in both sampling zones (Figures 21 and 22).

As potential indicators of the historical ecology of these killer whales, total population, and related food resource requirements, are variables that can more easily be extrapolated backwards at different time scales than can habitat-use. The former indicators are derived from population estimates, that vary only due to the birth or death of individuals on an annual time scale. The latter is an indicator of group behavior, sampled at smaller time scales (days, months, seasons), and is temporally tied to a public sighting data base with statistically unreliable effort. However, monthly habitat-use is potentially more sensitive to detecting variations in the ecological status of these killer whales than population measures, precisely because it is sampling behavior over shorter time samples. Furthermore, when a data base spans two decades, time begins to make the data more homogeneous, reducing the effect of effort biases, and increasing its value as a historical indicator (Hassan, 1994). In this respect, and as demonstrated by the example of the Dyes Inlet incident of 1997, the continuation of this sighting data set as a historical indicator should provide an increasingly powerful tool for detecting important events in the ecology of these killer whales.

In what follows, these ecological indicators for the Southern Resident Killer Whale population will be effectively linked with anthropogenic environmental variables, and examined at different time scales in order to build a historical context for management strategies.

Chapter 3

Identifying Indicators of Potential Human Impact on Salish Sea Resident Killer Whales

INTRODUCTION

A review of the information currently available on the ecology of the "Southern Resident Community" of killer whales (Chapter 2), provides a reasonable basis for choosing the salient limiting environmental factors with which this population of killer whales has to contend. Once these factors are identified, two other relationships also become apparent: 1) the human activities that are most likely contributing to environmental resistance on the killer whales, and 2) the sub-set of human activities that can be historically plotted as indicators of these anthropogenic influences. The primary objective of the present chapter is to systematically characterize this environmental resistance, and to link measurable indicators of human activities in the Salish Sea that are available for historical analysis at different time scales.

Over the last 25 years geographers, applied ecologists, and resource managers have developed methods for systematically identifying interacting ecological variables as part of simulation models (Holling, 1973; 1978; 1986; 1992; Clark, 1985; Mangel, 1985; Allen and Hoekstra, 1992), particularly in relation to standard environmental impact assessment (Leopold, 1971; O'Riordan, 1971; Mitchel, 1989; Allen and Hoekstra, 1992). These methods are applicable to analyses in historical ecology because of their similar lack of restrictions on the quality and completeness of available quantitative data, and the degree of complexity in the interacting variables (Holling, 1986; Worster, 1990;

Winterhalder, 1994). In a historical ecology of a population, the autecological concepts of "carrying capacity", and "limiting factors", would probably be the most widely accepted context within which to address these limiting environmental variables (Ricklefs, 1988; Mitchel, 1989; Botkin, 1990; Allen and Hoekstra, 1992), so they will form the basis for framing the categories presented here.

Human Contributions to Limits on Carrying Capacity

Paramount to identifying the most important ecological variables affecting a management unit is defining the boundaries of the system (Allen and Hoekstra, 1992; Ulanowicz, 1997). Boundary conditions in a biological population (autecology) are ultimately measured in relation to population size and composition over time, essentially birth and death rates of different age and sex classes (Watt, 1962; Kormondy, 1969; Ricklefs, 1988; Allen and Hoekstra, 1992). Given a stable environment, the point at which a population stops growing over time is known as its *carrying capacity*, and the most influential variables responsible for maintaining these upper limits on population growth are known as the "limiting factors", or the "environmental resistance" on the population (Hardesty, 1977; Simmons, 1979; Ricklefs, 1979; Botkin, 1990; Allen and Hoekstra, 1992; Ulanowicz, 1997).

The original concept of carrying capacity grew out of the *logistic equation* of P. F. Verhulst (1849), which characterizes population growth in terms of the biotic potential of the individual relative to the detrimental effects of other individuals in the population on that biotic potential (Street, 1969; Ricklefs, 1979; Botkin, 1990; Allen and Hoekstra, 1992). A more recent definition has been generalized to mean *the maximum size of a population over time, that can be supported by the habitat without damage to other species, or to the functioning of the ecosystem of which it is a part* (Botkin, 1990). Limiting factors are those key variables in the environment that implement carrying capacity, by serving as negative feedback on growth of the population (Simmons, 1979; Botkin, 1990; Allen and Hoekstra, 1992). How carrying capacity is lowered for a population by anthropogenic impacts has always been of key interest to geographers, anthropologists and environmental scientists (Marsh, 1864; Sauer, 1925; 1941; Leopold, 1949; Steward, 1963; Street, 1969; Holling, 1973; 1978; Hardesty, 1977; Holt and Talbot, 1978; Simmons, 1979; Worster, 1979; Butler, 1980; Hardin, 1986; Allen and Hoekstra, 1992; Ulanowicz, 1997), and the specific focus of modern "historical ecologists" as well (Bilsky, 1980; Turner, 1990; Schmidt, 1994).

In the present study the management unit is a population of approximately 80-90 killer whales who have long, socially complex life spans, a very low reproductive output, and who exhibit a high preference upon a single food resource for their primary sustenance (Chapter 2). Due to the life spans involved, natural carrying capacity for a population like this is only going to be reached over very long periods of fairly stable environmental conditions (Eisenberg, 1981; Botkin, 1990; Allen and Hoekstra, 1992; Ulanowicz, 1997).

Human population growth and industrial development in the Salish Sea region over the life spans of the oldest individuals in this killer whale population (since approx. 1910; Bigg *et al.*, 1987; Olesiuk *et al.*, 1990), is clearly documented in the historical records as an over-all increase in human environmental influences that has been increasing up to the present (McKervill, 1967; Gregson, 1970; Kimerling and Jackson, 1985; Lyons, 1989; Levings and Thom, 1994; Schwantes, 1996). When this basic human history is combined with the demographic studies that have been conducted on this population of killer whales (Olesiuk *et al.*, 1990; Brault and Caswell, 1993; Baird, 1999; Ginneken and Ellifrit, 1999; Center for Whale Research, in prep.), it appears likely that the present population is not at historical levels of "carrying capacity", but it is not known what those historical levels might have been.

For the Southern Resident killer whales, increases in mortality will be the result of predation, starvation, accidents, disease, toxic poisoning, or some combination of these limiting influences (Calambokidis and Baird, 1994; Baird, 1999). Fertility will be negatively affected due to any reductions in the percentage of breeding females, or their physiological ability to produce offspring (Ricklefs, 1979; Eisenberg, 1981; Robinson and Bolen, 1989; Allen and Hoekstra, 1992). Thus, on a population-wide scale, fertility is also affected by disease, toxic poisoning, and/or behavioral disturbance (Robinson and Bolen, 1989; Allen and Hoekstra, 1992). Increases in mortality and reductions in fertility are further compounded if there are periods of insufficient food resources for the population (Ricklefs, 1979; Robinson and Bolen, 1989; Allen and Hoekstra, 1992). It is within the scope of these "carrying capacity" impacts that the overriding constraints on the stability of the population will be found, whether they be human induced or not.

As a corollary to carrying capacity, Liebig's "law of the minimum", has also been applied *ad hoc* in biology and ecology for over 100 years, as a way of further identifying critical components in ecological systems that are the "bottom line" in the persistence of the system (Erhlich *et al.*, 1977; Ricklefs, 1979; Ulanowicz, 1997). In chemistry this law is well known simply as a special case of either the Ideal Gas Law and/or the Arrhenius Law of chemical kinetics (Nebergall *et al.*, 1980, *and* after Ulanowicz, 1997). When applied in ecology, this concept of minimum conditions, provides a narrower focus for identifying the potentially limiting variables affecting the population. If these minimum conditions aren't met, any other potential impacts are erroneous. A "law of the minimum" delimitation for the killer whale population in this study can be narrowed to include six vectors of potential human impacts (after categories suggested by Calambokidis and Baird, 1994; Baird, 1999): 1) human predation, 2) toxic poisoning, 3) disease, 4) impacts on the availability of food, 5) behavioral disturbance from vessels, and 6) behavioral disturbance from underwater noise. Non-anthropogenic factors such as climate, lithographic change, and ecosystem stability, will be considered as background noise for the purposes of this chapter.

Comparing Ecological Variables with an Interaction Matrix

Interaction matrices have been the standard systematic process managers have used for identifying environmental impacts (Leopold, 1974; Holling, 1978; 1986; Mitchell, 1989), and they have served as important heuristic devices for theoretical ecologists when they are framing ecological relationships for the development of dynamic computer models (Holling, 1978; 1986; 1992; Clark, 1985; Mangel and Clark, 1988; Ulanowicz, 1997).

The classic example of an interaction matrix is the Leopold Matrix, which was developed by the U.S. Geological Survey in order to comply with the U.S. National Environmental Policy Act of 1969 (Mitchell, 1989). The purpose of the matrix was to quickly assess impacts for a wide range of variables in relation to a potentially diverse number of projects, but with limited empirical information (Holling, 1978; 1986; Mitchell, 1989). The matrix itself contains 100 project actions on one axis, in relation to 88 environmental conditions and characteristics in the other dimension. All actions of the project are identified in relation to the 88 environmental variables, and each interaction is given two scores on a scale of 1-10 for the magnitude of the impact and its relative importance (Leopold, 1974; Holling, 1978). The scores in a Leopold Matrix are not added or otherwise manipulated beyond this (Leopold, 1974), but simply serve as identifiers of components in the system that can be analyzed further using other methods (Mitchell, 1989). However, in some of the many varieties of interaction matrices that have been developed for different management situations, these qualitative scores are often cross-tabulated into simple rank scores for relative comparisons (Holling, 1978; Mitchell, 1989; Allen and Hoekstra, 1992; Ulanowicz, 1997).

There are many other variations on these systematic matrices that have been utilized in resource management (Holling, 1978; 1986; Clark, 1985; Mitchell, 1989) and in the heuristics of dynamic computer modeling (Holling, 1978;1986; Mangel and Clark, 1988; Allen and Hoekstra, 1992; Ulanowicz, 1997). Interaction matrices have also been recommended as a useful device for directly dealing with the framing of interacting variables in historical ecological analysis (Winterhalder, 1994). To that end, the following interaction matrix for "Southern Resident" killer whales is presented for the purpose of: 1) formalizing the list of limiting environmental variables that will be used to characterize impacts on this population of killer whales, 2) identifying the vectors of human activities that most directly contribute to those impacts, and 3) linking these vectors of human impact with quantifiable indicators of recorded human history.

METHODS

In an attempt to understand the nature of ecological interactions between humans and Salish Sea resident killer whales better, an interaction matrix has been constructed that compares areas where these killer whales are vulnerable to impact, with vectors of human activity. The interaction matrix provides the basis for a systematic evaluation of these categories relative to each other, and facilitates identification of the types of human activity that will best serve as indicators of historical change in the environment of these killer whales. The objective is to then plot these indicators of human impact with the three indicators of the ecological status of these killer whales identified in Chapter 2, and compare them at different time scales (Chapter 4). It is this comparison of historical trends in multiple indicator variables that will form the basis for assessing the resiliency of this killer whale population relative to both past and present potential impacts.

The Matrix

The simple 6 X 5 interaction matrix constructed for the purposes of the present assessment lists six limiting environmental factors to growth of this killer whale population on one axis, and five vectors of human interaction on the other (Table 7). The six limiting factors attempt to address the main areas of environmental resistance in this population relative to their theoretical carrying capacity. The five vectors of human interaction attempt to list the primary human activities that would be expected to affect the habitat of these whales based upon a survey of existing information on human impacts upon the Salish Sea ecosystem (Ward and Sullivan, 1980; Chasen, 1981; Fleming, 1987; Lyons, 1989; Kruckeberg, 1991; PSWQA, 1992; Yates, 1992; Levings and Thom, 1994; Schmitt *et al.*, 1994; 1995; Crecelius *et al.*, 1995; West, 1997; PSWQAT, 1998). The assumption is that by starting with these general categories of potential human impacts, measurable historical indicators can be identified, and a more empirical historical assessment of these potential impacts can be performed.

The values in the matrix are simple *yes/no* scores in relation to how the human vector would theoretically be expected to contribute as a limiting environmental factor on the killer whales. A score of ***1*** = a perceived increase in environmental resistance on the killer whales, and ***0*** = no known potential effect on environmental resistance.

The scores are then tallied to provide a rank score for each category in both directions: a) in terms of which limiting factors were potentially the most vulnerable to human impacts, and b) which vectors of human activity potentially contribute to impacts for the largest number of limiting factors. The distribution of rank scores for each category are then plotted in both directions to illustrate the comparisons (Figures 25 and 26).

Table 7

Matrix Design for Comparing Limiting Environmental Factors with Potential Vectors of Human Influence on "Southern Resident" Killer Whales

	Vectors of Human Interaction					
Limiting Environmental Factors	Killing, Capture & Shooting	Salmon Elimination	Air & Water Contamination	Ambient Vessel Traffic	Seasonal Vessel Pursuit	Score:
Predation						0
Disease						0
Food Resource Depletion						0
Toxic Exposure						0
Surface Disturbance						0
Underwater Noise						0
Score:	0	0	0	0	0	

Definitions of Matrix Categories:

In this section the rational for each category listed in Table 7 is presented. These are the definitions for categories of potential anthropogenic influences that will ultimately form the basis of the historical analysis that follows in the next chapter.

I. Limiting Environmental Factors:

The objective of this axis of the matrix (Table 7) is to identify the primary classes of variables that are imposing environmental resistance on the carrying capacity of these killer whales. This environmental resistance is considered to be ultimately expressed as either, increased mortality outside of senescence, or anything that reduces female fertility.

Under pristine Holocene conditions the carrying capacity of the "Southern Resident" population of killer whales can only be imagined, but it is possible that the ancestral line of this population did have as much as 5,000 years of the existing Salish Sea ecosystem (Borden 1968; Thomson, 1981; 1994; Knox, 1983; Kruckeberg, 1991) in which to actually exhibit a theoretical carrying capacity. The limiting factors impinging upon the killer whales under these prehistoric conditions should be essentially the same ones they are confronting today, minus any modern anthropogenic sources.

Under pristine conditions the limiting environmental factors can be categorized as predation, disease, food resource depletion, and unpredictable catastrophic accidents. However, for environmental conditions that have existed over the last 100 years it is necessary to add a few over-riding variables that have come with the advent of human domination of the ecosystem. These latter categories are anthropogenic limiting factors that, by analogy with research findings on other species, would also contribute environmental resistance to these killer whales. *Unpredictable catastrophic accidents* are considered background noise for the purposes of present analysis and so it has not been included as a category in the matrix.

Predation:

Predation on this population would include outright killing by other species and/or conspecifics, shooting and killing by humans, live capture for removal into captivity, and parasite infestation (Calambokidis and Baird, 1994; Baird, 1999). The most direct effects of predation are expressed as mortalities outside of senescence, but predation can also have a significant effect on fertility by deleteriously impacting age distribution in the population; or in the case of parasitism, by directly interfering with reproductive systems, or indirectly by reducing overall fitness in the population through infestation stress to individuals.

Disease:

Disease outbreaks have never been documented in wild populations of this species, but regional viral epidemics have been documented in other species of coastal odontocetes in recent decades (Kennedy, 1996). However, very few post mortems have ever been undertaken on wild-stranded killer whales that would be capable of identifying disease conditions even if they were present (Olesiuk *et al.*, 1990; Baird, 1999).

Historically there are no known or suggested records of an epidemic disease outbreak among killer whales, but there is no reason to believe they are any less susceptible to infectious diseases than any other mammals. The environmental resistance on carrying capacity from disease finds expression equally as the source of mortalities outside of senescence, and as both direct and indirect impacts on the fertility of females.

Food Resource Depletion:

Food availability is always going to be a fundamental limiting variable affecting the reproductive output of a population (Ricklefs, 1979; Robinson and Bolen, 1989) and must be given consideration in any assessment of the population's carrying capacity (Street, 1969; Botkin, 1990; Allen and Hoekstra, 1992). The variety of food items that have been documented for killer whales worldwide (Jefferson *et al.*, 1991; Felleman *et al.*, 1991; Baird and Dill, 1996; Baird, in press) make it hard to believe free-roving killer whales would ever starve to death; unless they were accidentally trapped in a sterile environment, or had lost the physical ability to process food due to an accident, parasites or disease. The availability of species-typical food in the environment of Southern Resident killer whales has probably always been sufficient to sustain population growth, except possibly until very recently during some seasons (i.e. since the late 1980s: Schmitt *et al.*, 1994; 1995; Beamish and Riddel, 1995; and in 1999: Wash. State, 1999; Pac. Salmn. Commis., 1999). The environmental resistance on carrying capacity from malnutrition finds expression equally as a source of mortalities outside of senescence, and as both direct and indirect impacts on the fertility of females.

Toxic Exposure:

As predators at the top of several different food chains in the environment, killer whales are especially vulnerable to the bioaccumulation of toxic substances (Calambokidis and Baird, 1994; Jarmen *et al.*, 1994; Ross *et al.*, in press). Natural toxic disasters such as toxic algae blooms (Cherfas, 1990; Horner, 1995) and toxic geochemical releases from seismic activity (Thomson, 1981; Kruckeberg, 1991) are extremely rare, and are relegated to the category of *unpredictable catastrophic accidents* in this study. However, anthropogenic contamination of Salish Sea marine food webs by a host of toxic chemicals has been chronic for the last 100 years (Ward and Sullivan, 1980; Lyons, 1989; MacDonald and Crecelius, 1994; Horner, 1995), and now is an ever-present source of environmental resistance for this killer whale population, as well as most other organisms in the bioregion.

Examination of the remains from both resident and transient forms of killer whales stranded in the study area have produced some extremely high levels of mercury, DDT, and PCB compounds (Calambokidis *et al.,* 1990; Calambokidis and Baird, 1994; Jarman *et al.,* 1996; Ross *et al.,* in press). Concentration of contaminants found in these killer whales are some of the highest reported for marine mammals globally, and are at levels thought to cause reproductive problems in other species (Calambokidis, 1995; Johnston *et al.,* 1996; Jarman *et al.,* 1996).

The environmental resistance of toxic exposure in mammals is expressed as mortalities outside of senescence, particularly in terms of failed pregnancies and neonate deaths, and has a significant effect on fertility by deleteriously impacting age distribution in the population; or by directly interfering with reproductive systems in both males and females (Addison, 1989; Johnston *et al.,* 1996; Ross *et al.,* in press).

Surface Disturbance:

The surfacing and breathing space of marine birds and mammals is a critical aspect of their habitat (Bateson, 1974; Norris and Dohl, 1980; Ridgway, 1986; Osborne, 1996). Access to the surface is an over-riding priority for their survival and it potentially effects carrying capacity at all levels. The way in which surface impacts are most likely manifested in marine birds and mammals falls roughly into three types: 1) collisions, 2) collision avoidance, and 2) respiratory stress from exhaust inhalation (Osborne, 1996).

Under prehistoric conditions the natural chronic sources of surface disturbance were sea ice (which disappeared from this environment some 8-9,000 years ago), and floating logs and other debris which may have caused impacts for several years following a major seismic, pyroclastic, or forest blow-down event (Kruckeberg, 1991). These environmental circumstances were rare and therefore are categorized as *unpredictable catastrophic accidents* in this study.

Under present conditions surface disturbance is primarily an anthropogenic factor produced as the result of intensive vessel use of the ocean surface at the same time and location as the whales (Watkins, 1986; Mayo *et al.*, 1989; Blane and Jaakson, 1996). In one case interactions with the killer whales occur because of focused human vessel activity around their primary food resource (e.g. salmon harvesting), in the other case it is because of focused human vessel activity specifically around them (e.g. whale watching).

The environmental resistance on the carrying capacity of these killer whales from surface disturbance would rarely be from direct mortalities, but would mostly be a result of long-term indirect impact on the fertility of females as a result of reduced returns from feeding and breathing efforts, and increased behavioral stress (Ray *et al.*, 1986; Kriete, 1995).

Underwater Noise:

For cetaceans the underwater sound environment is a critical component of their sensory and behavioral lives (Herman and Tavolga, 1980; Norris and Dohl, 1980; Reeves *et al.*, 1996). Killer Whales acoustically communicate with each other over both long and short distances in order to coordinate their social existence. They actively employ echolocation as a primary sensory channel, and likely also rely heavily on passive listening as a primary sensory source (Herman and Tavolga, 1980; Norris and Dohl, 1980; Ford, 1989; 1991; Bain, 1986; 1989; Hoelzel and Osborne, 1986; Barrett-Lennard *et al.*, 1996; Baird, 1994; Heimlich-Boran and Heimlich-Boran, 1999).

Extrapolating from studies world wide, noise in the underwater habitat of these whales must have changed significantly over time in relation to anthropogenic sources (Myerberg, 1990; Richardson *et al.*, 1995; Gordon and Moscrop, 1996), and has likely required adaptive responses on the part of the whales that have remained undetectable by managers up to this point (Miller and Willis, 1997; Bain, 1999). Recent interest in this subject by mangers however, has brought to light the potentially serious acoustic impacts that whales have been exposed to over the last 70-80 years in relation to: military operations, geologic and oceanographic testing, commercial fishing operations, shipping traffic, and whale watching (Myerberg, 1990; Richardson *et al.*, 1995; Gordon and Moscrop, 1996).

Long term impacts from noise pollution would likely be exhibited as noticeable behavioral changes in habitat use when the impact is spatially discrete, and as sensory damage or gradual reduction in population health (Richardson *et al.*, 1995; Gordon and Moscrop, 1996; Miller and Willis, 1997). The environmental resistance on carrying capacity from underwater noise would be similar to surface disturbance. Underwater noise stress would rarely, if ever result in direct mortalities, but would mostly be a result of long-term indirect impact on the fertility of females as a result of increased behavioral stress (Ray *et al.*, 1986; Kriete, 1995; Richardson *et al.*, 1995).

II. Vectors of Human Interaction

The objective of this axis of the matrix (Figure 25) is to identify the main anthropogenic factors that are contributing environmental resistance to the carrying capacity of these killer whales. This assessment of human contributions to environmental resistance will then provide the basis for identifying specific human activities that can serve as measurable indicators in a historical analysis (Chapter 4).

Human Predation:

For the purposes of the present study, the primary vectors of human interaction involved in direct physical attack on these killer whales include: 1) opportunistic shootings, 2) military operations that use killer whales for target practice, and 3) live capture for public display.

Accounts of human attacks on killer whales are scattered in the historical human record from late in the last century to the mid-1970s (Scheffer and Slipp, 1948; Pike and MacAskie, 1969; Olesiuk *et al.*, 1990; Hoyt, 1990). Initially a few Southern Resident killer whales were probably opportunistically killed as part of commercial whaling in Georgia Strait, however killer whales were never a target species of the commercial whaling industry (Olesiuk *et al.*, 1990). The whaling stations were shore-based operations that used catcher boats to kill the whales, and then the bodies were towed back to shore for processing (Pike and MacAskie, 1969; Merilees, 1985). Whaling in Georgia Strait ended by about 1910 because all the commercially valuable species (primarily humpback whales and fin whales) had by then been extirpated (Merilees, 1985).

Prehistorically, the local killer whales were revered in the myth and art of Salish Sea aboriginal peoples (Drucker, 1965; Cavanagh-Ford, 1984; Hoyt, 1990; Yates, 1992), and although these cultures regularly hunted marine mammals, only one killer whale has ever been recovered from coastal archaeological digs of the region (Olesiuk, 1990). However, for most of this century, the majority of humans in the Salish Sea region have believed that killer whales are voracious competitors for salmon resources, and a threat to humans in small boats (Griffin, 1982; Hoyt, 1990; Olesiuk *et al.*, 1990). This belief lead to regular attacks on the killer whales from humans in large boats and from shore (Hoyt, 1990; Olesiuk *et al.*, 1990). Old gun shot wounds were commonly noted on living individuals from the Southern Resident Community during capture operations (25%), and in strandings from that era (Olesiuk *et al.*, 1990; Hoyt, 1990; 1992a).

Other attacks by humans on the Southern Resident Community came from military operations that were sanctioned to use killer whales for target practice. During the 1940s the Royal Canadian Air Force regularly used killer whales for bombing practice, and in 1960, the Department of Fisheries and Oceans temporarily installed a machine gun in

Georgia Strait in an attempt to cull the population, though records indicate no killer whales were culled at that time (Olesiuk *et al.*, 1990).

Human attacks on these killer whales continued until the 1970s, after a decade of repeated live captures on the population (8 captures w/46 individuals removed: Hoyt, 1981; 1990; 1992a; Olesiuk *et al.*, 1990). As a result of increased familiarity with killer whales in the captive setting, cultural attitudes among Salish Sea humans again returned to where the overwhelming majority of people revered the killer whales and made it illegal to attack or capture them (Duffus, 1988; Hoyt, 1992b; Duffus and Dearden, 1993).

Salmon Elimination:

The elimination of salmon in the marine waters of the Salish Sea to the point that there are not enough left to support this killer whale population year-round, would not have seemed possible until very recently (Pac. Salmn. Comm., 1999; DFO, 1999; Wash. State, 1999). However, direct human exploitation of salmon resources through over-fishing (Schmitt *et al.*, 1994), in combination with the destruction of salmon habitat (Groot and Margolis, 1991; Beamish and Riddel, 1995; Wash. State, 1999), has now managed to diminish these salmon resources to the point that some stocks are considered threatened under the U.S. Endangered Species Act (Wash. State, 1999). As a result it is quite possible that the Southern Resident Community of killer whales will likely have to rely more heavily on other food resources (Chapter 2).

The primary vectors of human interaction that have led to the elimination of salmon include: 1) commercial and sport fishing of salmon, 2) interference with pelagic food webs in the Eastern North Pacific through over-fishing and climate change, 3) habitat destruction from blockage of fresh water rivers and streams by dams and upland development, 4) alteration of fresh water flow rates, temperatures, and silting by forest harvesting practices and upland development, and 5) elimination of estuaries through coastal development (Schmitt *et al.*, 1994; Washington State, 1999).

Air and Water Contamination:

Air and water contamination is the most diffuse vector of human ecological interaction with these killer whales. It includes the release of any unusual proportions of both natural and artificial chemicals into the Salish Sea environment as a result of human activities. The chemicals enter the killer whale's habitat through non-point sources via the Salish Sea watershed (Figure 4) and regional atmosphere, and as point sources at waste outfalls for sewage as well as industrial by-products (Segal *et al.,* 1980; Lyons, 1989; Macdonald and Crecelius, 1994; Johnston, *et al.,* 1996; Ross *et al.*, in press). The chemicals become incorporated into the physiology of the killer whales primarily through bioaccumulation in their food (salmon and other fish), but killer whales also likely incorporate some contaminants through respiration and directly from the sea water in acute situations; such as an oil or chemical spill (Dahlheim and Matkin, 1994), or when the killer whales are in the immediate vicinity of an outfall (Johnston et. al, 1996).

The primary vectors of human interaction that acutely contribute to air and water contamination include: a) sewage outfalls, b) industrial waste outfalls, c) vessel spills, d) spills from shoreline facilities, and e) combustion by-products from vessels (Lyons 1989; P.S.W.Q.A., 1988; P.S.W.Q.A.T.,1998). The secondary human vectors that contribute to non-point air and water contamination are so diverse that it would be inappropriate to try and enumerate them here. They potentially include any release of toxic or hazardous chemicals, or excess natural chemicals from human activity that enter the habitat of these killer whales through atmospheric and hydrological processes.

Vessel-Based Whale Watching:

Whale watching involves boats targeting killer whales for hours at a time and repeatedly driving up to them whenever they surface. Vessel pursuit of these killer whales was originally practiced during periods of whaling and military target practice, and more recently, in relation to capture operations. Since the early 1970s, however, whale watching from vessels as part of scientific research and recreational wildlife viewing has been the primary source of vessel pursuit (Mayo *et al.*, 1989; Osborne, 1991; Kruse, 1991; Burgen and Otis 1995; Hoyt, 1995; Williams, 1998).

Ambient Vessel Traffic:

Ambient vessel traffic in the Salish Sea amounted to dugout canoes for most of its history, and progressed to occasional square-rigged sailing ships and rowing dories from the late 1700s to the 1850s. By the 1860s steamships started to become the preferred form of commercial shipping (Chasen, 1981; Schwantes, 1996; Fleming, 1997), but sail and human powered craft have remained prevalent into modern times. By 1891 over 2,600 vessel transits were recorded for Victoria Harbor alone (Gregson, 1970), and this has increased fairly steadily right up to the 1980s, when Salish Sea shipping began to level off at about 200,000 commercial ferry and shipping transports per year (Chasen, 1981; USCG, VTS records, 1989; DOE, 1998). The original steamships were paddle wheelers, but this rapidly shifted to propeller driven vessels by the turn of the century, and the internal combustion engine after World War I (Gregson, 1970; McNeill, 1971; Chasen, 1981; Roos, 1990; Schwantes, 1996).

The primary vectors of human interaction that presently contribute to ambient vessel traffic in the Salish Sea include: 1) commercial shipping, 2) commercial and recreational fishing, 3) recreational boating, 4) vessel-based military operations, and 5) vessel -based scientific research.

RESULTS

The six limiting factors of environmental resistance for this killer whale population, and the five vectors of human interaction that have just been defined, will be compared using the interaction matrix presented in Table 7. The findings will be presented in relation to assessing two aspects of the interaction matrix: 1) which * *limiting factors* on the killer whales are potentially the most vulnerable to cumulative human impacts from multiple vectors, and 2) which **vectors of human interaction* potentially contribute to impacts for the largest number of limiting factors.

In Table 8 the values in the matrix are simple *yes/no* scores in relation to how many times the human vector theoretically contributes to the limiting environmental factor.

Table 8
Interaction Matrix Scores for Limiting Environmental Factors and Vectors of Human Influences on Southern Resident Killer Whales.

	Vectors of Human Interaction					
Limiting Environmental Factors	Human Predation	Salmon Elimination	Air & Water Contamination	Ambient Vessel Traffic	Vessel-Based Whale Watching	Score:
Predation	1	0	0	0	0	1
Disease	0	0	1	0	0	1
Food Resource Depletion	0	1	1	0	0	2
Toxic Exposure	0	1	1	1	1	4
Surface Disturbance	1	0	1	0	1	3
Underwater Noise	1	0	0	1	1	3
Score:	3	2	4	2	3	

A score of ***1*** = a perceived increase in environmental resistance on the killer whales, and ***0*** = no known effect on environmental resistance. The ultimate objective of this matrix is to systematically relate the limiting factors exercising environmental resistance on "Southern Resident" killer whales, with specific human activities that can be used as reference points in a historical analysis of the ecology of this killer whale population in Chapter 4.

* ***Italics*** is used throughout this section when ever "categories" identifiable in the tables and figures are referred to.

Limiting Environmental Factors

In Figure 25 the distribution of matrix scores for each of the *limiting environmental factors* in Table 8 (row scores) are presented in their rank order from left to right. These scores represent an index of the relative contribution of environmental resistance from all the human interaction vectors for each limiting factor.

Toxic Exposure

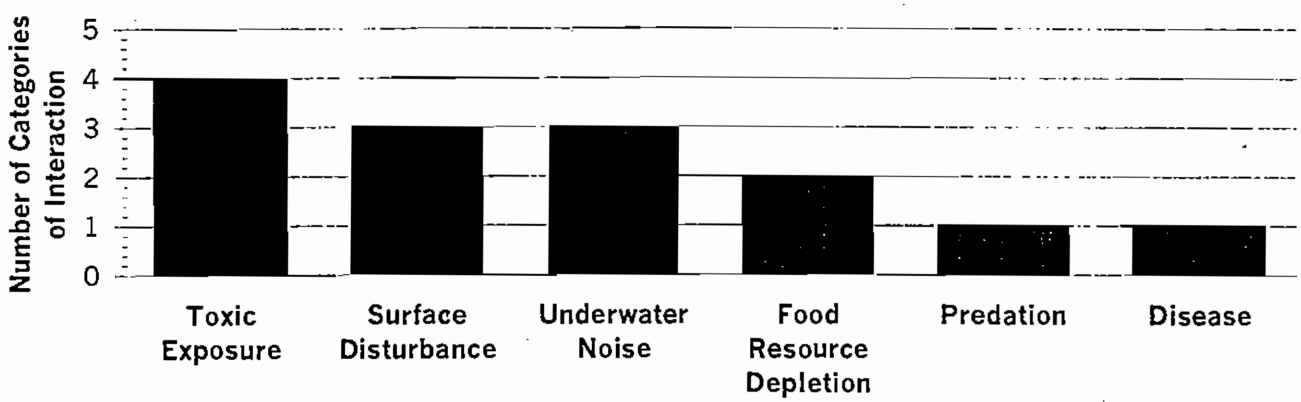
Toxic exposure exhibits the highest score because it received environmental resistance contributions from the most vectors of human interaction (Table 8). Only *human predation* was not considered to be synergistically involved in increasing environmental resistance on *toxic exposure*. Although the latter could conceivably expose the population to toxic chemicals through vessel-based components of the activity, the relative infrequency of these interactions is such that any toxic chemical contributions along those lines were considered negligible.

Salmon elimination was scored as contributing to toxic exposure because most of the other species of fish, and all of the marine mammals, carry higher toxic loads than do salmon (Calambokidis and Baird, 1994; West and O'Neill, 1995; Casillas *et al.*, 1995; Johnson *et al.*, 1995). Prey shifting away from salmon therefore increases the toxic exposure of Salish Sea resident killer whales.

Air and water contamination is obviously included as a human vector for *toxic exposure* and needs no further explanation. *Ambient vessel traffic* is scored as a contributor to *toxic exposure* in relation to air and water petroleum emissions, and the small toxic spills that are part of basic operations for any vessel (Goodwin, 1982; P.S.W.Q.A., 1988; 1995). *Ambient vessel traffic* is also included here in relation to inevitable large-scale spills that occur less frequently (P.S.W.Q.A., 1988; 1995; Johnston *et al.*, 1996).

Figure 25

Ranked Matrix Score on the Relative Sensitivity of Southern Resident Killer Whales to Multiple Vectors of Human Impact.



Vessel-based whale watching is included as a contributor to *toxic exposure* in relation to petroleum emissions in the air and water, particularly in terms of the high concentrations of "operating" vessels that accumulate in the immediate vicinity of the killer whales during whale watching (Osborne, 1991). Further contributing to toxic exposure in this instance is the fact that the vessels pursue the killer whales, which increases their exposure time, and eliminates the opportunity for the whales to avoid the exposure (Burgen and Otis, 1995).

Surface Disturbance and Underwater Noise

The next two highest scores in Table 8 and Figure 25 are *surface disturbance* and *underwater noise*. *Surface disturbance* receives contributions of environmental resistance from three *vectors of human interaction*. *Human predation* and *vessel-based whale watching* both involve direct one-on-one interactions between killer whales and humans at the air/water interface, often aggressively on the part of the humans. *Air & water contamination* contributes to *surface disturbance* in the form of ambient air pollution, particularly down wind from urban areas, and in terms of buoyant debris and chemicals that collect on the sea surface (Hardy and Antrim, 1988).

Underwater noise receives human contributions of environmental resistance in relation to underwater vessel noise in all three of its *vectors of human interaction* (Table 8 and Figure 25). In the case of *human predation* the use of explosives for herding during captures (Hoyt, 1981; 1990; Griffin, 1982), and explosives during military target practice (Olesiuk *et al.*, 1990), are also included as contributing to *noise pollution.*

Food Resource Depletion

In Table 8 and Figure 25 *food resource depletion* receives scored contributions of environmental resistance from two *vectors of human interaction*, *salmon elimination* and *air & water contamination*. In the first instance, since salmon are the primary food resource of Salish Sea resident killer whales (Bigg *et al.*, 1990b; Felleman *et al.*, 1991; Ford *et al.*, 1995; 1998), anthropogenic reductions in salmon resources will contribute environmental resistance directly. Anthropogenic contributions of *air & water contamination* contribute environmental resistance on all food resources of the killer whales, relative to its role in overall habitat destruction of underlying food webs (Segal *et al.*, 1980; Robinson and Bolen, 1989; Allen and Hoekstra, 1992; P.S.W.Q.A., 1988; 1995).

Predation and Disease

In Table 8 and Figure 25 *predation* and *disease* each exhibit one vector of human interaction that contributes to environmental resistance on these killer whales. In the first instance, *human predation* in the form of killings, shootings and captures, is appropriately linked with *predation*. Out side of *human predation*, the only other predators that Southern Resident killer whales would be subject to would be potential conspecific predation and parasites (Baird, 1994; Baird, 1999).

Disease as a *limiting environmental factor* for these killer whales was only scored in one vector of human interaction, *air & water contamination* (Table 8). This is based upon the well documented connection between high levels of toxic exposure to certain chemicals (e.g. organo-chlorines) and increased susceptibility to disease and reproductive failure in marine mammals (Addison, 1989; Calambokidis and Baird, 1994; Kennedy, 1996; Reijnders, 1996).

In summarizing the results illustrated in Figure 25, it can be seen that all six categories of *limiting environmental factors* can be associated with *vectors of human interaction*. *Toxic exposure*, and to a lesser extent *surface disturbance* and *underwater noise*, show the highest numbers of vectors potentially enhancing environmental resistance on these whales in a synergistic fashion.

Vectors of Human Interaction

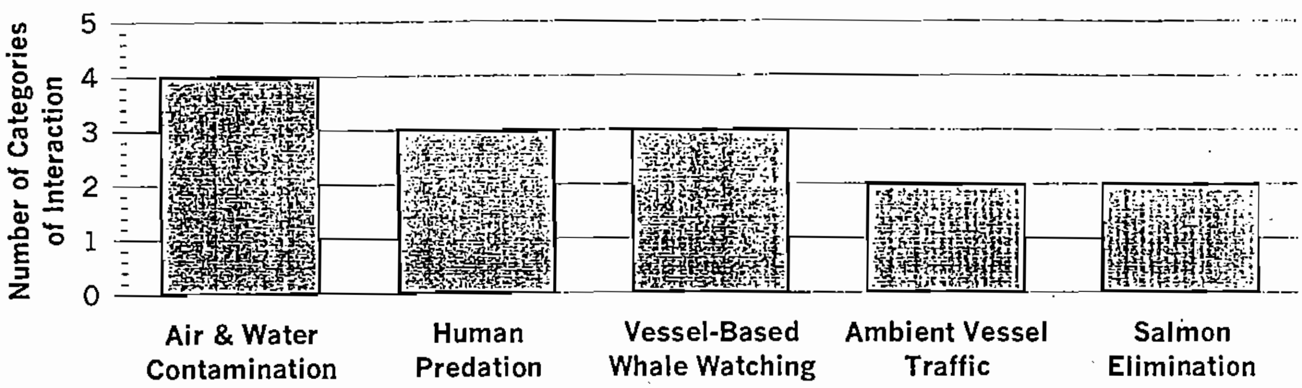
In Figure 26 the distribution of matrix scores for each of the *vectors of human interaction* in Table 8 (column scores) are presented in their rank order from left to right. These "reversal" scores represent the relative number of *limiting environmental factors* on Salish Sea resident killer whales that each human interaction vector is potentially affecting in terms of environmental resistance. It provides a qualitative basis to rank human activities in terms of the multiplicity of impacts unique to this management unit.

In Figure 26 *Air and water contamination* have the broadest impacts on Salish Sea resident killer whales, affecting their carrying capacity in relation to four *limiting environmental factors*. The only areas where *air and water contamination* are not a factor, are for *predation* and *underwater noise*.

The next highest additive scores are for *human predation* and *whale watching*, where they each contribute to environmental resistance in three categories of *limiting environmental factors* (Figure 26). Both contribute environmental resistance to *surface disturbance* and *underwater noise* as they relate to vessel activities (Table 8). *Vessel-based whale watching* additionally contributes to *toxic exposure* as a result of pollution

Figure 26

Ranked Matrix Score on the Relative Distribution of Environmental Resistance for Different Vectors of Human Interaction w/ Southern Resident Killer Whales



from high concentrations of operating vessels. *Human predation* has its obvious direct impact on *predation,* as a *limiting environmental factor.*

The lowest scores in Figure 26 were for *ambient vessel traffic* and *salmon elimination. Ambient vessel traffic* contributes environmental resistance to the *limiting factors* of *underwater noise* and *toxic exposure. Salmon elimination* contributes environmental resistance to *food resource depletion,* since salmon are the killer whales primary food resource. Less directly, *salmon elimination* also contributes to *toxic exposure*, as a result of increasing the amount of non-salmonid food species the killer whales must consume; almost all of which are known to carry higher toxic loads than salmon (Addison, 1989; P.S.W.Q.A., 1992; Calambokidis and Baird, 1994; Casillas *et al.*, 1995; Johnson *et al.*, 1995; P.S.W.Q.A.T., 1998; Baird, 1999).

In summarizing the results illustrated in Figure 26, it can be seen that all five *vectors of human interaction* can be associated with at least two categories of *limiting environmental factors* for the Salish Sea resident killer whale population. *Air and water contamination*, and to a lesser extent *human predation* and *vessel-based whale watching*, show the highest numbers of ways to inflict environmental resistance on these whales.

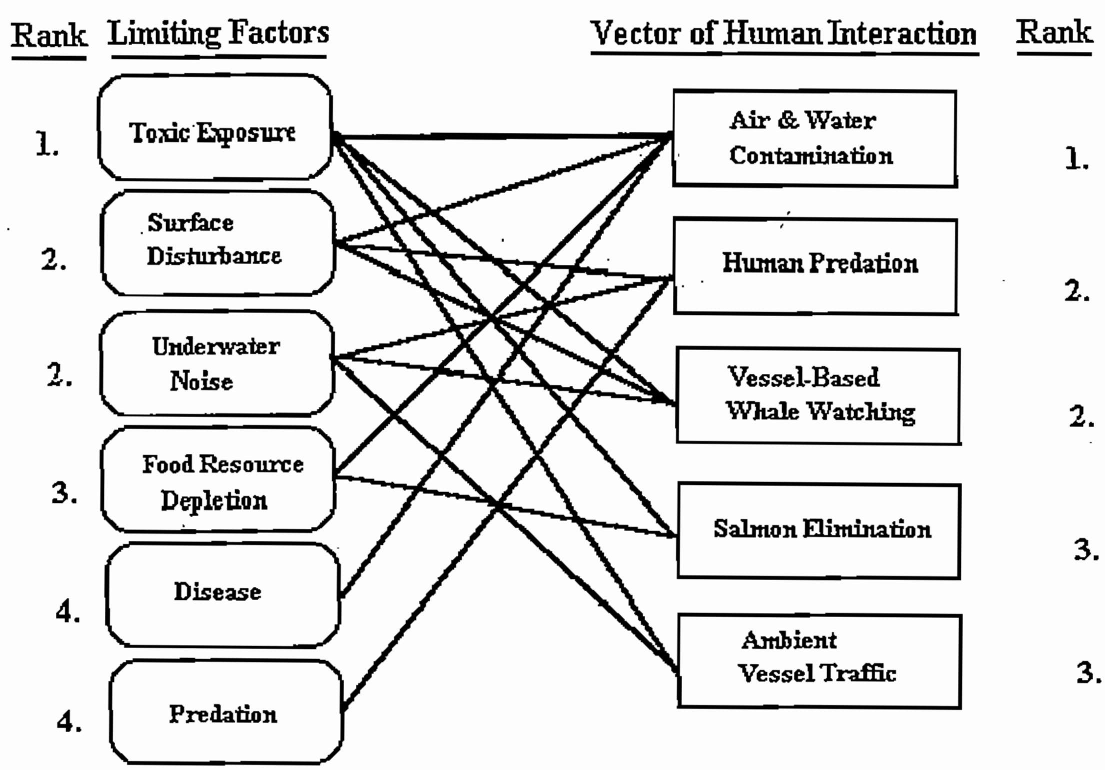
This qualitative assessment provides useful information for management by identifying which vectors of human interaction are contributing impacts in multiple ways, and which ones are potentially acting synergistically with others (Figure 27).

Conclusions

The primary objective of this chapter was to: 1) identify and define a set of limiting environmental factors for the study population of killer whales, and to link these variables with key human activities that: 2) affect the carrying capacity of these whales, and 3) are traceable to specific longitudinal measures that can be incorporated in a historical analysis.

The first two steps of this process were accomplished by utilizing an interaction matrix that systematically related the first two sets of variables with each other (Figure 27). This qualitative process allowed each category of variables to be explicitly identified and defined, and revealed some basic characteristics about how they interrelate with each other. The final step in this process is to link these categories with human activities that have longitudinal records that are long enough to be used in a historical analysis.

Figure 27 Killer Whale / Human Ecological Interaction Web



In Table 9 the results of the interaction matrix are paired with each other in terms of their relationship with the six categories of limiting environmental factors that were identified as contributing to environmental resistance on the carrying capacity of this killer whale population. In the final column is a list of human environmental variables for which longitudinal data is known to exist for each of these categories. These measurable human environmental variables will be utilized in Chapter 4 as indicators of historical environmental conditions affecting the study population. The interaction matrix has facilitated this linkage and allows these variables to be compared with the longitudinal indicators of the ecological status of these killer whales presented in Chapter 2.

The utilization of interaction matrices for qualitative assessment of ecological interactions for management regimes and computer based dynamic modeling, have been proven very effective in numerous studies over the last 25 years (Leopold, 1974; Holling, 1978; 1986; 1992; Mangel and Clark, 1988; Mitchell, 1989; Ulanowicz, 1997). Recently the use of interaction matrices have also been recommended for studies in historical

Table 9

Killer Whale Limiting Factors and Human Vectors of Interaction, Linked with Historically Measurable Variables.

Limiting Environmental Factor	Matrix Score	Vector of Human Interaction	Matrix Score	Potentially Measurable Human Environmental Variables
Predation	1	Human Predation	3	Number of orcas killed or captured.
Disease	1	Air & Water Contamination	4	Human population.
Toxic Exposure	4	Air & Water Contamination	4	Marine sediment cores. Human population.
Food Resource Depletion	2	Salmon Elimination	2	Salmon commercial catch data. Estimated salmon run sizes. Seasonal sport catch data
Surface Disturbance	3	Vessel-Based Whale Watching	3	Mean # of whale watching boats w/whales. Number of commercial whale watch boats. Number of commercial fishing boats. Number of commercial fishing openings.
Underwater Noise	3	Ambient Vessel Traffic	2	Mean # of boats w/out whales. Number of registered private vessels. Number of commercial shipping transports. Number of vessel custom clearences.

ecology (Winterhalder, 1994). In this study an interaction matrix was found to be an effective tool for framing theoretical variables of carrying capacity so that they could be systematically linked with available empirical data on human impacts. Secondarily, the interaction matrix has also qualitatively identified the vectors of human interaction that are contributing impacts on this killer whale population in multiple ways, and which ones are potentially synergistic.

In chapter 4 the measurable human variables identified in Table 9 will be combined with the three indicators of the ecological status of these killer whales identified in Chapter 2, in order to construct a historical ecology of this killer whale population in relation to the human record at different time scales. In the final chapter this historical assessment will be combined with the effects just described in order to cinstruct a list of management options where history, synergistic effects, and the resiliency of the management unit are combined.

Chapter 4

A Historical Analysis of Salish Sea Resident Killer Whale Ecology in Relation to Human Activities

INTRODUCTION

In order to understand the ecological condition of any population of organisms, and reasonably predict their fate, it is necessary to consider the cumulative impact of that population's specific ecological history (Popper, 1990; Worster, 1990; Winterhalder, 1994). The way a population behaves under present conditions is always going to be the result of: 1) the population's species specific biological potential, 2) the historically unique set of environmental conditions the population has had to face, and 3) the population's learned experience and traditional adaptive response. In what follows a specific population of killer whales (*Orcinus orca*) will be examined in relation to indicators of their historically unique set of ecological conditions. The objective is to review the record of major events, and environmental trends that have influenced their adaptive response in the past and present, so that adaptive responses of this population of killer whales can be better predicted when making management decisions in the present.

In the preceding chapters indicators of the ecological status of this killer whale population that can be measured longitudinally were identified (Chapter 2), as were longitudinal indicators of human activities that can be expected to contribute to environmental resistance on these killer whales (Chapter, 3). In this chapter these ecological indicators are compared for similarities and differences in temporal trends.

These temporal patterns will be distinguished by plotting trends and identifying extreme perturbations from the sample mean of each indicator at different time scales.

The methodological assumptions in this historical analysis are: 1) an extreme perturbation away from the temporal sample mean of any one variable, identifies that perturbation event as a potential influence on the killer whales, 2) an extreme perturbation away from the temporal mean in one variable is expected to temporally correspond with an extreme perturbation in other variables if the variables mutually influence each other, and 3) its corollary, an absence of temporal coincidence between extreme perturbations of variables means the variables do not strongly influence each other. However in the third case, if no perturbations occur between indicators this will not necessarily be considered validation of a lack of mutual influence. It would be impossible to distinguish whether an absence of extreme perturbations in an indicator is truly due to a lack of influences, bad measurements, mutual compensatory interactions, stochasticty of the system, or some combination of all these effects (Popper, 1990). Hence, only the presence of extreme perturbations will be examined as potentially valid sources of interaction.

These findings should minimally demonstrate whether any of the variables being plotted are potentially useful indicators of influences on the killer whales. If obvious temporal patterns between extremes in indicators emerge, then an important insight on the resiliency of adaptive responses in these killer whales can be identified. Any measurable influences will also provide valuable information on how these killer whales might be expected to adapt to similar conditions of their habitat in the future, and would identify relevant variables to continue to monitor.

However, even in the absence of statistically valid correlation between extreme perturbations, the process of bringing the full range of ecological indicators for this population together at once, and subjecting them to a multi-scale examination, will present the unique story of this killer whale population with a coherence and breadth that would otherwise not be possible.

The Historical Setting

The earliest written records that these killer whales existed are scattered among personal accounts and regional newspaper articles since the late 19th Century (Reekie, 1962; Stenzel, 1975; Hoyt, 1990; Yates, 1992; Olesiuk *et al.*, 1990). Natural history descriptions were anecdotal until the early 1970s, and provide little more than a record that resident humans have always regularly seen pods of killer whales in the vicinity (Carl, 1946; 1959; Scheffer and Slipp, 1948; MacAskie, 1966; Pike and MacAskie, 1969; Martinez and Klinghammer, 1970; Norris, 1974; Bigg and Wolman, 1975; Hoyt, 1981; 1990; Olesiuk, *et al.*, 1990), and that there was a minimum of 100 killer whales in the population in 1854 (Stenzel, 1975).

Prior to the geologic birth of the Salish Sea, which came with the recession of the Vashon Glaiciation 8 to 10,000 years ago (Thomson, 1981; 1994; Knox, 1983; Kruckeberg, 1991), there was conceivably an existing population of fish eating killer whales inhabiting the coastal waters; similar to the "Offshore Community" that has been documented off the Queen Charlotte Islands and the entrance to Juan de Fuca Strait over the last decade (Ford *et al.*, 1994; Figure 7). Recent genetic studies of these populations strongly suggest that the "Offshores" are in fact the direct descendants of the ancestral populations for both the Southern and Northern Resident communities (Hoelzel and Dover, 1991; Hoelzel *et al.*, 1998), and it can't be completely ruled out that the Offshore Community is still engaged in some degree of genetic exchange with either one, or both of the Vancouver Island pod communities.

When the glaciers receded at the end of the Pleistocene (Thomson, 1981; 1994; Burke and Birkeland, 1983) the existing inland marine waters soon developed an ecosystem with most of the same basic characteristics as the present (Baker, 1983), but with an over-all complexity and through-put that must have been many times greater than present conditions (Kruckeberg, 1991; Levings and Thom, 1994). Over the last 100 years this diminishment of the ecosystem can be measured in terms of the loss of primary production and biodiversity that has resulted from deforestation (Baker, 1983; Kruckeberg, 1991), the transformation of Salish Sea coastal wetlands (Fleming, 1977; Levings and Thom, 1994), and the levels of human extraction of marine fisheries (Roos, 1990; Schmitt *et al.*, 1994; Appleby and Doty, 1995; West, 1997; WDFW, 1999).

Unlike most other regions of the world that exhibit temperate, moist, marine climates, the Salish Sea region remained essentially unaffected by human agriculture, mineral extraction, and over population throughout the Holocene (Kruckeberg, 1991; Levings and Thom, 1994; Diamond; 1997). The temperate rain forests of the Salish Sea region had accumulated a minimum of 6 millennia of ecological development under relatively stable conditions by the time human influences came into play (Baker, 1983). The early human inhabitants were apparently able to live within the existing carrying capacity of the region, without resorting to drastic anthropogenic modifications (Kruckeberg, 1991; Levings and Thom, 1994).

Salmonid fish are one of the preeminent examples of the biological abundance and ecological stability that existed in the Salish Sea for millennia prior to the mass migration of Europeans into the region (Siemens, 1966; McKervill, 1967; Nehlsen *et al.*, 1991; Kruckeberg, 1991; Yates, 1992). The reproductive potential of salmon (Groot and Margolis, 1991), combined with the extensive watersheds of the Salish Sea (Figure 4), provided an annual distribution of large amounts of salmonid biomass throughout terrestrial and marine food webs (Groot and Margolis, 1991; Schmitt *et al.*, 1994). Salmon provided a stable, easily accessible, and naturally abundant food resource base for many species of consumers throughout habitats along the salmon's anadromous life cycle particularly for killer whales and humans (Drucker, 1965; Borden, 1966, Siemens, 1966; McKervill, 1967; Yates, 1992).

The real changes in the ecosystem began with Euro/American settlement in the region after about 1850 (Hayner, 1929; Siemens, 1966; McKervill, 1967; Gregson, 1970; Fagen, 1987; Schwantes, 1989; Fleming, 1997). Since the turn of the century, human activities have singularly dominated the ecosystem in terms of resource extraction and habitat alteration (Kruckeberg, 1991; Levings and Thom, 1994; Fleming, 1997; West, 1997). This is most fundamentally due to the fact that human population density has increased one hundred fold during this period (Wash. State Dept. Finance, 1995; P.S.W.Q.A., 1995), as have the resource requirements of each individual human (Durning, 1991; PSWQA, 1992). This increase in human use of the Salish Sea has therefore resulted in severe competition with most other local species of mega-fauna in terms of space and resources. Hence, long-term measures of trends in human activities over the last 100 years should be excellent indicators of the environmental changes that have occurred between the post-Pleistocene ecosystem and the present for the resident killer whales.

METHODS

Analytical Procedures

The analytical objective of this chapter is to compare the three ecological indicators of this killer whale population identified in Chapter 2 with the 15 potential indicators of human impacts on their carrying capacity identified in Chapter 3 (Table 9), in order to identify historical patterns in the adaptations of these killer whales. This will be accomplished by plotting these sequences of indicators in terms of trends in their variance over different time scales. Points in the temporal sequences that represent perturbations from the mean of the sample greater than one *standard deviation* (> 1 SD) are also plotted separately in some instances. Perturbations greater than 2 *standard deviations* from the *sample mean* in a single direction (+ / -) are counted as statistically significant ($P < 0.05$) according to the Gaussian Distribution (Zar, 1996). These perturbations are then tallied in a matrix that allows comparison of the context of the variables for each time scale (months, years, decades, centuries).

In addition, as the findings on each set of variables are systematically defined and presented, the plots and matrices provide the basis for a historical assessment of the adaptive resiliency of this killer whale population, and also allows for the systematic consideration of potential effects from singular historical events.

Coding of Data

There are two basic types of data being utilized for the historical analysis presented here: 1) empirical data that uses a multitude of different temporally based measurement scales, and 2) estimated longitudinal values based upon the author's "educated guess". The priority was to use empirical data, but in order to produce the historical plots in the largest time scales (particularly centuries and millennia), breaks in sequences were estimated in some cases, rather than dropped. In all cases the distinction between empirical data and estimated values is explicitly indicated.

For each data set the *sample mean* and *standard deviation* are calculated as basic qualitative indicators of the character of the data (Zar, 1996). In most figures, and all plots involving empirical data, individual values at each time scale are calculated as *standard deviations* above or below the *sample mean*, where *standard deviation from the sample mean*, ***SDM* = (*X-x*) /*SD*.**

In a few instances plots of data in their original scale are also presented first, in order to demonstrate some of that data set's unique characteristics, such as seasonality, or to illustrate relative scale between groups of indicators. In two cases these data are plotted on a logarithmic scale because the magnitude of changes over time are so large (e.g., salmon abundance and human population).

Measures of Temporal Perturbations

By plotting the *Standard deviation* from the *sample mean* using the simple relation identified above, temporally distinct patterns can be easily identified in a comparable fashion between data types, without resorting to statistical procedures that would be inappropriate for the lowest common quality of data. Temporal perturbations can be defined as points along the time sequence that vary more than 1 or 2 *standard deviations* from the *sample mean*, thus representing perturbations < 15.87% and < 2.28% of the Gaussian Distribution respectively (Zar, 1996). These values also conveniently supply a uniform procedure for tabulating perturbations for the historical matrices described below.

Historical Interaction Matrices

The historical interaction matrices list all variables in the study with perturbations greater than 1 SD on the ordinate axis and time on the abscissa (Table 10 and Appendix II). A different matrix is produced for each time scale (monthly, annual, and decadal; Appendix II, Tables 24, 26 and 28). All *standard deviation* values greater or less than 1 SD from the *sample mean* (the extreme 31.73% of the sample) are recorded in the matrix cell. Values less than one *standard deviation* receive a score of 0, values below 1 SD are negative (15.87%), and above 1 SD are positive (15.87%). Values greater than 2 SD above or below the *sample mean* (< 2.28%) are marked in bold within the matrix. Estimates in the historical matrices are only included in the largest time scale (decades), and only for historically recorded extreme events.

The historical interaction matrices are also plotted as histograms, so that they display the cumulative perturbations for each time period (Figures 54 to 56 and 58 to 60). These summary tables and histograms serve as an important heuristic device

Table 10 Examples of Historical Interaction Matrices

Monthly Scale

Historical Variable	Time Scale:	1978	Feb "78	...	Nov "97	Dec "97
Orca Habitat-Use:	San Juan Gulf Islands (Zone 1)					
Food Resource Depletion:	Fraser River Run Estimates					
	Sport Salmon Catch					
	Southern Oscilation Index					
	Active Pass Sea Surface Temperature					

Annual Scale

Historical Variable	Time Scale:	1978	1979	...	1996	1997
Orca Population Ecology:	Number of Individual Orcas (Ctr. Whale Res.)					
Salmon Requirements:	Orca Community Salmon Requirements					
Human Predation:	Mean Number of Whale Watching Vessels Present					
Toxic Exposure:	Human Population					
Food Resource Depletion:	Fraser River Run Estimates (Intl. Pacific Salmn. Comm.)					
	Salmon Sport Catch (Wash. St. Dept. Fish & Wildlife)					
Surface Disturbance:	Number of dedicated Whale Watching Boats					
Underwater Noise:	Commercial Fishing Openings(P.S. Gillnetters Assoc.)					
	Shipping Traffic U.S. Coast Guard / Wash. Dept. Ecology)					
	Number of Commercial Fishing Boats (P.S. Gillnetters Assoc.)					

Decal Scale

Historical Variable	Time Scale:	1800	1810	...	1980	1990
Orca Population Ecology:	Pop. Growth					
Salmon Requirements:	Orca Food Requirements					
Human Predation:	Shootings					
	Captures					
Toxic Exposure:	DDT					
	PCBs					
	Mercury (Hg)					
	Human Population					
Food Resource Depletion:	Fraser River Run Estimates					
	Fraser River Catch					
	Subsustance Catch					
Surface Disturbance:	Number of dedicated Whale Watching Boats					
	Mean Number of Whale Watching Boats					
	Commercial Fishing Openings					
Underwater Noise:	Shipping Traffic					
	Number of Commercial Fishing Boats					

al., 1990; Center for Whale Research, 1998; Ginneken and Ellifritt, 1999). In the present study the annual population size and composition published in the above citations will be used directly for constructing the historical plots at the annual scale.

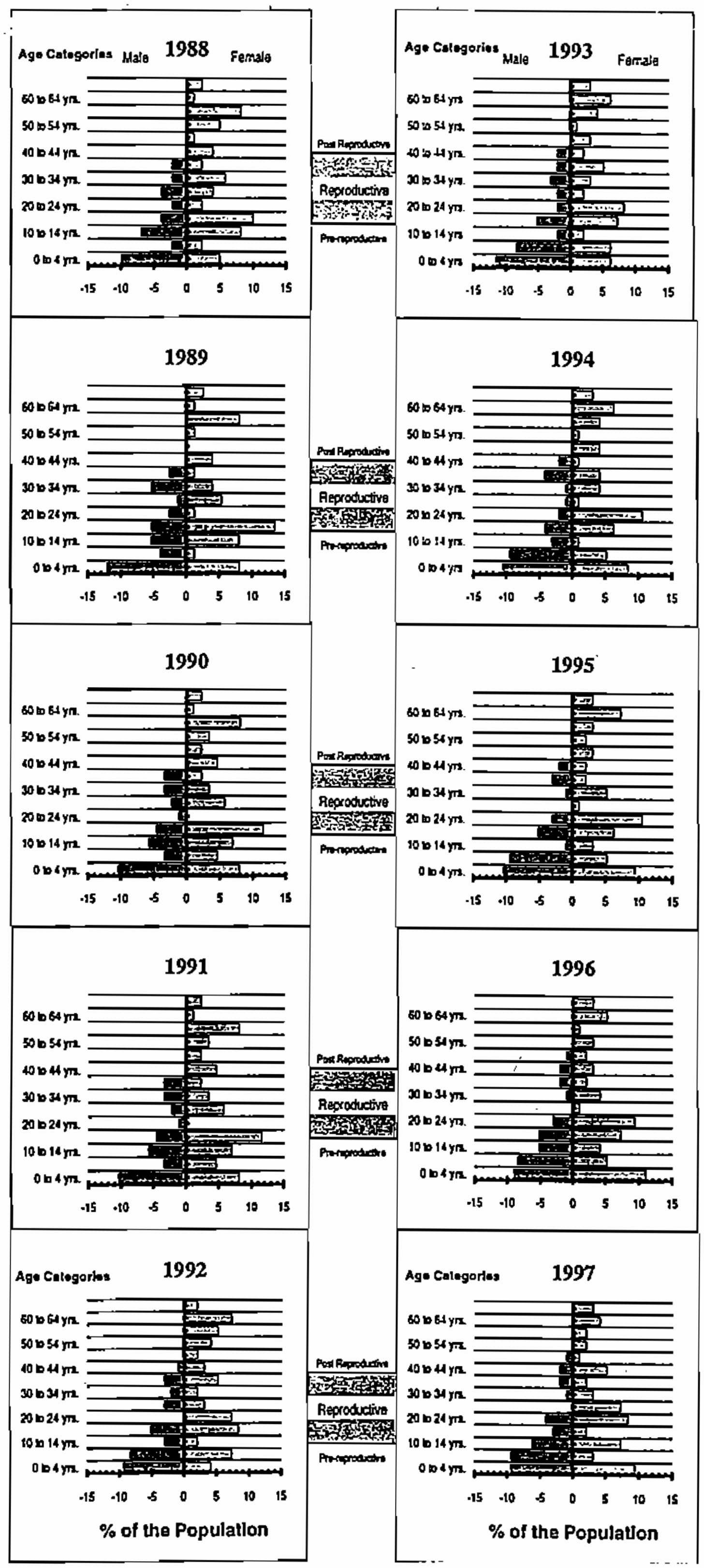
Pre-Photo-Identification Population Estimates

Using measures of empirical rates of population growth in relation to age-structure, Olesiuk *et al.*, (1990) applied their population model from photo-identification data backwards in time to reconstruct reasonable population estimates prior to the capture era. From this calculation they estimated the Southern Residents were at a population level of around 80 individuals in 1960 (Olesiuk *et al.*, 1990). In the present study these findings will be used directly for plotting population size for the period 1960-75 (Olesiuk *et al.*, 1990).

For periods prior to 1960 reconstructing a historical population estimate is much more problematic. If the projections from Olesiuk et.al. (1990) are accepted, and it is also assumed that this killer whale population was at or near carrying capacity prior to the mid-19th century, then this population must have had several significant negative swings in population size prior to the documented impacts of captures in the late 1960s and early 1970s (Olesiuk *et al.*, 1990). This low population size for the Southern Resident population in 1960 invites a historical explanation. To systematically address this historical population decrease, the number of females alive in the 1990s relative to their estimated birth year (Bigg *et al.*, 1987; 1990; Ford *et al.*, 1994) was used. Females alive between 1990 and 1997 were tallied and plotted as age structure pyramids (Figure 28), and as a temporal projection (Figure 29) allowing identification of time periods where there is an absence of female whales represented in the present population. It is hypothesized that the non-represented age classes indicate periods where either low fertility, high infant mortality, or both of these factors were affecting the population in

Figure 28

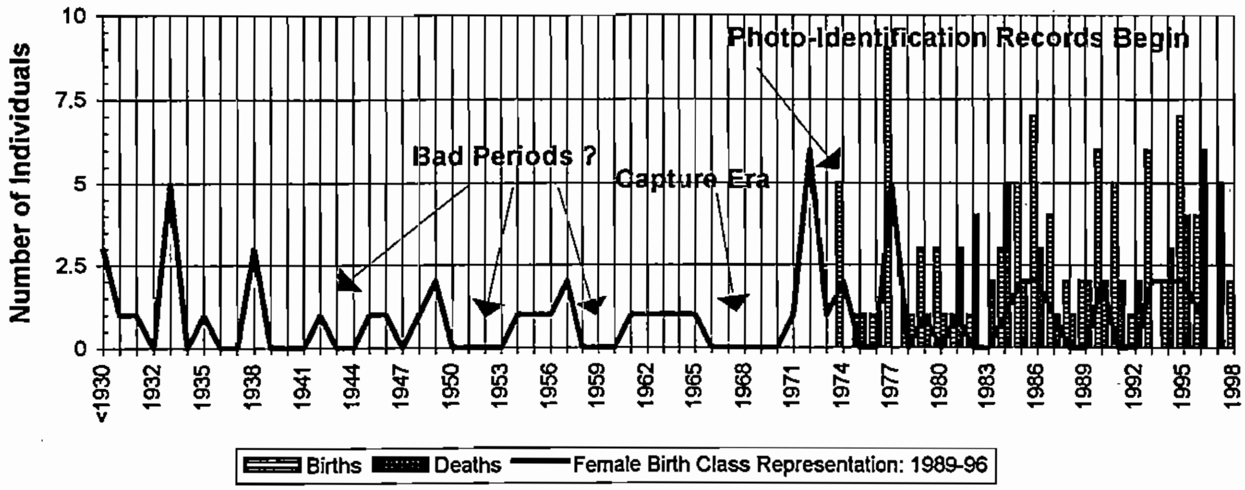
Age Structure Pyramid for Southern Resident Killer Whales 1990-97



Compiled from data records published by the Center for Whale Research and The Whale Museum's Orca Adoption Program

Figure 29 **Southern Resident Killer Whale Population Historical Impact Retrospection**

(Documented Births/Deaths 1974-99, and Female Age Class Survivorship 1989-96)



some fashion (Figure 29). This information was used to generate estimates as part of the decadal plots in the *Results* section.

Estimating the population size for periods prior to the last century is even more problematic, and represents the point at which an "educated guess" is the only choice for the purposes of generating a plot. The earliest written record that refers to a count of the Southern Resident killer whales describes 100 whales traveling east over the length of an August day in Juan de Fuca Strait and then turning north up Haro Strait (Stenzel, 1975). What is not known is what portion of the population these 100 killer whales may have represented, or if in fact it was the whole population. In the present study 250 was used for the estimation of the population size of the Southern Resident's prior to human impacts associated with European settlement. The choice of 250 came from conservatively using the Northern Resident Community as a model of what the Southern Resident Killer Whale Community could be under better conditions. The present population size for the Northern Residents is estimated at approaching 220, with no obvious indication that they

Definitions for Long-term Measures of Climate

Climate is considered a non-anthropogenic process, except for possible influences over the last 50 years due to "global warming" (Botkin, 1990; Newton, 1995), therefore it is treated separately from measures of human indicators. For the present study local sea surface temperature in three locations (over months, years and decades) serves as the climatic indicator. The assumption for time periods older than the present century is that climatic conditions were adequate for the Southern Resident killer whale population to have been at a carrying capacity of approximately 250 individuals.

Mean monthly sea surface temperatures collected at Race Rocks, Active Pass and Departure Bay were utilized as an indicator of Salish Sea climatic conditions. These are measurements published by the Institute of Ocean Sciences (DFO), and made available on their INTERNET web site (DFO, 1998). The data sets vary in the number of years they have been compiled and in the continuity of record keeping. They are published as monthly means of measurements made by various consecutive lighthouse keepers. The monthly means were utilized directly for the 240 month plots, and *sample mean*s were progressively calculated for annual, and decadal plots (N=20).

Definitions for Measures of Human Impacts on Southern Resident Killer Whale

Human variables will be the best indicators of environmental change in the habitat of the killer whale population resident to the Salish Sea, because these killer whales have likely been adapting to human activities for centuries, and the core habitat of this killer whale population is currently the most densely populated by humans of any other killer whale population in the world.

The justifications for using the human indicators that have been chosen were presented in Chapter 3 on the basis of their association to variables that are likely providing environmental resistance on these killer whales. In some cases it will be necessary to project these indicators beyond the scope of the empirical data sets, and to bridge gaps in the empirical data sets with reasonable estimates. The sources of empirical data for these human indicators, and the rationale behind estimates where data is unavailable, are presented in what follows (see also Appendix II, Table 22).

Predation Indicators

In the context of this study, human predation on the killer whales is considered directly in terms of captures, killings and shootings (Chapter 3). Capture data was plotted directly from Table 3 in Olesiuk *et al.*, 1990, which lists the date, location, pod (when known), and number of animals removed for each capture. Shootings are undocumented, except for three non-fatal instances between 1978 and 1985 (data archives The Whale Museum), and so were estimated on the basis of references to eras in which it has been reported to be common practice (Scheffer and Slipp, 1948; Bigg and Wolman, 1975; Griffin, 1982; Hoyt, 1990; Olesiuk, 1990). The estimates utilized for shooting incidents over large time scales prior to 1978 were as follows: 0.5/year in the 1970s, 10/year from the 1960s to the 1940s, 3/year in the 1930s, and an average of 1.7/year between 1850 and 1920. For periods prior to the 19th century anthropological evidence indicates human predation on killer whales was exceedingly rare to non-existent (Drucker, 1965; Cavanaugh-Ford, 1984; Tanami, 1984; Hoyt, 1990; Olesiuk *et al.*, 1990).

Toxic Exposure Indicators

Indicators for toxic exposure in these whales were examined directly by plotting published data on sediment cores in the region (MacDonald and Crecelius, 1994), and indirectly, by compiling and plotting published estimates on human population density for the Salish Sea.

The empirical measures of toxic exposure in these whales were derived by first identifying the three types of primary toxic chemicals that have been recorded at the highest levels in Southern Resident killer whale tissue samples: DDT, PCBs and mercury

(Calambokidis *et al.*, 1985; 1990; Calambokidis and Baird, 1994; Jarmen *et al.*, 1996), and then plotting published Salish Sea marine sediment core data for those three chemicals at three sites in Puget Sound (MacDonald and Crecelius, 1994). The toxic data was published as micrograms/gram based on dated sediment cores, and plotted as a decadal time series (1850-1990) based upon estimated residence times in the water (MacDonald and Crecelius, 1994). For the present study these levels were taken directly and re-plotted as *standard deviations* from the mean over the 15 decade period of the series.

Human population density for the Salish Sea was also plotted as a non-point source indicator of toxic exposure, given that the primary origin of toxic sources in any region is indirectly related to toxic chemical production per person (Segel *et al.*, 1980; Lyons, 1989; PSWQA, 1992). The Salish Sea human population plots were compiled from historical census data for southern Vancouver Island, the lower B.C. mainland, and the coastal counties of Puget Sound and Juan de Fuca Strait (Washington State Historical Society, 1950; McKervill, 1967; Kimerling and Jackson, 1985; Washington State Data Book, 1995; Canada, Ministry of Industry, 1996; Schwantes, 1996). For population estimates prior to government census data (prior to 1900), estimates from published histories were collected (Hayner, 1929; McKervill, 1967; Gregson, 1970; Schwantes, 1996) and averaged between data points when there were breaks in the specific plots. For population estimates at the centennial and millennial scales, the anthropological literature was utilized to come up with a Holocene base population of 60,000 for the Salish Sea (Drucker, 1965; McKervill, 1967; Borden, 1968; McMillan, 1988). This base population was then plotted with an arbitrary range of fluctuations of 32% (1 standard deviation) around the mean, and adjusted from there in relation to known periods of severe epidemics in the native population; reaching an extreme low of 10,000 estimated for 1840 (Drucker, 1965).

Food Resource Depletion Indicators

Salmon has clearly been shown to be the primary food resource utilized by Southern resident-type killer whales (J.R. Heimlich-Boran, 1986a; Bigg *et al.*, 1990; Felleman *et al.*, 1991; Ford *et al.*, 1994; 1995; Chapter 2). Therefore human measures of salmon escapement and/or salmon catch should provide suitable indicators of fluctuations in food resources, and/or levels of human exploitation on those food resources.

Washington State sport salmon catch data serves as the most consistent indicator of salmon abundance across all time scales (WDFW, 1967-95; Schmitt *et al.*, 1994; 1995). These data are the number of fish reported caught by anglers using Salmon Punch Cards that are turned into the Washington State Department of Fish and Wildlife (Appleby and Doty, 1994; Chapter 2). The data are presented as monthly totals by species within reporting areas of the Washington State inland waters. Reporting Area 7 was used as an indicator of salmon in the San Juan/Gulf Islands region (Zone 1), and reporting areas 8-13 were used as an indicator for Puget Sound (Zone 2; see Figure 15). These data were plotted directly in a 240 month sequence along with killer whale presence in Zones 1 & 2 (described earlier, and Chapter 2), Fraser River pink and sockeye salmon escapement estimates from the Pacific Salmon Commission (Pac. Salmn. Comm., 1985-1998; Roos, 1990; for Zone 1), and Washington State Department of Fish and Wildlife estimates on Puget Sound chum salmon escapement (WDFW, 1998) for Zone 2).

The annual plots included *sample means* calculated from the monthly sport catch data, and Fraser River salmon escapement estimates described above, but added Fraser River pink and sockeye salmon catch, and the combined Washington State and Fraser River native subsistence catch data from the Annual Pacific Salmon Commission reports (Pac. Salmon Comm., 1985-1998; Roos 1990).

The decadal salmon plots utilized the same data as the annual plots, but they were calculated as the *sample mean* for every ten years. The continuity of these data series started dropping off at different times: with the sports catch data disappearing prior to 1967, native subsistence catch having a large hole between 1910 and 1970, and the Fraser River escapement and commercial catch data reliably dropping off prior to 1920 (Roos, 1990; Schmitt *et al.*, 1994).

Decadal estimates for the native subsistence/sports catch prior to the 1970s were derived from historical accounts as single year estimates (Drucker, 1965; McKervill, 1967; Gregson, 1970; Roos, 1990; Schwantes, 1996), and plotted over the decades as an equivalent percentage of the regional native and human populations, respectively. Fraser River escapement and catch estimates for the decades prior to 1930, were educated guesses derived from single-year historical estimates in the 1890s that were based upon Cannery records (McKervill, 1967; Roos, 1990). These estimates were a maximum Fraser River Run size at 60 million salmon annually, fluctuating to as low as 40 million, and significantly dropping after 1850 with the advent of commercial canneries, to 20 million by the turn of the century (McKervill, 1967; Gregson, 1970; Roos, 1990; Kruckeberg, 1991; Schmitt *et al.*, 1994), and 7 million following the Hell's Gate landslide of 1914 (Roos, 1990). Century and millennial scale plots were not attempted for salmon resources.

Surface Disturbance Indicators

Surface disturbance as an impact on cetaceans has emerged as a variable of concern to managers in relation to two primary areas: 1) fishing gear entanglement (Bigg and Wolman, 1975; Matkin and Leatherwood, 1986; Matkin *et al.*, 1994; Calambokidis and Baird, 1994; Baird, 1999), and 2) whale watching disturbance (Watkins, 1986; Duffus, 1988; Mayo *et al.*, 1989; Osborne, 1991; Kruse, 1991; Duffus and Dearden, 1993; Burgen and Otis, 1995; Hoyt, 1995; Williams, 1998). Southern Resident killer whales have been acutely exposed to both these impacts, but the limited studies to date (Osborne, 1991; Kriete, 1995; Burgen and Otis, 1995; Otis, unpublished data) have not found any overt indications of disturbance. To examine this issue historically, the present study plots surface disturbance variables that are linked with levels of whale watching traffic, and levels of commercial fishing gear (salmon gill nets and purse seines) over years and decades.

Whale watching vessel traffic in the immediate surfacing area of the killer whales was measured in terms of: 1) the mean annual number of boats documented with whales at 30 minute intervals in the San Juan Islands by The Whale Museum's Soundwatch Boater Education Program for the period 1990-1997 (The Whale Museum, unpublished data 1990-97; in prep.), and 2) the annual number of commercial whale watching boats recorded seasonally operating with these whales (Osborne, 1991; and Osborne, unpublished data 1990-97). Other whale watching measures, namely: the mean annual number of boats seasonally documented with whales from Lime Kiln Lighthouse when ever killer whales passed by, and the ambient level of seasonal vessel traffic at Lime Kiln Lighthouse measured 4 times per day (Burgen and Otis, 1995; and Otis, unpublished data 1996-1997), are plotted later in the section on "underwater noise". The annual number of commercial whale watching boats was also used as a decadal indicator. This data set goes back to 1976 (Osborne, 1991), prior to the earliest recorded incident of commercial whale watching on these whales. At the decade scale it was plotted as the 10-year mean of annual means for the 1970s, 1980s, and the 8-year mean of the 1990s (through 1997); for the 1960s and earlier it was plotted as zero.

Surface disturbance from salmon fishing gear was measured in terms of the annual number of commercial salmon gill net openings in WDFW Fisheries Area 7 (San Juan Islands), and the annual number of gill net licenses issued for WDFW Fisheries Area 7 (WDFW, 1988-1994). Decadal plots used the 10-year mean of annually licensed vessels back to 1946, when Pacific Salmon Commission records began to be kept (Roos, 1990). Prior to 1946, estimates were made on the basis of historical records for 7 single years between 1894 and 1943 (McKervill, 1967; Roos, 1990). Decades prior to 1890, were estimated at 600 commercial boats for the 1880s (McKervill, 1967), 100 commercial boats for the 1870s, and zero for all earlier decades.

Underwater Noise Indicators

Since the source of most anthropogenic noise in the ocean is produced by propeller cavitation and through-hull noise of vessel engines (Myrberg, 1990; Richardson *et al.*, 1995), motorized vessel activity was the primary indicator used to historically plot change in the underwater noise environment of these whales. The other potential sources of underwater noise for this population of killer whales includes: coastal industrial noise, military operations, oceanographic and geological survey operations, and natural seismic activity (Myrberg, 1990; Richardson *et al.*, 1995; Miller and Willis, 1997). Except for coastal industrial noise, these latter sound sources are sporadic single events that do not provide the opportunity to be measured as trends from a *sample mean*. However, in instances when one of these events can be pin-pointed in time, they opportunistically offer a potentially valuable marker.

Vessel indicators for underwater noise were chosen with the idea of sampling for both ambient noise, as well as noise levels in the immediate vicinity of the whales. Ambient vessel noise was measured as the annual number of commercial shipping transits in Haro Strait. These data were recorded by the U.S. Coast Guard (1983-89, in Osborne, 1991), and from recent records by the Washington State, Office of Marine Safety (DOE, 1998). As an indicator of ambient noise from recreational traffic, boat counts made 4 times per day for May-August (1990-1997) at Lime Kiln Lighthouse were used (Burgen and Otis, 1995; and Otis, unpublished data 1996-1999).

The primary indicator for vessel-generated underwater noise in the immediate vicinity of the killer whales was the mean annual number of whale watching boats with whales whenever they passed Lime Kiln Lighthouse, May-August 1990-97 (Burgen and Otis, 1995; and Otis, unpublished data 1996-1997). The other variable used as an indicator for vessel noise in the near-field of whales was the annual number of commercial whale watching boats operating in Haro Strait (Osborne, 1991; and Osborne, unpublished data 1990-97). This latter data set is the same one plotted in the "surface disturbance" sections described earlier.

Anthropogenic underwater noise in the Salish Sea would not have occurred prior to the appearance of the first steamships, canneries, and lumber mills in the 1870s (Chasen, 1981), so of the larger time scales, only the decadal was plotted. For this long-term plot the number of commercial whale watch boats, number of licensed commercial fishing boats, and commercial shipping traffic were plotted. For the most recent decades the ten-year means of annual values were used. As discussed in the previous sections, the number of commercial whale watch boats empirically drops to zero in decades prior to the 1970s. The records on licensed fishing boats are fairly complete to the 1940s, and can be reasonably estimated for the decades from 1930 to 1870 (see discussion in previous section), when this variable also zeros out.

The most problematic indicator is commercial shipping traffic, which appears to be poorly documented as a general statistic on annual transits prior to the 1980s (Chasen, 1981; DOE, 1998; U.S.C.G., 1989). Shipping traffic data for most of the history of the region is embedded in measures of the import and export of commodities, and does not easily translate to "shipping transits", because the varieties of cargo capacity differ so much between vessels and eras (Chasen, 1981; Port of Seattle, 1995; DOE, 1998). Similarly, geographic compilations of port and tug boat records do not clearly indicate what route the vessel traveled to arrive there, although they do allow calculations of mean cargo size per vessel (Port of Seattle, 1996). U.S. Coast Guard, U.S. Customs and naval defense records on commercial clearances of transiting traffic must exist in some fashion in government archives for the period from at least W.W.II to the 1970s, but they were unattainable for this study. Given these complications, estimates were not attempted beyond calculating shipping traffic as a rough percentage of human population for the period from 1800-1970.

RESULTS

The historical plots for each ecological indicator defined in the methods section are displayed as graphs and/or histograms and described in terms of patterns of perturbation from the *sample mean* at different time scales. For each class of ecological indicators the findings will first be presented at the smallest scale (months, years, decades) and described in relation to patterns in the plot, and any patterns already discussed from previous plots.

All perturbations greater than 1 SD from the sample mean are also tabulated in a historical interaction matrix for three of the time scales (Appendix II). The results from these matrices will then be presented at the end of the results section, and will form the basis for a general discussion on the adaptive resiliency of this population of killer whales.

The Chronology for Southern Resident Killer Whales:

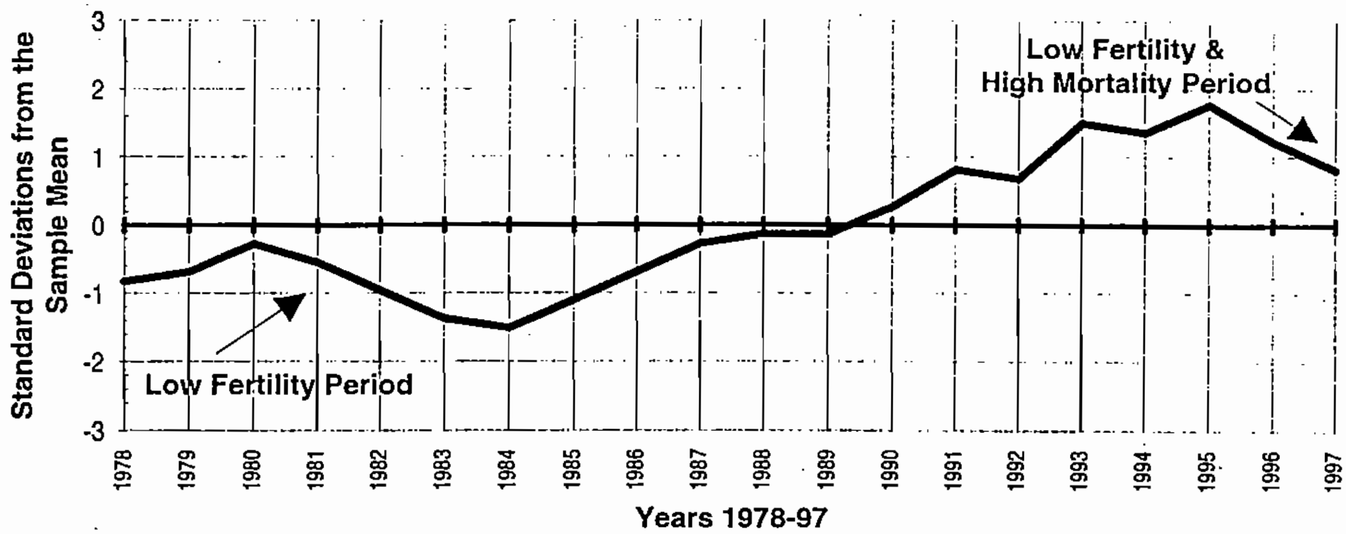
The first step in this historical ecology is to establish the chronology of the management unit so that the environmental indicators have something to be compared with. For this historical characterization the indicators will include the three indicators identified in Chapter 2: population, feeding requirements, and habitat-use.

Killer Whale Population Plots

Annual Scale

The trends in size and composition of this population, as documented through continuous photo-identification (Center for Whale Research, 1998; Ginneken and Ellifritt, 1999), have already been described in detail in Chapter 2 (Figures 7, 12, and 17), and previously discussed in this chapter (Figures 28 and 29). In Figure 30 the plot displays the

Figure 30 **Resident Killer Whale Population Size in the Salish Sea Over Twenty Years (1978-97)**



distribution of annual size in terms of standard deviations (SD) relative to its sample mean of 20 years.

In this plot an over-all positive increase is maintained up to 1995, illustrating a net population growth of approximately 2.5% over this period (Olesiuk, 1990; Brault and Caswell, 1993; Ginneken and Ellifritt, 1999). However, there are two periods of population decrease, the most recent of which has continued to the present. The first one led to a perturbation >1 SD below the mean over a 3 year period between 1980-84, and was primarily the result of a low fertility period , that appears to be associated with the low number of reproductive age females at that time (see also Figures 28 and 29). It has been suggested that this dip in population size might be related to the removal of most of that generation during the capture era from the mid-1960s to early 1970s (Bigg, 1982; Olesiuk, 1990; Brault and Caswell, 1993).

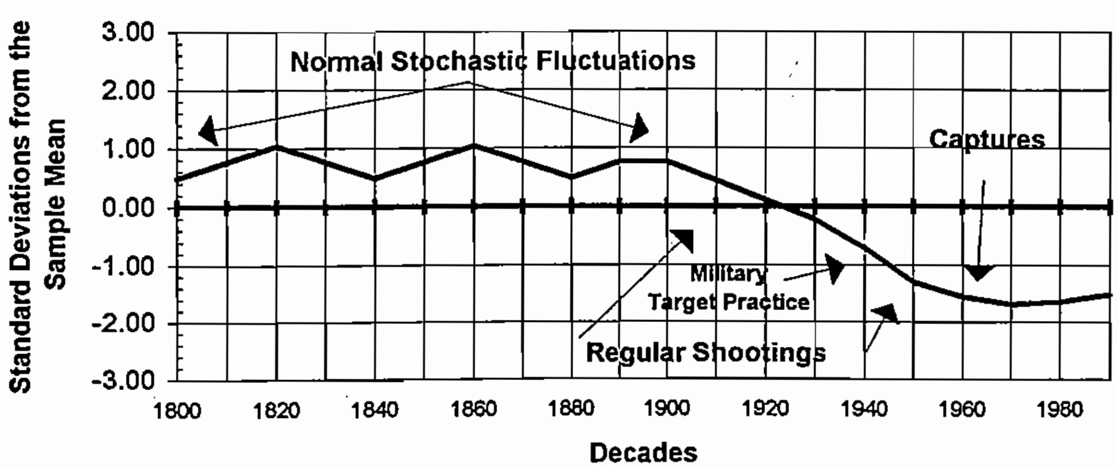
The most recent decrease in population size is coming down from a 3 year perturbation >1 SD above the mean. This drop in size appears to be a combination of low fertility and higher mortality (Figure 29). The low fertility could be a shadow of the low fertility period from the 1980s, since it is occurring 15 years later; roughly the amount of time it takes for a generation of killer whales to begin exhibiting fertility. The higher mortality rate since 1995, however, does not suggest any immediate explanations.

Despite the recent downward trend, it can be seen that the population is still in the overall range of growth above the twenty year mean, well within the boundaries of normal fluctuations.

Decadal Scale

The decadal plot in Figure 31 includes: 1) ten-year means from the data in the previous plot, 2) Olesiuk et al.'s (1990) projection for the 1960s, and 3) an educated estimate. The estimate bridges the 1960s projection of 86, to a mean estimated carrying capacity population of 250 at the turn of the century (see methods, pages 114-117). As part of the estimate, low surviving female birth-years (Figure 29), were combined with documented periods of known increased mortality due to military target practice and shootings from commercial fishers (Scheffer and Slipp, 1948; Bigg and Wolman, 1975; Olesiuk *et al.*, 1990; Hoyt 1990). These two periods (1940s and 1950s, Figure 29) were weighted to account for a decrease over the 5 decades.

Figure 31 Estimated Resident Killer Whale Population Size in the Salish Sea Over Twenty Decades (1800-1990)



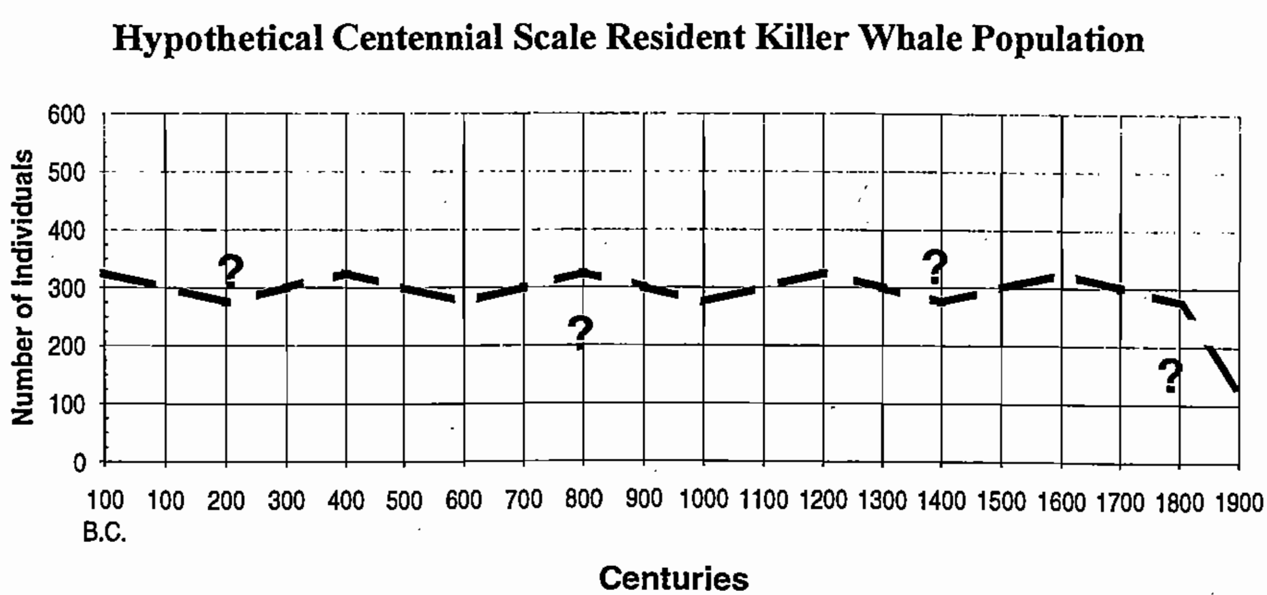
Trends at the decadal scale indicate that Southern Resident killer whales probably did not exhibit a perturbation > 1 SD below the mean until the 1940s, and that at their current rate of growth, it will be 4-5 decades before they could conceivably increase to within a standard deviation of this 20 decade mean.

Centennial and Millennial Scales

In Figure 32 means from the previous scale are plotted, along with the estimate for the population at carrying capacity prior to the turn of the century. In both plots the estimates for carrying capacity periods are graphed with arbitrary fluctuations within 1 SD of a hypothetical mean to simulate normal fluctuations.

The value of this plot stems from its demonstration of the contextual implications of changing time scales. It places the current low in the population in perspective with what this population has hypothetically experienced throughout most of its history.

Figure 32



Killer Whale Feeding Requirements

The feeding requirements of these killer whales were estimated as a function of their daily energetic requirements (Kriete, 1995) translated into salmon requirements (Chapter 2). This estimate of 25 salmon/whale/day was then used to calculate maximum salmon resource needs for the population over different time scales.*

For example, at a hypothetical maximum carrying capacity for the killer whales of 325 individuals (Figure 32), it becomes just under 3 million salmon per year that they would be consuming from the Salish Sea. Under the present population size of about 90 individuals, it equals just over 800,000 salmon per year.

Since this is a linear function of salmon to killer whale, plotting trends in consumption estimates illustrates exactly the same trends as the population plots presented in the previous four figures. However, later in the chapter under Food Resource Exploitation, the killer whale consumption estimates will be plotted at the annual and decadal scales for comparative purposes with sport, commercial and native subsistence catch.

Habitat Use

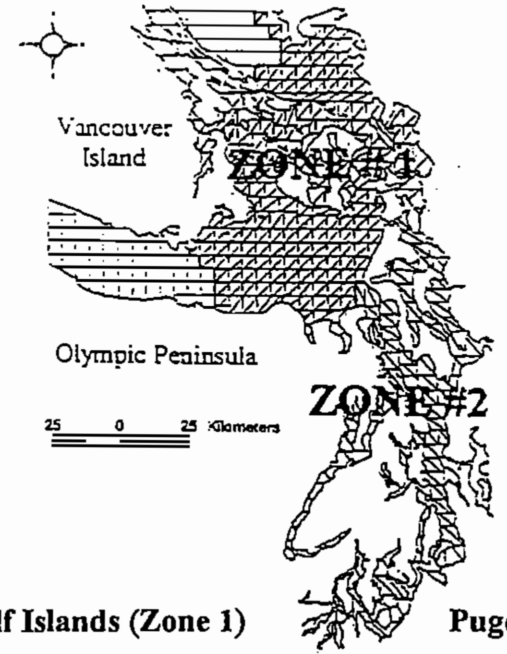
Habitat use in this population was measured as the number of days per month the killer whales were detected in two sub-regions of the Salish Sea: Zone 1 (San Juan/Gulf Islands), and Zone 2 (Puget Sound) (Figures 15, 18 and 33). The data base for these plots was described in Chapter 2, and plotted both as: 1) the number of days per month relative to the 20 year mean for each month (Figures 21 and 22), and 2) the annual seasonal variation from the sample mean in standard deviations (Figures 23 and 24).

---

* This value is considered a maximum because it assumes a 100% salmon diet, but it is well documented that these killer whales eat bottomfish and other marine mammals to some extent (Baird, 1994; Ford *et al.*, 1998).

Figure 33

Study-Zones for Southern Resident Killer Whale Habitat-Use



San Juan/Gulf Islands (Zone 1) **Puget Sound (Zone 2)**

In figures 34 and 35 this same data is plotted monthly and annually for both regions, and for their absence from these regions, to illustrate longitudinal trends. Also plotted are a set of monthly scale plots comparing indicators of salmon abundance with the presence of the killer whales in the two sub-regions (Figures 36 through 37). Since the data base utilized for the habitat-use indicator was not initiated until 1976, habitat use is not plotted beyond the annual scale.

Monthly Scale

The monthly scale is the finest grain temporal plot undertaken in this study, and as a result exhibits relatively more variance between points (Allen and Hoekstra, 1992). In Figure 34 the number of days killer whales were detected each month in Zone 1, Zone 2 and in "other areas" are plotted together as standard deviations over the full 240 month period from January 1978 to December 1997. The sample mean in this plot is for all 240 months, so seasonality is not compensated for; resulting in extreme exaggerations of the standard deviations when perturbations occur in the same direction as a seasonal trend. This seasonality effect will be dealt with in the immediately subsequent plots of this data, but for the present discussion it provides a basis for emphasizing the extremes: summer maximum and winter minimum.

In Figure 34 the hatched area indicates variance in standard deviations from above or below the mean for Zone 1 (San Juan/Gulf Islands), the stippled area indicates variance in Zone 2 (Puget Sound), and the line indicates variance in when the whales were "outside detection" in Zones 1 or 2. The detection of the killer whales between Zone 1, Zone 2, and "outside detection" fluctuates 2 SD from the sample mean on 44 occasions over the 240 month sequence. Zone 1 exhibited 16 perturbations, Zone 2 has 19 perturbations, and the "outside detection" category exhibits 9 perturbations.

For Zone 1 the early years show a tendency to be below the mean and a tendency to be above the mean in later years (Figure 34). This probably reflects the bias of improved sighting effort in Zone 1 in more recent years (after 1985); suggesting that any positive perturbations in early years, and negative ones in recent years, would be more indicative of an actual change in habitat use, as opposed to just background noise.

In Zone 2 the sighting effort has been consistently low over the entire sample, which results in a bias introduced by a low sample mean of only 3 days/mth. (as opposed to 11 days/mth. for Zone 1).* This creates a tendency for extreme perturbations above the mean when the killer whales spend an extended time in Zone 2. In Figure 34 there are 19 significantly extreme perturbations for Zone 2: 12 above the mean and 7 below. The positive perturbations in the early part of the series (1978-1983) are primarily in the summer months, strongly suggesting that the whales used to spend much more time in Puget Sound in the summer than they do now. The next 10 years show an over-all

* See Appendix I, for a comparison of means and standard deviations between samples.

Figure 34

Southern Resident Killer Whale Monthly Habitat-Use of Zones 1 and 2.

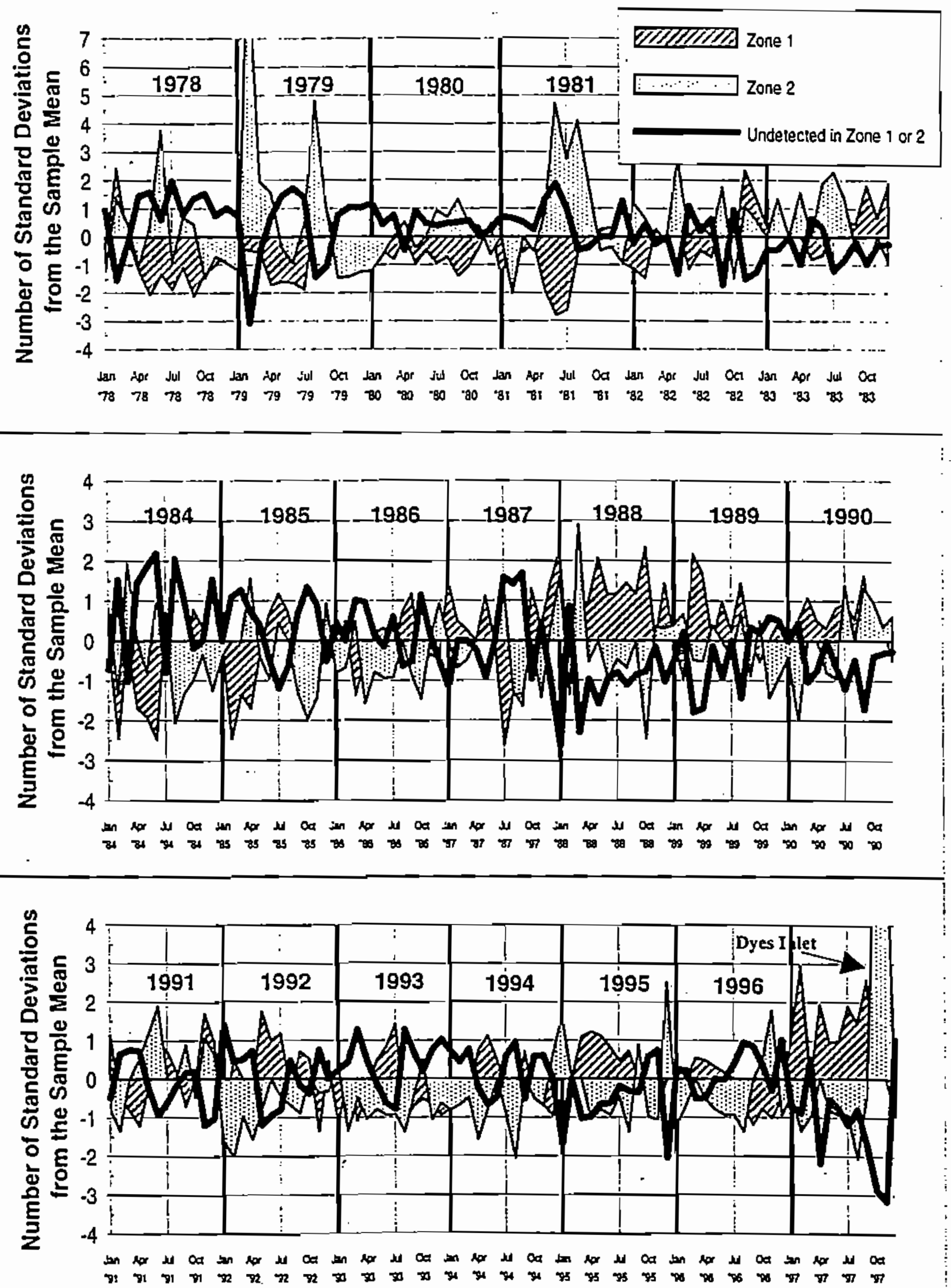
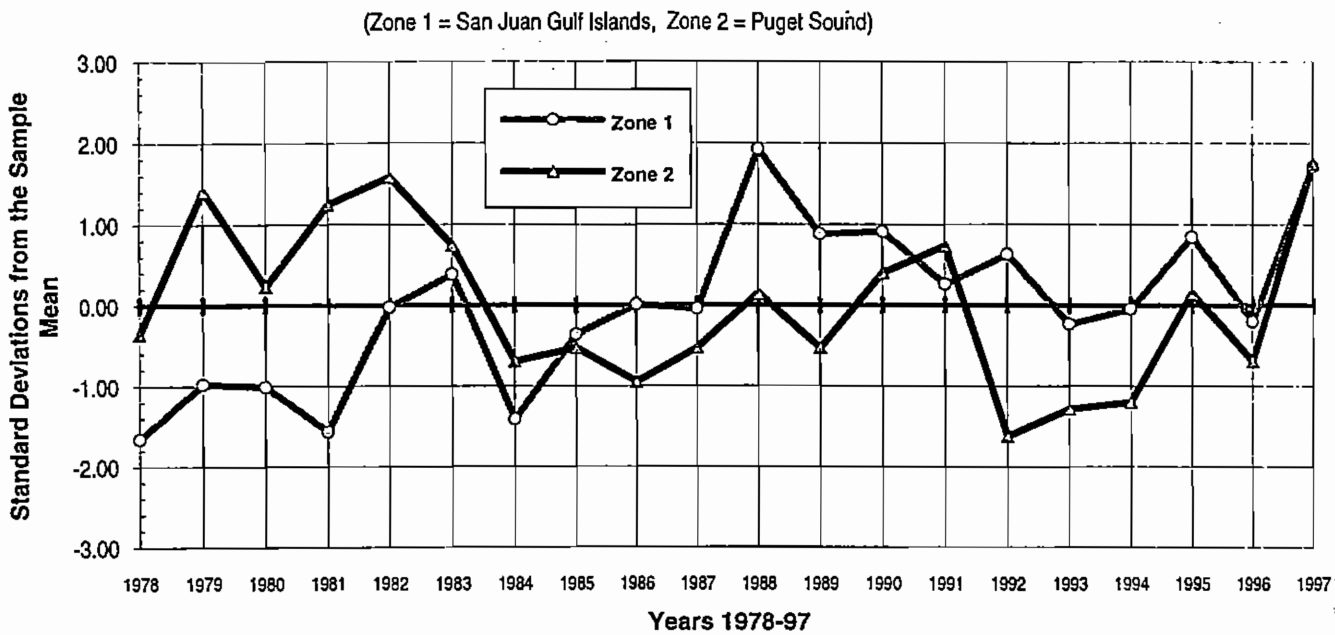


Figure 35
Southern Resident Killer Whale Annual Habitat-Use of Zones 1 and 2



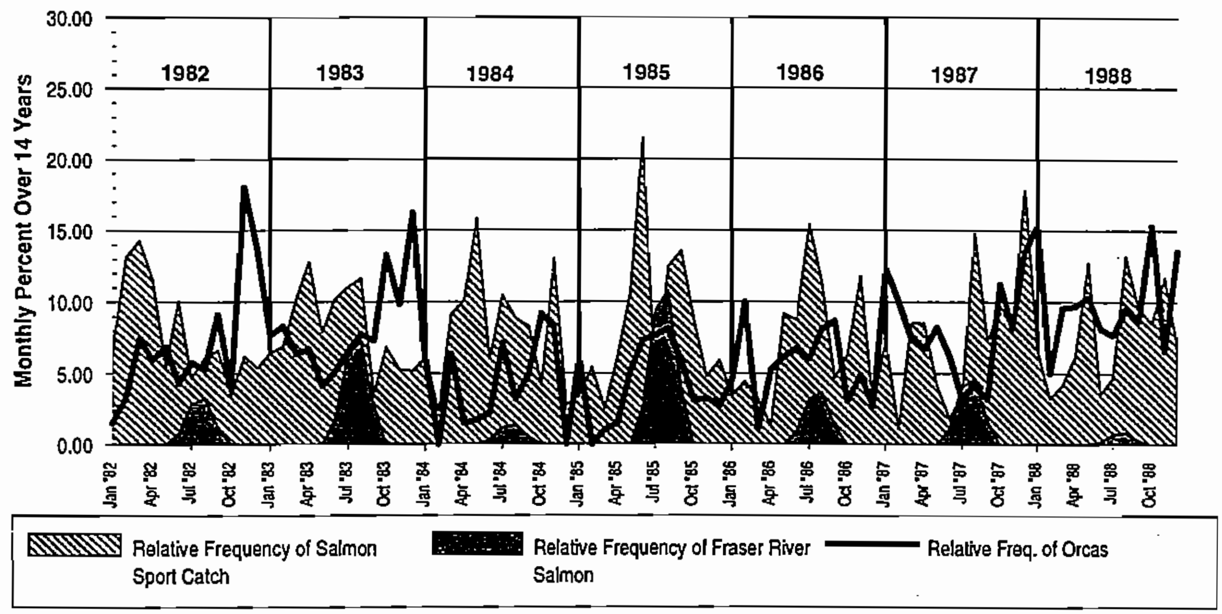
absence of the whales from Puget Sound, with a few sporadic positive perturbations in the springtime (1984, 1988 and 1991). All the other positive perturbations are concentrated in the Fall and early Winter following 1994, culminating in the extreme October/November perturbation of 1997 which corresponds with 30 days a portion of L-Pod spent confined to Dyes Inlet in central Puget Sound (Osborne, 1998; Smith *et al.*, in prep.).

In the next two monthly plots (Figures 36 and 37), salmon indicators are plotted with killer whale habitat use in the two zones, but the seasonal bias is eliminated by plotting the data as monthly percents for each month over the entire 14 year sample. In this fashion each month is only compared with itself among years. In Figure 36 sports catch data (WDFW Area 7; WDFW, 1997), and killer whale data are plotted, but added to the plot are the monthly Fraser River run estimates on pink and sockeye salmon (Pac. Salmon Commiss. 1985-98; Roos, 1990). In this plot the removal of seasonality has

Figure 36

Monthly Co-Occurrence of Salmon and Killer Whales in Zone 1

(San Juan/Gulf Islands, 1982-1996)



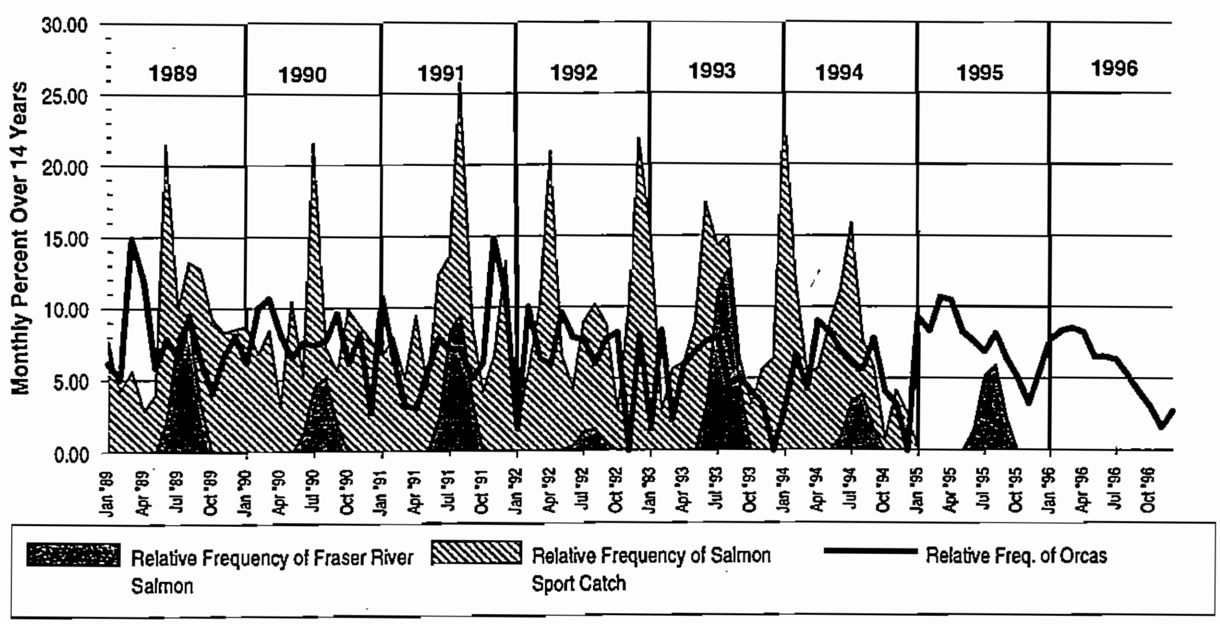
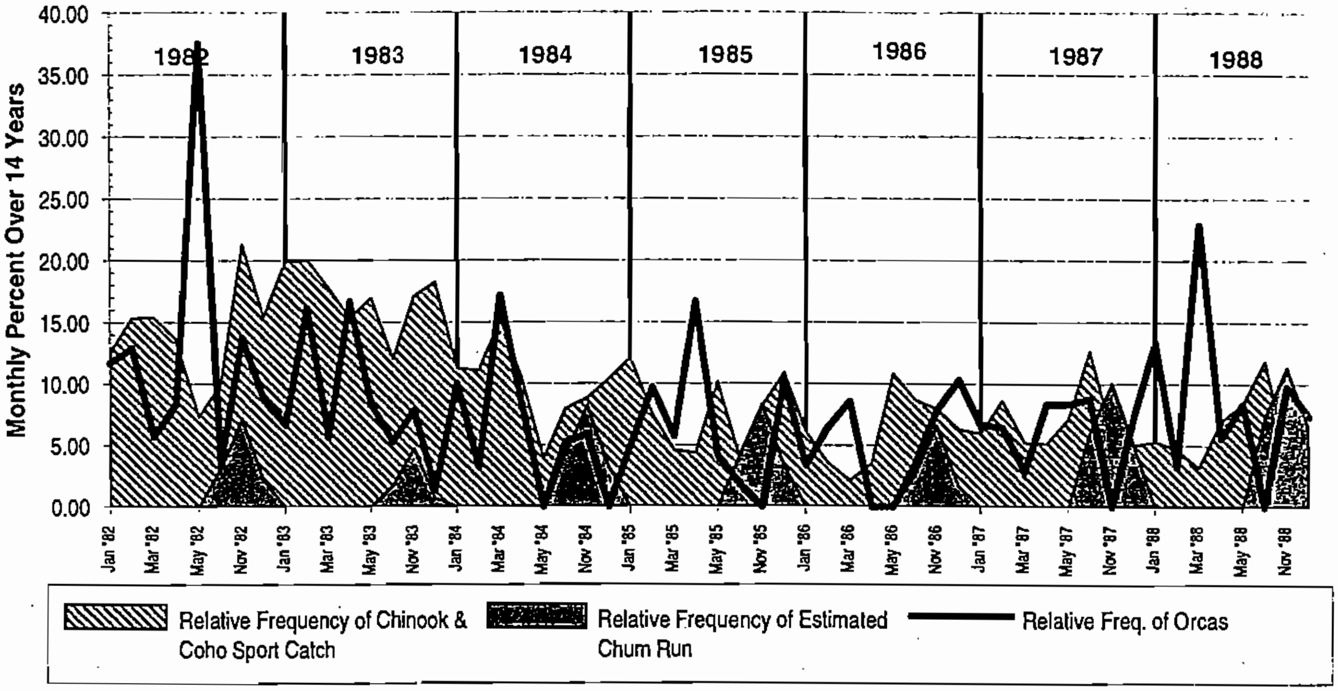
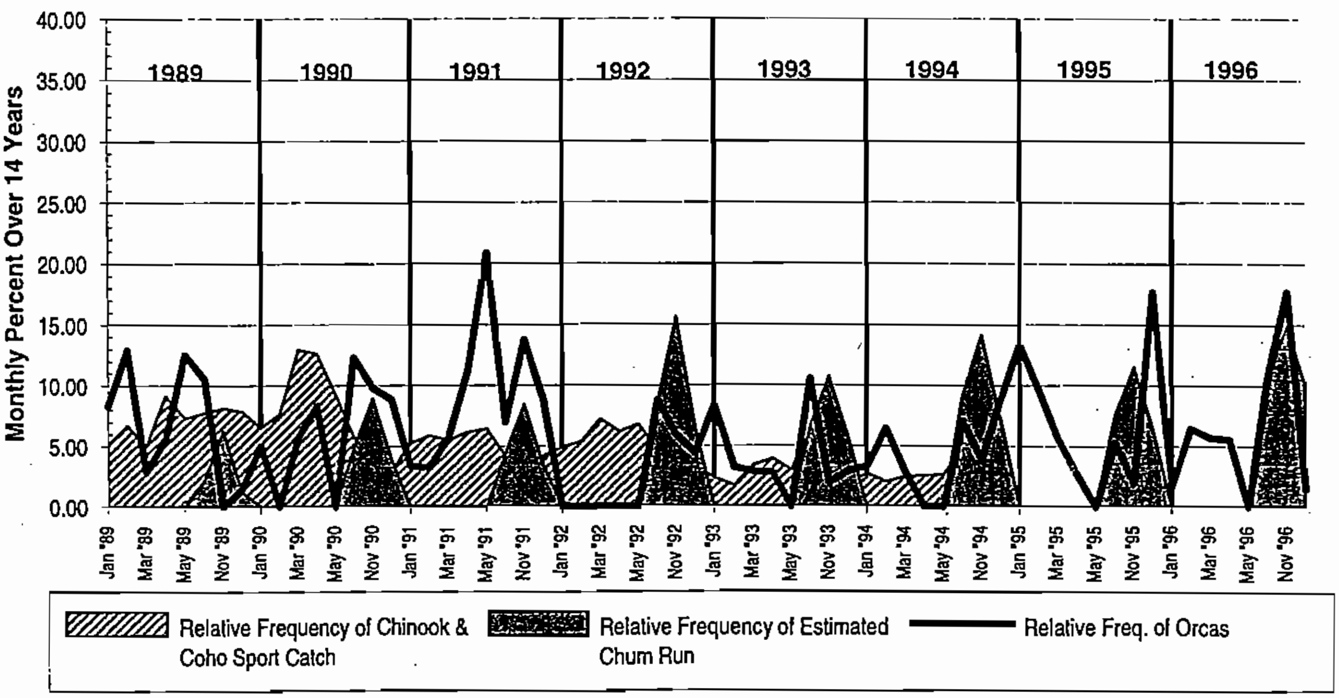


Figure 37

Monthly Co-Occurrence of Salmon and Killer Whale in Zone 2

(Puget Sound, 1982-1996)





made any semblance of correspondence between the salmon indicators and the presence of the killer whales virtually invisible. This suggests that either the indicators are bad measures, or that the relative amount of salmon in this zone does not strongly influence the number of days the killer whales are present.

In Figure 37 salmon sports catch data is restricted to just chinook and coho salmon WDFW Areas 8-13), and the WDFW estimates on Puget Sound chum salmon run size are added (WDFW, 1998). In this plot the removal of seasonal bias, and the plotting of more specific salmon indicators appears to have improved the semblance of some correspondence between the variables, particularly with the larger chum runs of the 1990s.

Annual Scale

In Figure 35 the annual scale of killer whale habitat use in zones 1 and 2 are plotted together to show patterns of variation from their independent sample means in terms of standard deviations. At this scale the two zones show a basic tendency to track each other, particularly since 1994, but in the 1970s and 80s annual increases and decreases in the use of the two zones rarely correspond in direction from the preceding year. None of the perturbations in either variable exceeds 2 standard deviations, except in Zone 1 where in 1988, and 1997, the perturbations are approaching statistical significance (SD = 1.93 and 1.71, respectively). However, the primary finding from these plots is that these whales have exhibited rather stable use of the habitat during these two decades (Figure 35).

The Climatic Chronology:

Fundamental to assessing anthropogenic influences on the historical environment of the Southern Resident killer whale population, the stability of climatic factors should be taken into account. Published accounts on the atmospheric climate of the Salish Sea region during the Holocene, indicate relatively warm stable conditions over the last 6,000 years, punctuated by occasional cooling trends during the last two millennia (Andrews *et al.*, 1981; Baker, 1983; Roberts, 1989; Kruckeberg, 1991). The focus here will be trends in local sea surface temperatures over the last century at three scales: months, years and decades.

Monthly Scale

In Figure 38 the seasonal variation in monthly sea surface temperature is displayed as a 20 year mean (1978-97). The seasonal variations in these three locations demonstrate the modifying oceanic influences on water temperature between the outer and the inner reaches of the Salish Sea. Race Rocks, along the Strait of Juan de Fuca, exhibits an annual temperature pattern closer to coastal conditions in the Pacific than the other two sites (Thomson, 1994). Departure Bay in the northern Gulf Islands, along Georgia Strait, exhibits the most extreme seasonal pattern, and Active Pass in the southern Gulf Islands exhibits a pattern that lies between the two.

As can be seen in Figure 38 the primary differences between the three sites is in how much they vary between summer and winter temperatures; with Departure Bay exhibiting the highest temperatures in summer months and the lowest temperatures during winter months.

Figure 38

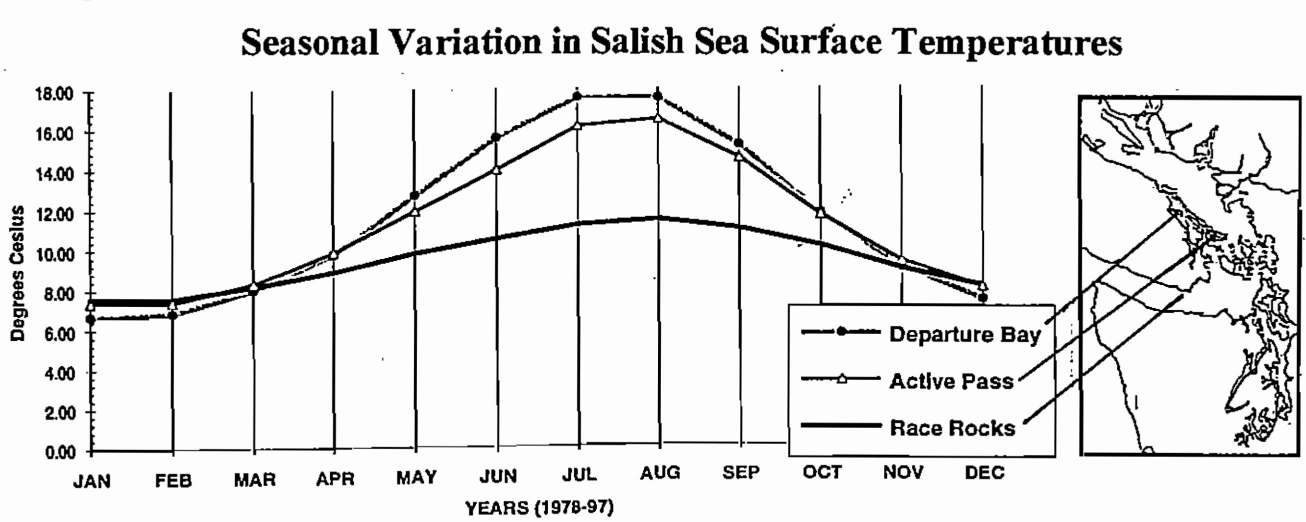
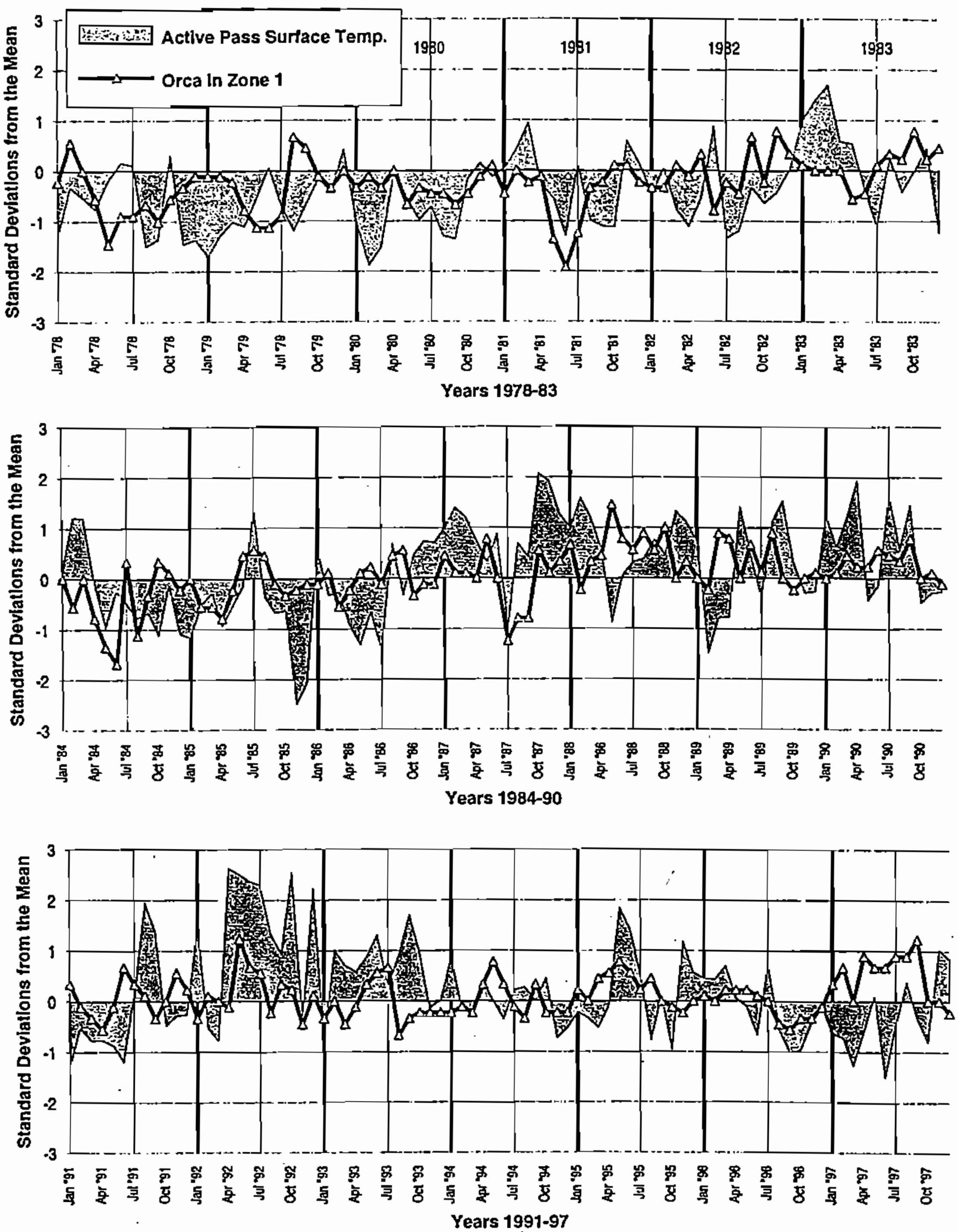


Figure 39

Active Pass Sea Surface Temperature & the Presence of Killer Whales in Zone 1 (San Juan/Gulf Islands)



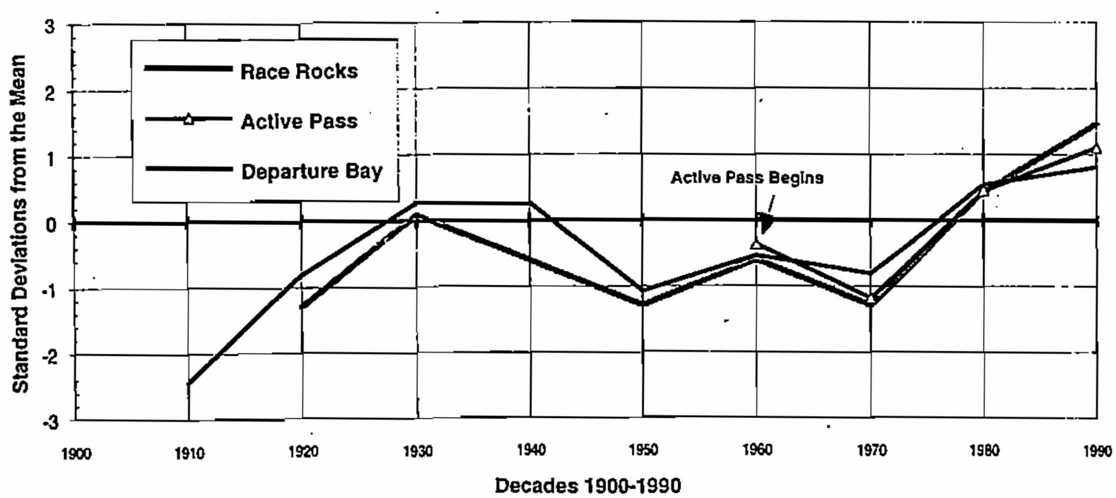
In Figure 39 Active Pass sea surface temperature is plotted with the number of days/month killer whales were recorded in the San Juan/Gulf Islands (Zone 1), and similar plots were run comparing the El Nino Southern Oscillation Index (SOI) Pacific Interdecadal Oscillation with the number of days/month the killer whales were detected in both Zone 1 and Zone 2. In none of these plots did any particular pattern of relationship stand out, suggesting either that they are completely independent variables, or are beyond the measurements being utilized in the present study.

Decadal Scale

In Figure 40 temperature is plotted as distributions of decadal standard deviations from each sample mean for Race Rocks, Active Pass and Departure Bay, relative to their combined mean for the entire extent of each data set, which covers the nine decades since 1900. In this larger scale plot the trend towards significantly warmer temperatures in recent decades, can be clearly seen. The only exception is a cooler than normal period between the 1950s and 1970s.

Figure 40.

Mean Decadal Variation in Sea Surface Temperature in the Salish Sea



The Human Impact Chronology

Historical trends in indicators of human influences on this ancestral community of killer whale pods are presented in this next section. These are plots of the anthropogenic indicators that were identified as the most relevant to the ecology of these killer whales in Chapter 3, namely: predation, food resource depletion, toxic exposure, surface disturbance, and underwater noise.

Predation on Killer Whales

The indicators of human predation on these killer whales that were plotted are:

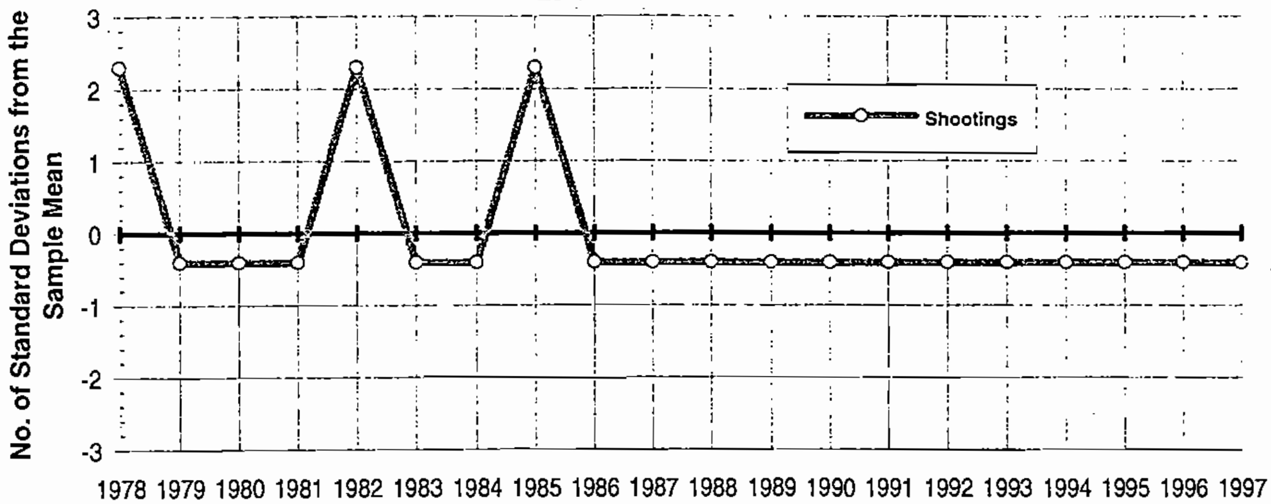
1) documented incidents of captures, 2) reported killings, and 3) estimated rates of humans shooting at them.

Annual Scale

In Figure 41 variation from the sample mean is plotted in standard deviations for the annual number of documented shooting incidents. During the twenty year sampling period there were not any captures, or killings. The shooting incidents include two animals photographed with fresh bullet wounds and one incident which was prosecuted under the U.S. Marine Mammal Protection Act. In Figure 41 these 3 incidents display such extreme perturbations for the time period because there are so few of them, and they are all at the same very low rate (1 per/year). Hence, a single event is the maximum for the time series, and 0 is the only other possible value. The shooting incidents are plotted here to illustrate their current rarity, and the effect of rare events on these types of plots. Figure 14 also provides perspective in relation to the larger scale plots of this variable that immediately follow.

Figure 41

Annual Indicators of Predation on Southern Resident Killer Whales 1978-1997

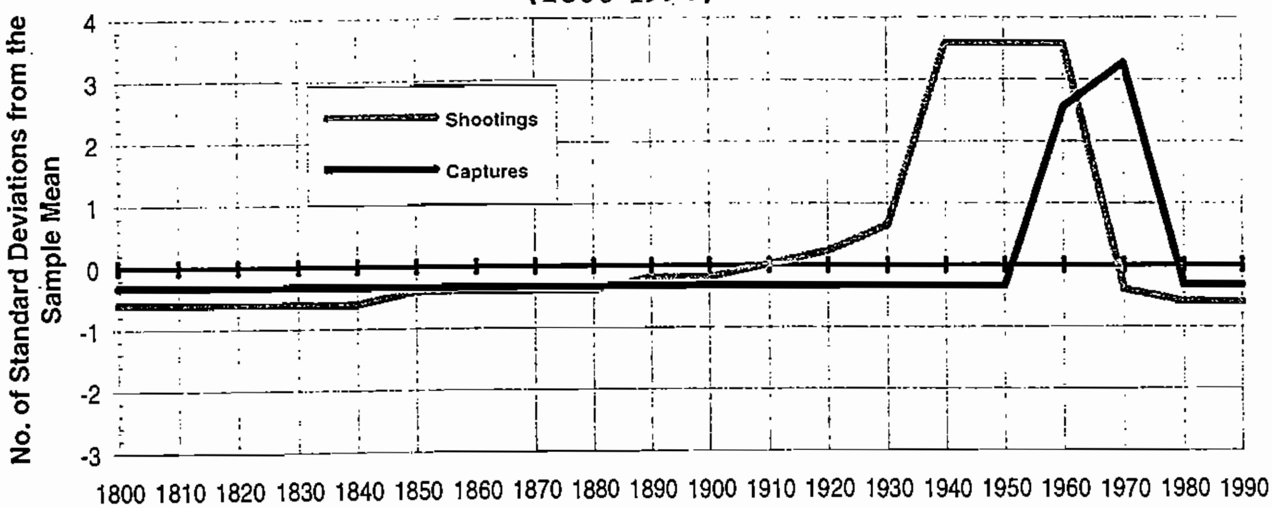


Decadal Scale

In Figure 41 the estimated number of shootings, documented captures per decade are plotted. Over this span of 200 years essentially all the predatory activity is focused on the last 60 years, during the lifetime of most of the older killer whale matriarchs (almost 20% of the current population = females over 48 yrs. old). This statistically significant perturbation of predatory activity appears in three waves beginning with shooting incidents in the 1930s, when references of shooting at killer whales as a nuisance competitor of salmon are first explicitly mentioned in historical accounts (Scheffer and Slipp, 1948; Pike and MacAskie, 1969; Olesiuk, 1990; Hoyt, 1981; 1990). However, a low level of shootings were plotted for the period 1850 to 1930 (mean of 13/decades),given that shooting at predators was a prominent cultural attribute of Europeans from that era (Botkin, 1990; Diamond, 1994), and from personal accounts of commercial fishers (C.Nash,pers. com). As one fisherman was quoted, "it was always

Figure 41

Decadal Indicators of Predation on Southern Resident Killer Whales (1800-1990)



possible to know when the killer whales were coming through the gill net fleet in Haro Strait by listening to the sounds of gun fire" (G, Hertel, pers. com.).

The highest levels of shooting were estimated to occur in the 1940s (100/decade or 10/year), when killer whales traveling in Georgia Strait were subject to government sanctioned military target practice (Olesiuk *et al.*, 1990). Under these circumstances it is possible that whole pods may have been eliminated as a result of repeated strafing runs in a single target practice session. The practice of shooting continued into the 1960s, as attested by the installation of a machine gun in Georgia Strait by the Canadian Department of Fisheries, specifically as a means to cull killer whales and reduce their competition on salmon resources; though records indicate the machine gun was never actually used (Olesiuk *et al.*, 1990). It has been reported that up to 25% of the killer whales examined in the capture operations from the 1960s showed scars from recent bulletwounds (Hoyt, 1981; 1990). Hence, the estimates used for this plot are conservative, and primarily serve as an indicator of these anecdotal historical accounts.

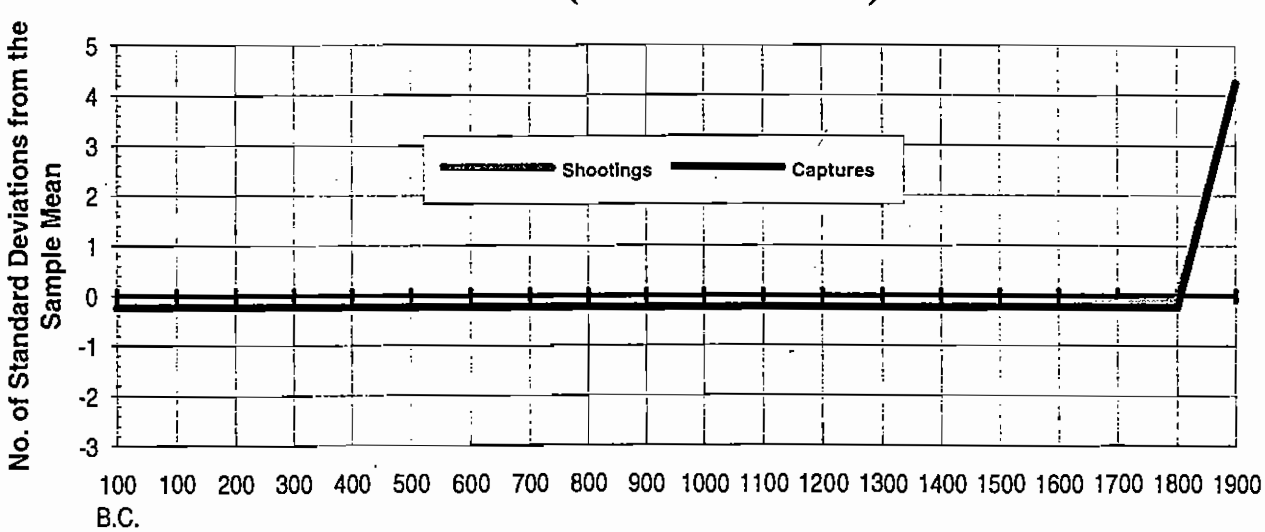
The plot in Figure 41 illustrates: 1) the period in which the highest mortality rates for this population likely occurred, 2) the relative timing of this activity within the living memory of these killer whales, and 3) the fact that this aggressive human behavior started to drastically disappear in the 1970s, and has completely disappeared since 1985.

The next variable that is plotted in Figure 44 is documented captures of these pods. This is data provided in Olesiuk et.al. (1990). The plot represents 4 captures in the 1960s, 5 for the 1970s, and 0 for all other decades. Again, the objective of the plot in this instance, is more to illustrate the relative timing and sequence of these events in the memory of the killer whales, rather than to make a quantitative comparison.

Centennial Scale

In keeping with the methodological approach of examining this history at different time scales, Figure 43 plots these same three indicators on a centennial scale. Again, this is simply a qualitative demonstration of how recent and severe these impacts are relative to the history these killer whales in the Salish Sea. If the millennial scale were plotted here, it would show the same relationship, except the perspective would be relative to the last 8,000 years. Hence, these findings suggest that predation from humans is not a condition these killer whales had to adapt to prior to the present century.

Figure 43 Indicators of Human Predation on Salish Sea Resident Killer Whales (100 B.C. - Present)



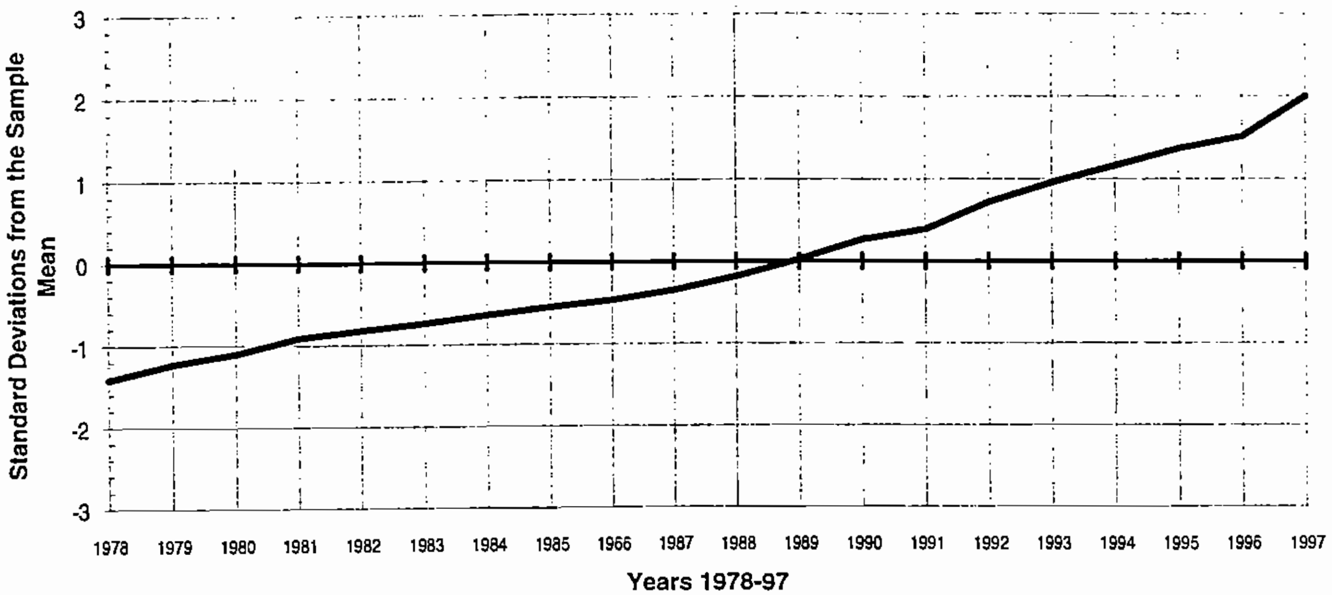
Toxic Exposure

The historical pattern of toxic exposure for this killer whale population was plotted using human population for the coastal region of the Salish Sea as a common indicator at each time scale, and published marine sediment core estimates for three sites in Puget Sound at the decadal scale only. The Salish Sea human population plots were compiled from historical census data for southern Vancouver Island, the lower B.C. mainland, and the coastal counties of Puget Sound and Juan de Fuca Strait (Wash. State Hist. Soc., 1950; Drucker, 1965; Urquhart and Bukley, 1965; P.S.W.Q.A., 1992; Wash. State Dept. Finance, 1995; Canada, Ministry of Industry, 1996; Schwantes, 1996). The toxic data was originally published as *u*g/g values based on dated sediment cores, and plotted as a decadal time series (1850-1990) based upon estimated residence times in the water and sediments (MacDonald and Crecelius, 1994). For the present study these levels were taken directly and re-plotted as standard deviations from the mean over the 15 decade period of the series.

Annual Scale

In Figure 44 the annual increase in human population for the Salish Sea is plotted over the last twenty years, under the assumption that the addition of each human to the Salish Sea ecosystem represents an annual incremental addition in the release of toxic chemicals. In this plot the steepness of the slope varies only slightly from year to year, and exhibits a steady increase for the entire series. The steepest increase is in the final year, when it comes to just within 2 SD above the mean. Using humans as a general indicator of toxic out-put on a per person basis (Segel *et al.*, 1980; Waldichuk, 1983; Lyons, 1989), would suggest that there has been a steady increase in toxic exposure over this period, but as mentioned in the methods section, and can be seen in the decadal plot (Figure 45), the relationship is not a direct one and should be interpreted cautiously.

Figure 44 Annual Scale Human Population as an Indicator of Toxic Exposure in the Salish Sea

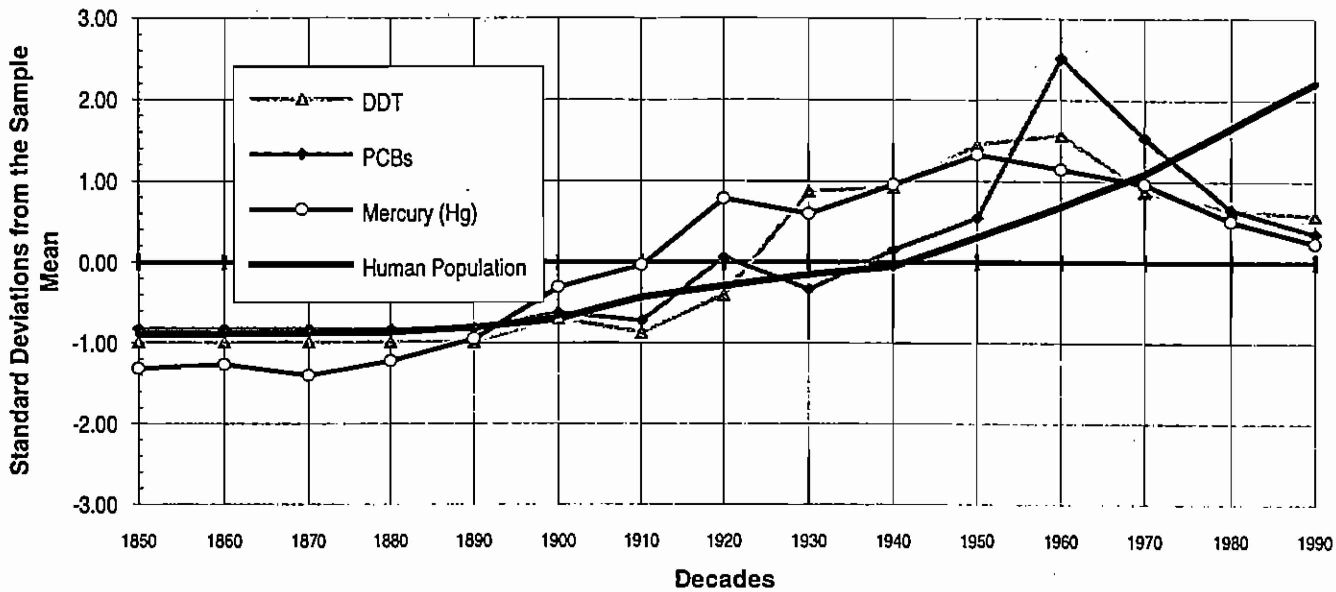


Decadal Scale

In Figure 45 human population for the Salish Sea is plotted along with decadal levels of DDT, PCBs, and mercury as measured at three sediment sites in Puget Sound. In this plot human population again displays a steadily increasing slope for the entire series, following a minor drop between 1860 and 1870; which corresponds with the declining effects of repeated Smallpox epidemics among natives (Drucker, 1965; McKervill, 1967; McMillan, 1988) just prior to the major influx of European immigrants at the end of the 19th Century.

The three toxic chemicals found at the highest levels in killer whales (mercury, DDT and PCBs, after Calambokidis, 1995; Jarman *et al.*, 1996; Ross *et al.*, in press) make their appearance in Salish Sea sediments approximately one to two decades prior to their actual release into the environment (MacDonald and Crecelius, 1994). This skew backwards from the initial deposition time is a result of sediment settling that increases with time, particularly for heavy metals such as mercury (Thompson *et al.*, 1980; Crecelius

Figure 45 Decadal Scale Indicators of Toxic Exposure for Southern Resident Killer Whales



et al., 1983). Figure 45 initially shows mercury levels increasing just prior to 1900, and DDT and PCBs beginning in the 1920s. However, historically mercury contamination from industrial processes did not begin in Puget Sound until 1900, and DDT and PCB compounds were not in regional industrial use until the 1930s and 40s (Waldichuk, 1983; Lyons, 1989; MacDonald and Crecelius, 1994).

The relationship between increasing toxic release and increasing human population displayed in Figure 14 appears steady up until the 1950s and 1960s, but due to the effects of increasing government regulation and specialization of industrial effluents since the early 1970s, this simple relationship has recently become more complicated. Beginning in the 1950s, first mercury levels begin to drop, and then PCBs and DDT levels begin to decline after peaking in the 1960s (Figure 14). By 1990 all three of these toxic chemicals are continuing to decline in the sediments, despite the increasing slope of human population growth. Thus, toxic exposure trends, at least for the chemicals being plotted here, are on a decreasing slope that is approaching the levels of these chemicals that were present in the environment in the early part of the century when the human population was about 20% of its current levels.

These findings demonstrate that human population is not a simple indicator of toxic exposure, at least not since the advent of legislation controlling the release of these chemicals into the environment in the late 1960s and 1970s (Krukeberg, 1991; Lyons, 1988; Nasser, 1992). It also indicates that the chemicals that are presently at the highest levels in the tissues of the killer whales (Jarmen *et al.*, 1994; Calambokidis, 1995), are significantly decreasing in their environment; suggesting that the younger generation of killer whales is facing less of a threat from this impact than are their elders. However, present levels of these chemicals in sediments are still above the mean for the last 100 years, so they are still being released at measurable levels, and the increasing human population of the Salish Sea illustrated in Figure 44 indicates the ambient source of toxic chemical release is not decreasing.

Food Resource Depletion

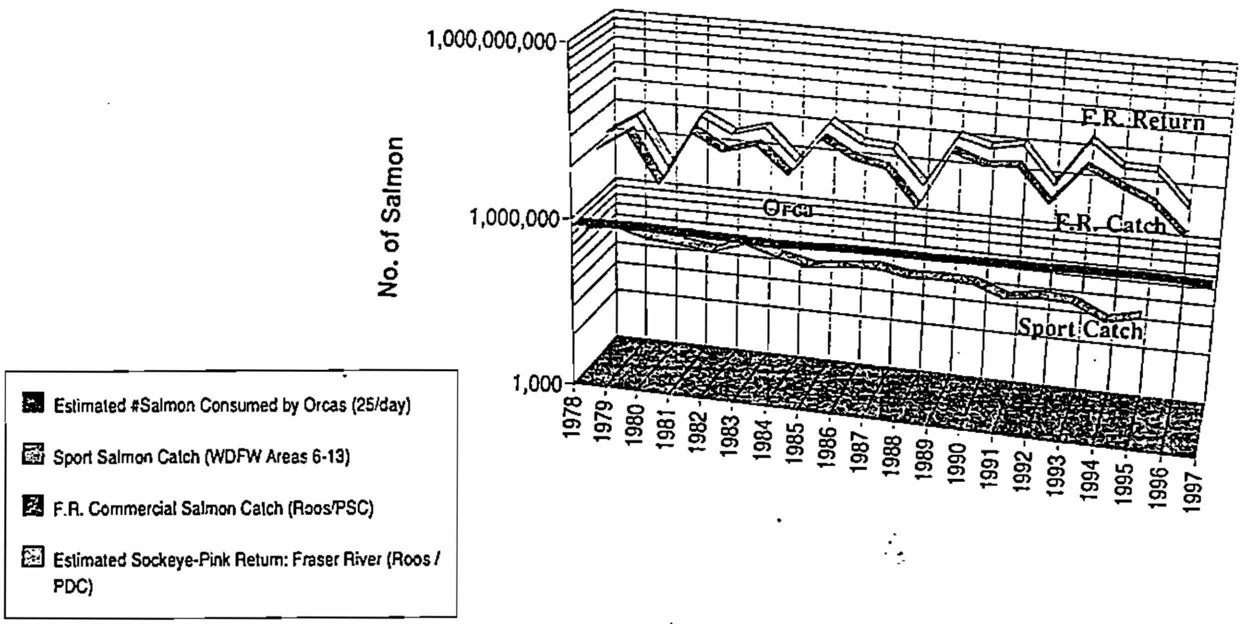
The historical indicators for human influences on food resource depletion for this population of killer whales focuses only on salmon in this study because it has been conclusively shown that salmon comprises the majority of the diet for these killer whales (Bigg *et al.*, 1990; Ford *et al.*, 1998), and data on the history of salmon exploitation for the region is readily available.

Annual Scale

In Figure 46 four variables are plotted over twenty years on a logarithmic scale in terms of annual numbers of salmon: 1) the amount of salmon maximally estimated to be consumed by the killer whales based on their annual population size; 2) the sport catch of all species of salmon in the Washington State inland waters (WDFW Areas 6-13; WDFW, 1996); 3) Fraser River pink and sockeye salmon commercial catch (Pac. Salmn. Comm.,

Figure 46

Relative Levels of Annual Salmon Exploitation by Humans and Killer Whales (1978-96)



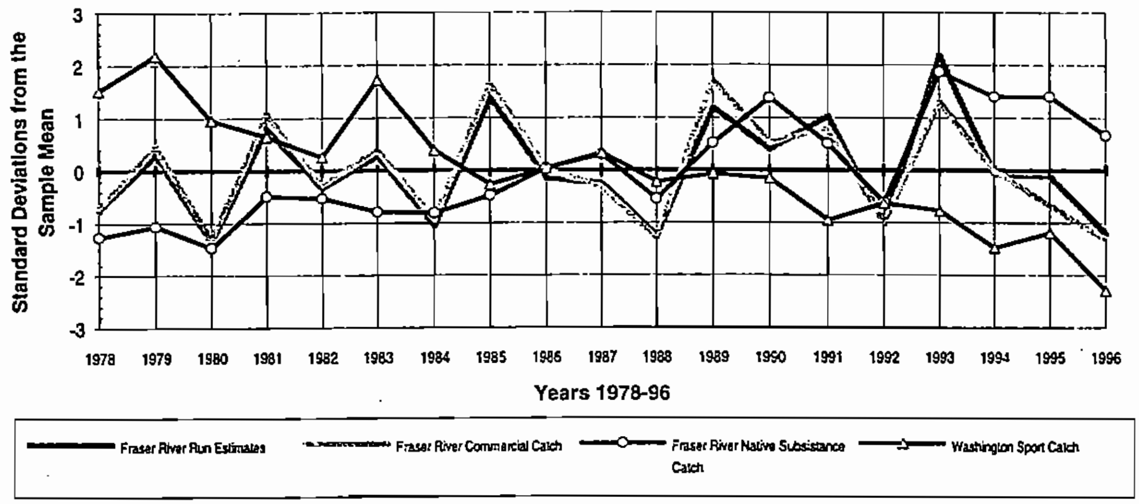
1985-1998; Roos, 1990); and 4) Pacific Salmon Commission estimates of the Fraser River pink and sockeye salmon return (Pac. Salmn. Comm., 1985-98).

In this plot the fairly steady amount of salmon estimated to be consumed by the killer whales can be contrasted with the magnitude of salmon taken by humans. The killer whale take is roughly at the same level as all the sport fishers in Washington's inland waters, and only a fraction of what is annually exploited by commercial fishing for the Fraser River alone. Missing from this plot is the native subsistence catches in Washington and B.C., the B.C. sports catch, and the Washington and B.C. commercial catches of non-Fraser River fish.

In Figure 47 three of the indicators from Figure 46 are plotted (minus the killer whale consumption estimate), and the Fraser River native subsistence catch is added as a new variable. This plot covers the same time period (1978-1996), but is

Figure 47

Annual Indicators of Salish Sea Salmon Depletion (1978-96)



plotted as annual variation in standard deviations away from the mean. In this plot Washington inland waters sports catch begins the series well above the mean, with a significantly high catch in 1979 (>2 SD), but then shows a steady decline following a particularly good year in 1983, to drop significantly below the mean by the end of the series in 1996. The Fraser River native subsistence catch starts out below the mean and builds to a high in 1990, and then experiences a two year decline to below the mean in 1992; only to jump to a record high in 1993, which erodes to near the twenty year mean by 1996.

The other Fraser River indicators: Pacific Salmon Commission pink and sockeye run estimates, and commercial pink and sockeye catch, show a four year cycle of slowly building fluctuations above and below the mean that track each other very closely. This close tracking illustrates how fisheries managers have attempted to maximize the commercial catch of these salmon runs relative to the necessary amount of escapement to keep these stocks slowly increasing (Roos, 1990).

Using the run size estimates of the Fraser River as an index of the availability of summer salmon for the killer whales (see Figures 14 and 36 for comparison), there is no indication that the Fraser River salmon resource has reached levels of depletion for these killer whales over the last twenty years. The salmon were in fact becoming more abundant until 1998 and 1999 (Wash. State, 1999; Pac. Salmn. Comm., 1999). However, using the sports catch data in Figure 47 as an index (see also Figures 14, 36 and 37), then the recent downward trends in these indicators provide some evidence that salmon levels may be approaching depletion levels outside the summer season for the smaller runs of chinook, coho and chum salmon not associated with the Fraser River watershed (Schmitt *et al.*, 1994; Wash. State, 1999).

Decadal Scale

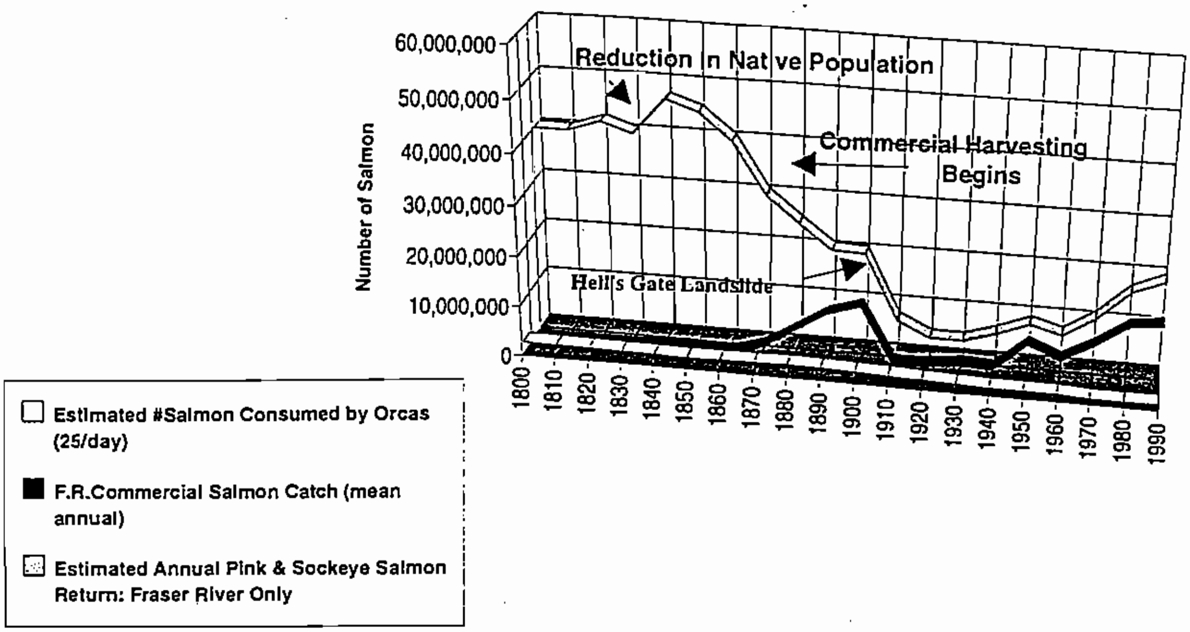
In Figures 48 and 49 salmon depletion indicators are examined for the last twenty decades. The indicators for these plots include decadal means of the estimated annual Fraser River pink and sockeye runs sizes (Roos, 1990), the Fraser River estimated commercial catch (Roos, 1990; McKervill, 1967), and the estimated subsistence catch for the Salish Sea based on combined estimates of native subsistence catch, Washington Sport Catch, and salmon catch as a proportion of native and white populations (see methods).

In Figure 48 the estimated maximum salmon requirements of the killer whales based on estimated population size are plotted for comparison with the Fraser River indicators, which are plotted as number of salmon, instead of standard deviation. As in Figure 46, it can be seen that the magnitude of salmon consumed by the killer whales is dwarfed by the size of the resource.

In Figure 49 the same three salmon indicators, minus the killer whales, are plotted as variation in standard deviations from the mean over the twenty decades. In this plot the

Figure 48

Relative Levels of Decadal Salmon Exploitation by Humans and Killer Whales (1800-1990)

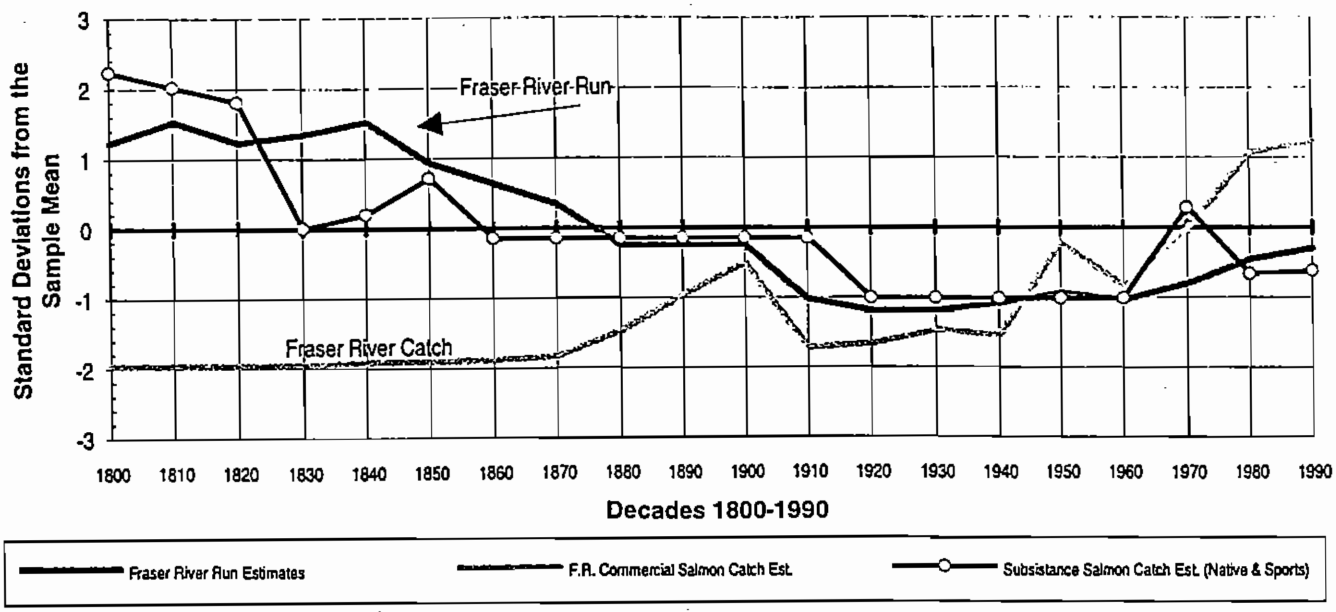


overall trend is for a continuing downward trend in both Fraser River run size and subsistence catch over the first half of the series, and then it levels off below the mean, where it has remained with only minor improvements. The subsistence catch exhibits an initial significant drop due to the decimation of the native population from Smallpox, and then temporarily builds with the addition of European settlers, until they shift their focus to the commercial harvest, and the native population drops even further from disease. The temporary increase in the subsistence catch in the 1970s is primarily due to the implementation of treaties with the natives that resulted in a significant increase in their "subsistence" catch.

The trend in the Fraser River commercial catch shows rapid growth after it was initiated in the late 1800s, and then crashes after the Hell's Gate incident of 1913; which eliminated spawning habitat for a large proportion of the Fraser River salmon runs over

Figure 49

Decadal Indicators of Salish Sea Salmon Depletion (1978-96)



several years (McKervill, 1967; Roos, 1990). From the low of the 1920s and 1930s, the Fraser River commercial catch then shows a continuous increase right up to the present.

From the perspective of the killer whales, this history of the exploitation of their salmon resources has probably affected the availability of specific favored runs at times, but the magnitude of salmon resources even up to the present, would indicate they have never actually ever faced a depletion of their food resources until now (Wash. State, 1999; Pac. Salmn. Comm., 1999). Only during the latter half of the present decade has the seasonal shortage of winter salmon been a possibility (Schmitt *et al.,* 1994). Hence, the situation is probably only now becoming of major adaptive importance to the killer whales, and they likely do not have historical cultural knowledge to draw upon in dealing with it.

Surface Disturbance

Variables chosen to represent surface disturbance for the killer whales include indicators of whale watching traffic and indicators of commercial salmon fishing operations in the vicinity of the whales, plotted over both the twenty year scale (1978-97) and the twenty decade scale (1800-1990). In both plots the indicators are presented as standard deviations above and below the sample mean of the specific time series.

The whale watching indicators plot non-consumptive predation on the whales, and will be used again in the section on underwater noise. The commercial salmon fishing indicators focus on the impact of fishing gear as a potential disturbance, rather than impacts of salmon depletion. For all these indicators the idea is that they represent an obstacle to the whales when they come to the surface.

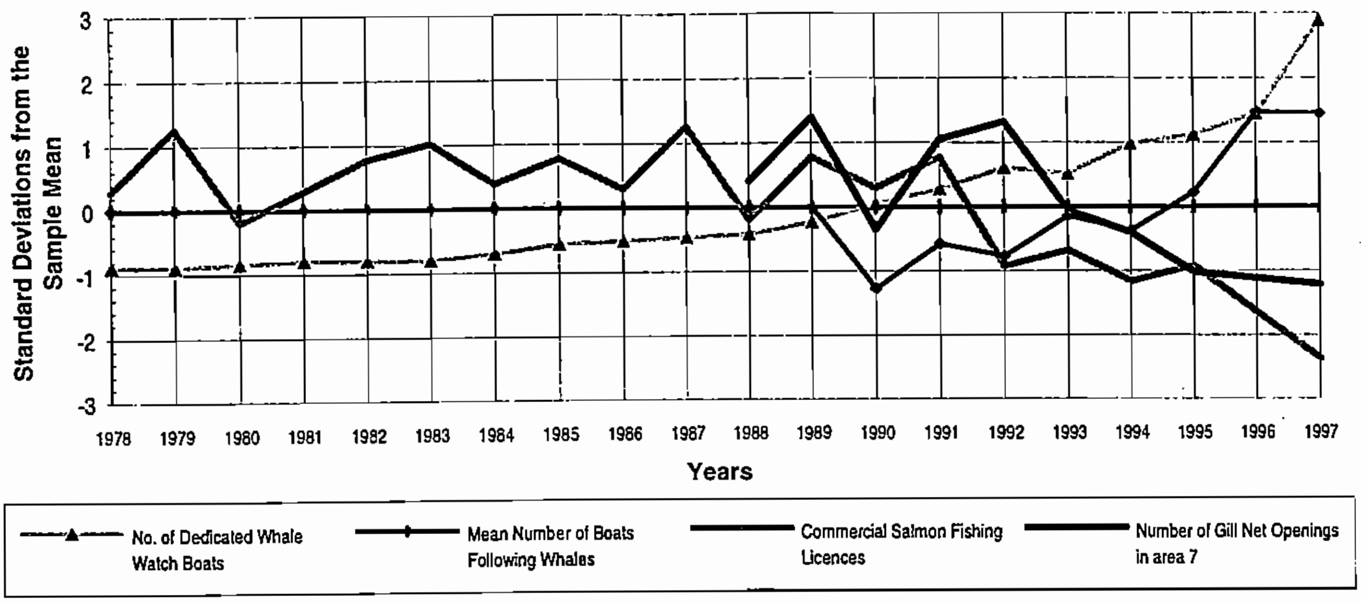
Annual Scale

In Figure 50 two of the indicators represent incomplete data sets that were not estimated further. The mean annual number of boats following the whales is only plotted for the years 1989-1997, and the mean annual number of days for salmon gill net openings in WDFW Fisheries area 7 (San Juan Islands) is only plotted for the years 1988-1997.

Looking first at the indicators of commercial fishing, it can be seen that the number of licensed boats shows a trend of annual fluctuations mostly above the twenty year mean until 1992 when they level off until 1995, and then exhibit a downward trend that reaches significance for the series by 1997 (> 2 SD). The shorter series on the annual number of days allocated for commercial gill net fishing, basically mirrors this trend, and together they indicate that any surface disturbance impacts that might be associated with commercial fishing operations are diminishing in the environment of the whales.

On the other hand, indicators for whale watching over this same period show the opposite trend of being below the mean during the first part of the sequence, and

Figure 50

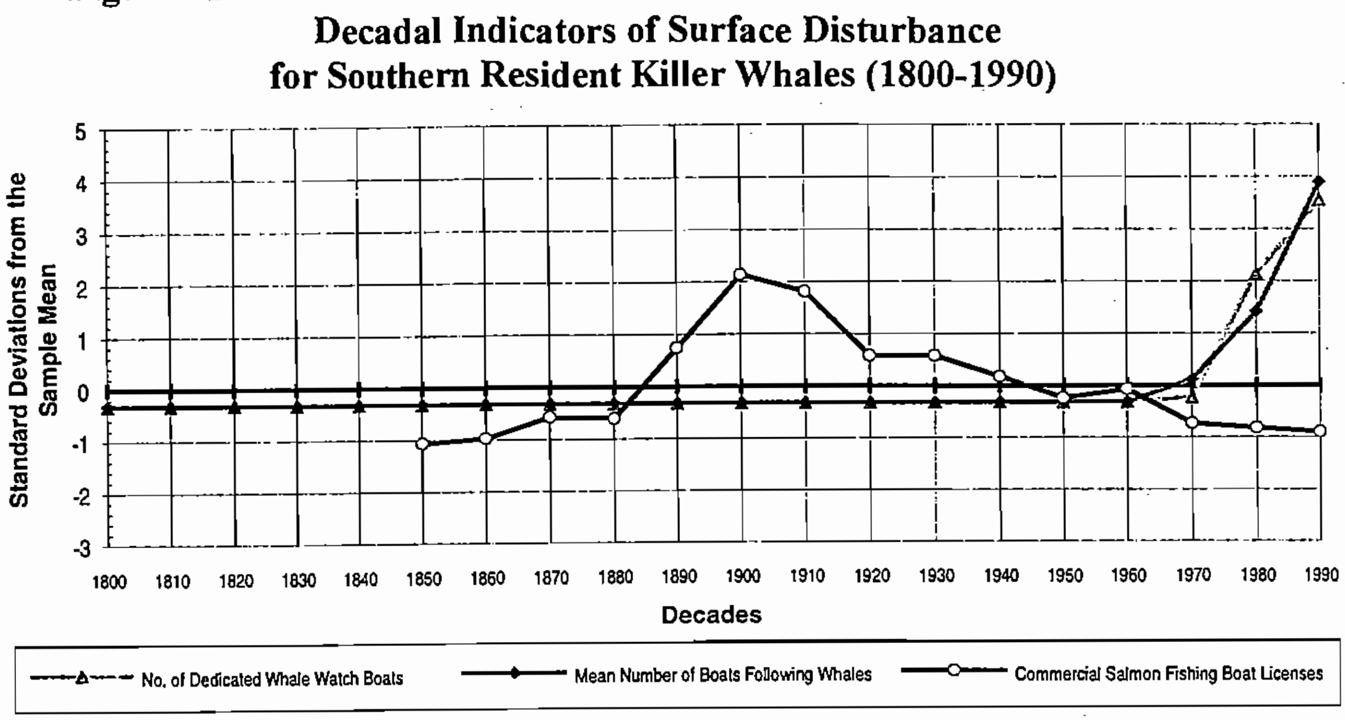


culminating at a significant level above the mean at the end of the series. Of interest in this plot is the way the two types of potential impacts replace each other, with only about a four year period in the early 1990s where they are both present at levels above the mean in a manner that would be suggestive of a cumulative impact.

Decadal Scale

In Figure 51 three of the indicators from the annual scale are plotted as standard deviations around their sample means over either 15 or 20 decades, depending upon the variable. These include the estimated decadal number of commercial fishing boats (15 decades), commercial whale watch boats, and whale watch boats around the whales (both at 20 decades). In this plot the whale watching indicators obviously did not actually exist for the entire series, but as has been noted earlier, lack of existence is important within the context of the historical adaptive requirements for these killer whales, so in this case they were plotted for all twenty decades to provide this perspective.

Figure 51



In Figure 51 it can be seen that the trend for commercial fishing activities in the vicinity of the killer whales' primary food resource has been a part of their environment for over 100 years. The maximum number of boats occurred early in the present century, and then leveled off after the 1940s, due primarily to increases in the efficiency of gear relative to the number of salmon annually available to be commercially harvested (Roos, 1990). By the 1970s, when whale watching activities first appeared, the number of commercial salmon fishing boats in the environment of the whales had already begun its downward trend.

From the historical perspective of the oldest living individuals in this killer whale population, coping with commercial salmon gear has always been a part of their adaptation to the Salish Sea, and although commercial fishing still exists, it has dropped to levels that haven't previously existed within the lifetime of the oldest individual whales. Whale watching traffic, on the other hand, presents a relatively new adaptive challenge for this killer whale population, raising the question of how much of what they have utilized in adapting to commercial fishing operations over the last century is now being applied in their adaptation to whale watching boats?

Underwater Noise

The indicators plotted to show the historical progression of the underwater noise environment for these killer whales includes published and estimated levels of commercial shipping traffic, and two of the indicators just presented in the previous section: annual number of dedicated commercial whale watch boats, and annual number of commercial fishing boats. The assumption is that through-hull engine noise and propeller cavitation represent the primary sources of anthropogenic underwater noise pollution in the Salish Sea (Myrberg, 1990; Scrnger and Heitmeyer, 1991; Richardson *et al.*, 1995; Gordon and Moscrop, 1996; Miller and Willis, 1997). All three variables are plotted over both the twenty year scale (1978-97) and a fifteen decade scale (1850-1990). In both plots the indicators are presented as standard deviations above and below the sample mean of the specific time series.

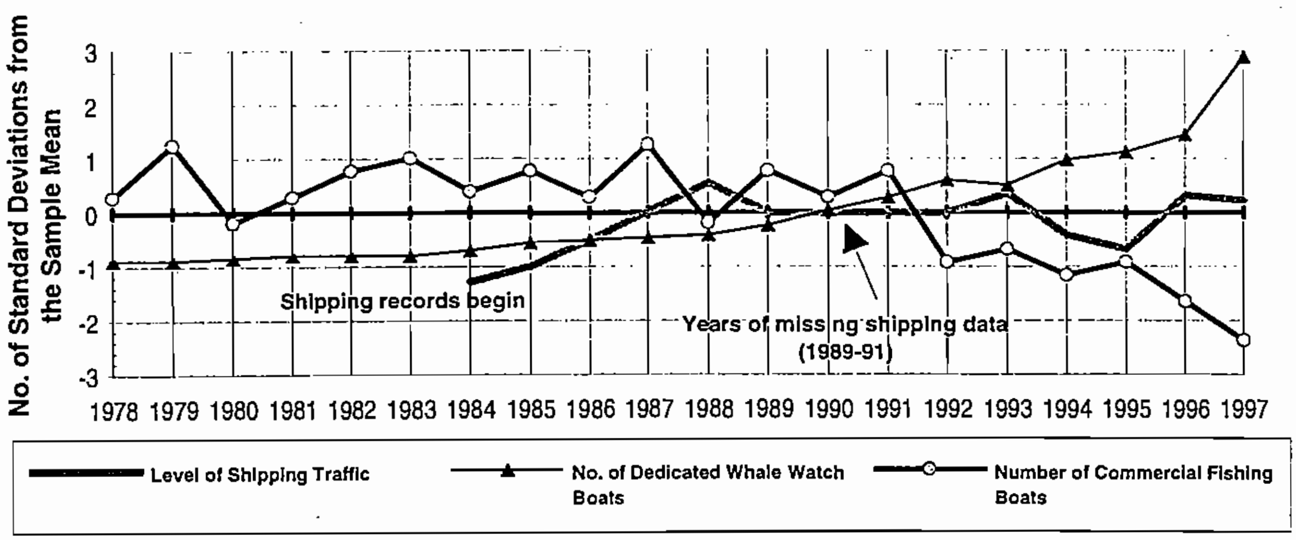
Annual Scale

In Figure 52 the only indicator that has not been previously presented in one of the other plots, is shipping traffic. At this scale shipping traffic has been measured as the number of commercial shipping transits in the inland waters east of Cape Flattery at the entrance to Juan de Fuca Strait from 1984 to 1997. These are data published by either the U.S. Coast Guard (1984-1988), or the Washington State Dept. of Ecology, Office of Marine Safety (1992-1997). The unfortunate 4 year break in the data set occurred during the transition period between jurisdiction of the two agencies.

From the plot in Figure 52 it can be seen that a fairly steep increase in shipping traffic occurred during the mid 1980s, and that since then it appears to have leveled off.

Figure 52

Annual Indicators of Underwater Noise Exposure for Southern Resident Killer Whales (1978-1997).



As noted in earlier plots, the number of licensed commercial gill net boats remained fairly steady during this twenty year period until the early 1990s, when they began their current decline. Mirroring this decline in commercial fishing boats is the steady increase in commercial whale watch boats at about the same time.

From the perspective of underwater noise pollution for the killer whales, Figure 52 suggests that levels of these indicators have remained fairly stable for the last twenty years. The only exception concerns whatever increases are attributable to whale watching traffic, which significantly increased over the last years of the plot, and at a higher rate than commercial fishing boats dropped. Furthermore, since whale watching boats tend to be more dense in the immediate vicinity of the whales relative to other boats, noise levels associated with whale watching would logically be higher.

Decadal Scale

In Figure 53 the same variables graphed in the annual plot are used. However, except for the decadal number of commercial whale watch boats, the values of the indicators have been estimated, as previously described in the methods section. Values of these indicators are plotted as standard deviations from the sample means for the entire 15 decade series for each variable. As before, the number of whale watching boats obtains the value of zero for most of the series, since they did not exist prior to 1977.

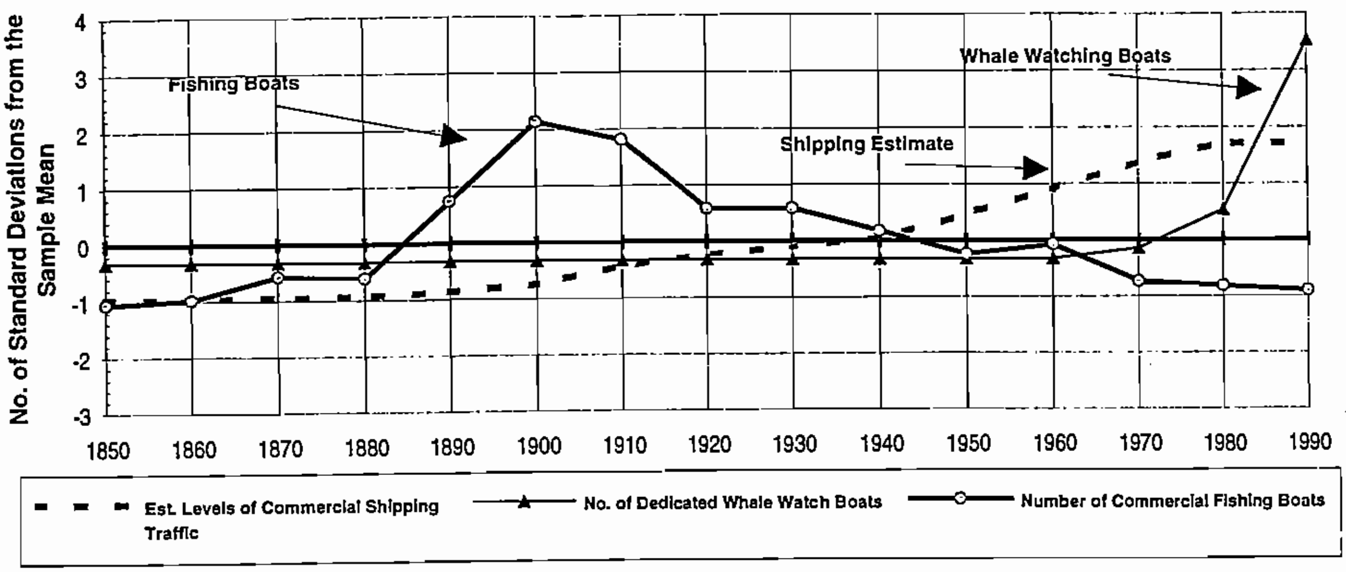
The trends in Figure 53 show shipping traffic with a steady increase from its beginnings in the 1870s, up through its entire sequence, with a leveling off in the 1990s; as indicated from the annual plot (Figure 59). This trend reflects what would be expected for levels of ambient background noise in the Salish Sea under the steady increase in human industrial development and population over this period (Figure 44). Fishing boats and whale watch boats represent patchy periods of excessive noise in the immediate environment of the killer whales, and so should be viewed as acute additional noise on top of this ambient background of shipping.

In Figure 53 it can be seen that fishing boats peaked at the turn of the century, then leveled off by the 1920s, and remained relatively constant for 50 years before their recent decline (Figure 52). From the killer whales perspective, the acute impact of underwater noise from fishing vessels has not been known to deter them from feeding in the immediate vicinity of vessels under operation (Griffin, 1982; Hoyt, 1981; 1990), and although the killer whales do not have a choice about whether or not to feed, they always have some choice of not feeding directly in the vicinity of fishing activities.

Whale watching boats, on the other hand, do not offer as much of a choice for avoidance should the whales be experiencing some physical impact from their underwater noise. The current trend in whale watching traffic in respect to being significantly above the sample mean, in all the plots and at all scales, including Figure 53, places it at the top of the list as a potential source of underwater noise impacts on this population of killer whales, if underwater noise actually turns out to be an issue for these whales.

Figure 53

Decadal Indicators of Underwater Noise Exposure for Southern Resident Killer Whales 1850-1990)



The Historical Interaction Matrices:

The objective of the historical interaction matrices is to provide a pallet for viewing the historical patterns in a consistent fashion between time scales. The matricies themselves are too large (up to 6 pages for Table 24) to present in the text so they are presented as appendices (Appendix II). The matrices allow the horizontal *context* of the indicators to be assessed at different perspectives. In the plots, the cumulative scores above 1 standard deviation of all variables for each point in time are displayed. These plots allow perturbations in multiple variables to be identified and provides a view of the overall trends. However, the matrices (Appendix II: Tables 24, 26 & 29), rather than the plots, will serve as the primary basis for assessing the results described in this section.

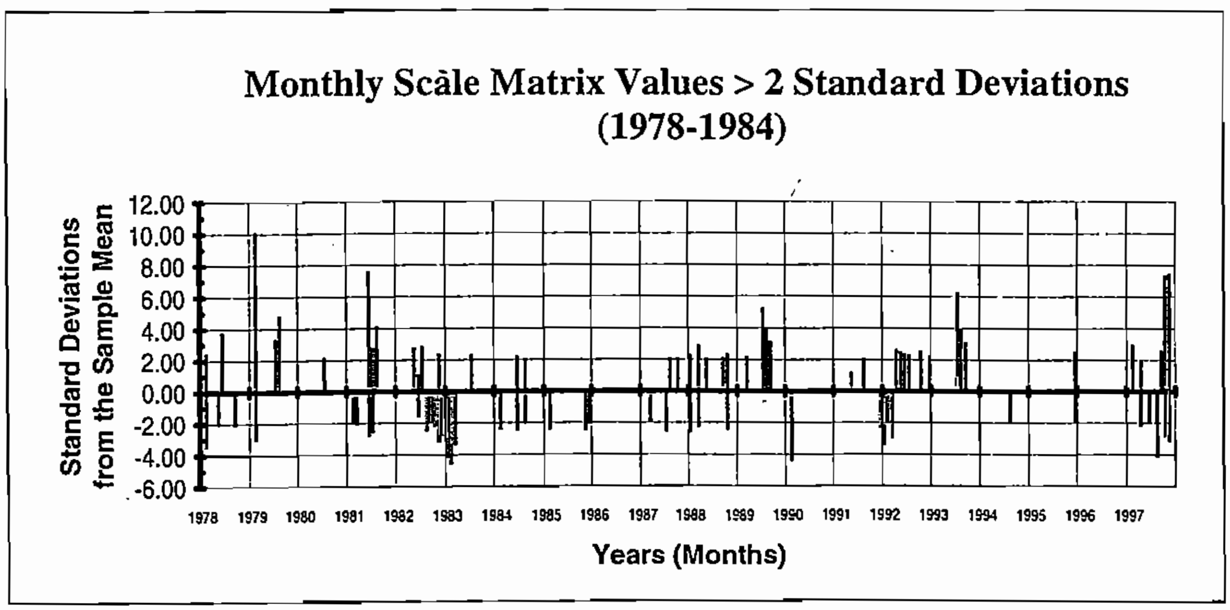
The Monthly Scale Matrix

The monthly patterns are plotted as cumulative monthly perturbations that are statistically outside 68% of the sample mean (>1 SD: Figure 58), and 95% of the sample mean (>2 SD: Figure 54). In this context the indicators are assembled at their smallest temporal scale and they exhibit many fluctuations from their sample means between temporal points. One reason for this stems from the fact that the monthly scale exhibits the extremes associated with seasonality in some variables. Hence the transition conditions of spring and fall are the only equilibrium times, though not continuously. However mostly this plot is useful in pointing out the lack of equilibrium of indicators at this time scale.

In order to dampen the effects of these fluctuations, in Figure 54 the largest perturbations in the overall 240 month sequence are plotted as cumulative monthly scores above 2 standard deviations. As can be seen in Figure 54 and Appendix Table 24, rarely do the perturbations occur in temporal clusters of more than one type of variable.

All the rest of the statistically significant perturbations in environmental indicators for these whales are associated with positive fluctuations in salmon sports catch (Table 24 and Figure 54). The summers of 1979, 1980, 1982, 1987, 1989, 1991 and 1993 were

Figure 54



significantly good years for the salmon sport catch in the San Juan Islands. However, the occurrence of the killer whales in these years are consistently average, with little or no corresponding perturbations at all (Table 24).

The detection of the killer whales Between Zone 1, Zone 2, and "other areas" fluctuates above 2 SD on 44 occasions over the 240 month sequence (Table 11). These significant fluctuations occur independent of any of the environmental indicators, but exhibit some patterns internally. Beginning with Zone 1, this indicator exhibited 16 perturbations, 8 above expectation and 8 below. On five occasions a significant perturbation in Zone 1 is temporally linked with a perturbation in Zone 2, by either preceding, following by a month, or occurring at the same time (Table 11). On four occasions Zone 1 is temporally associated with statistically significant perturbations in the "other areas" category (Table 24).

On five occasions Zone 1 exhibits positive fluctuations that are not linked with any other indicator: February 1978, November 1982, May 1988, March 1989, and February 1997 (Table 11 & 12). Zone 2 exhibits unlinked positive perturbations on three occasions: August 1979, May 1982 and July 1983. Not surprisingly, the "other areas" category does not show any unlinked perturbations (Table 11 & 12).

Table 11

Temporal Associations Between Geographic Zones

(Over 240 Months)

Habitat Area	Zone 1	Zone 2	Other Areas	Totals
Zone 1	5	5	4	14
Zone 2	5	3	9	17
Other Areas	4	9	0	13
				44

Values = Number of Positive Perturbation above 2 SD within +/- 1 month

Zone 1 = San Juan/Gulf Islands

Zone 2 = Puget Sound

Other Areas = Not in Zone 1 or Zone 2

Table 12 Anomalous Periods of Increased Presence (>2 SD) for Southern Resident Killer Whales Over a 240 Month History

(January 1978 - December 1997)

Time Period:	Location:	Pod(s):
1. February 1978	San Juan/Gulf Islands	J-Pod. *
2. June 1978	Puget Sound	J-Pod
3. August 1979	Puget Sound	J,K, & L-Pods. *
4. February 1979	Puget Sound	J-Pod
5. June - August 1981	Puget Sound	J,K, & L-Pods.
6. May 1982	Puget Sound	J-Pod. *
7. November 1982	San Juan/Gulf Islands	J-Pod. *
8. July 1983	Puget Sound	J,K, & L-Pods. *
9. January 1988	San Juan/Gulf Islands	J-Pod.
10. March 1988	Puget Sound	J-Pod.
11. May 1988	San Juan/Gulf Islands	J and K-Pods. *
12. October 1988	San Juan/Gulf Islands	J,K, & L-Pods.
13. March 1989	San Juan/Gulf Islands	J and K-Pods. *
14. December 1995	Puget Sound	J-Pod.
15. February 1997	San Juan Gulf Islands	J-Pod. *
16. September 1997	San Juan Gulf Islands	J,K, & L-Pods.
17. October-November 1997	Puget Sound (Dyes Inlet)	J and L-Pods

* = an incidence of high occurrence not temporally associated with any other variable.

Since "positive" perturbations in killer whale habitat-use indicators represent months where the killer whales were *detected* a significant number of days, the complications of low sighting effort are not as much of a factor as it is for significantly low perturbations. Therefore these statistically significant positive perturbations of killer whale detection in the Salish Sea strongly suggest that something of importance to the killer whales was going on in these areas at those times; especially on the 8 occasions that are not temporally associated with any other indicators in this study. These dates serve as historical markers in and of themselves, that can have value in respect to focusing a search for correlation's with indicators not addressed in this study, and in light of providing a basis for future explanations (Table 12). For the purposes of the present study however, these dates stand alone as anomalies.

In Table 13 the historical contexts of the six variables examined at this monthly time scale are summarized by comparing the historical trend (20 years) with present trends over the last five years. Historically all variables fluctuate above and below the sample mean over the entire series without any clear trends, except for sea surface temperature, which has been increasing for the last 30 years (Figure 40). Present trends over the last five years at this monthly scale indicate 1) an increase in the presence of the killer whales in the inland waters, 2) decreasing salmon resources, and 3) increasing sea surface temperature (Table 13).

Table 13

Historical Context at the Monthly Scale
(January 1978 - December 1997)

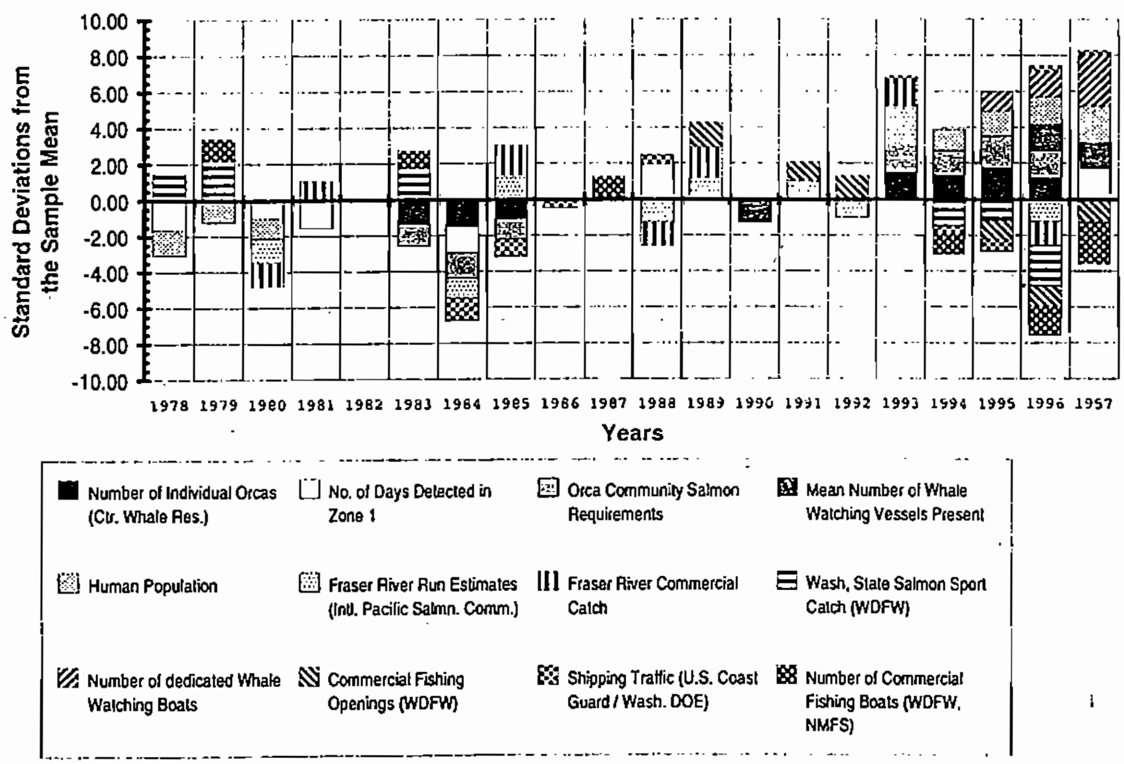
Historical Variable	Historical Indicator	240 Month Historical Trend	Seasonally Adjusted Present Trend
Orca Habitat-Use:	San Juan/Gulf Islands (Zone 1-Use)	Fluctuating	Increasing
	Puget Sound (Zone 2-Use)	Fluctuating	Increasing
	Other Areas (Use = SD # days/mm)	Fluctuating	Decreasing
Food Resource Depletion:	Fraser River Run Estimates	Fluctuating	Decreasing
	Sport Salmon Catch in Area 7	Fluctuating	Decreasing
Climate:	Active Pass Sea Surface Temperature	Increasing	Increasing

The Annual Scale Matrix

The annual scale perturbations from the sample mean are presented in Figure 55 and in Appendix II in Figure 59 and Table 26. In these plots all perturbations >1 SD are presented. At this scale the number of fluctuations > 1 SD around the mean are noticeably reduced relative to the monthly scale, and they show consistently longer trends of increase and/or decrease over the series. The over all trend shows a cluster of higher variation at either end of the time sequence, and an equilibrium condition in the middle part of the sequence (Figure 55). This is what would be expected if variables are exhibiting either increasing or decreasing trends relative to the mean over the entire sample period.

The annual matrix shows that at the beginning of the 20 year sequence below average conditions exist for: 1) the detection of the whales in Zone 1, and 2) Salish Sea human population size. Above average conditions initially exist for: 1) salmon sport catch, and 2) the number of licensed commercial fishing boats. At the end of the sample period all four of these variables are exhibiting opposite extremes from where they were at the beginning as the result of progressive trends over the series (Figure 55 and Table 26). Thus, over the series salmon indicators are decreasing and human population is increasing.

Figure 55 Annual Scale Matrix Plot of All Indicators



However, positioned in the middle of the series there are two periods of cumulative perturbations that stand out from these basic trends. The first cluster is from 1983-85, and the second one is in 1988-89. The early 1980s perturbations are negative detection of the killer whales in all areas, and positive salmon indicators, except for 1984, which was negative for the Fraser River summer runs. The second set, are the 1988-89 perturbations, which again involve killer whale detection and salmon variables operating in an opposing fashion, with 1988 being a record year for the killer whales in the inland waters (1.93 SD), and a low year for salmon, and 1989 being a good year for salmon, but a slightly below average year for the presence of killer whales (Figure 55).

Overall, the 1990s show a progressive increase in perturbations, involving a progressive number of variables, indicating an annual decrease in the stability of most indicators. By the end of the sequence in 1996 and 1997 the only variable at equilibrium is the number of days the whales were detected in the San Juan/Gulf Islands (Zone 1); which annually remained within 1 SD of the sample mean over eight years, from 1988 through 1996; and finally broke the trend with an increase in the number of days detected in 1997 (>1.7 SD). During the 1990s all other indicators exhibit increasing perturbations > 1 SD away from the 20 year mean right up to the last year they are measured. Again this indicates that all indicators are currently exhibiting increasing extremes relative to prior conditions

In Table 14 the trends for the eight variables examined at this time scale are summarized: 1) the Southern Resident killer whale population shows an over all increase over the last twenty years, except for the last three years where it has been decreasing; 2) their annual detection around the San Juan and Gulf Islands shows periodic fluctuations until it reaches a maximum in 1988 and begins a slight downward trend to 1994, when it begins fluctuating upward in 1995 and 1997; 3) the salmon requirements of the

Table 14 **Historical Context at the Annual Scale**
(1978-1997)

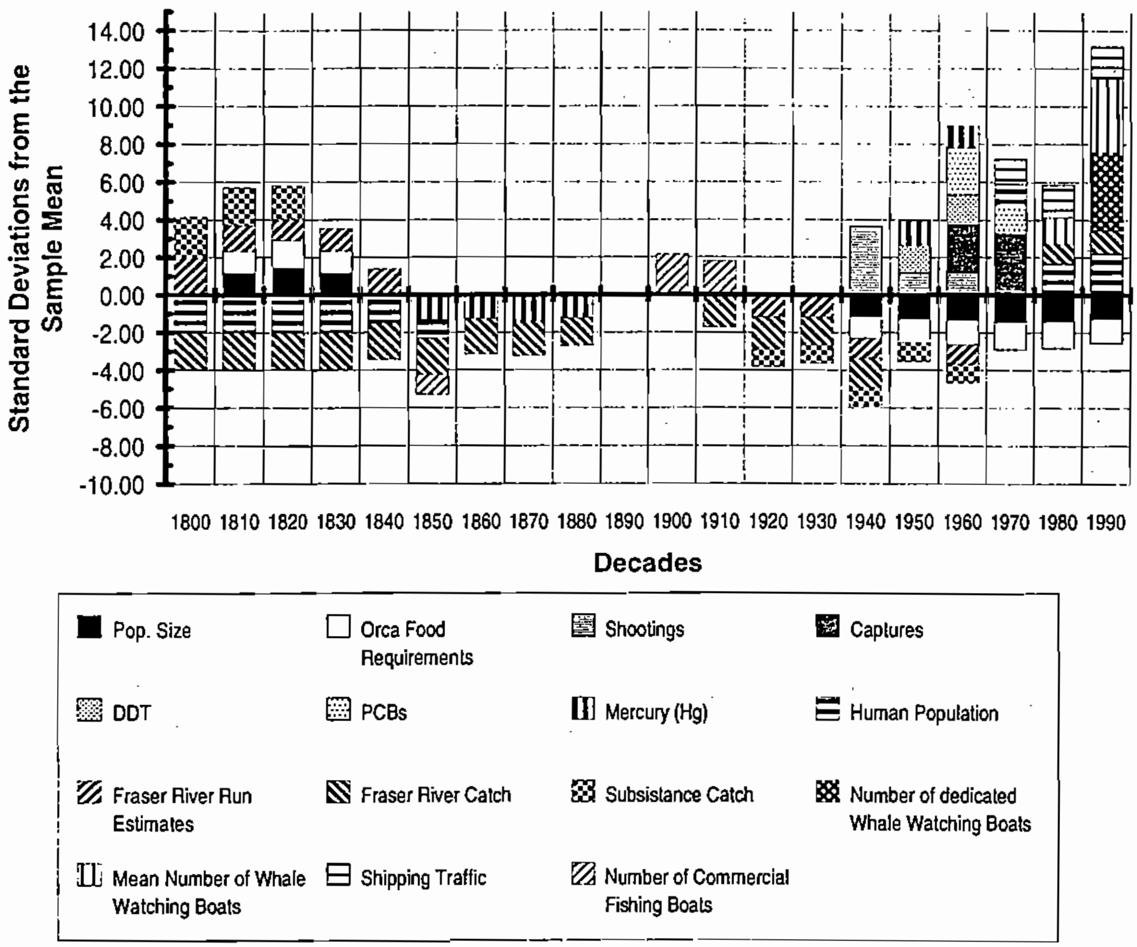
Historical Variable	Historical Indicator	Historical Trend	Present Trend
Orca Population Ecology:	Number of Individual Orcas	Increasing to 1995	Decreasing
Orca Habitat Use	No. of Days Detected in Zone 1	Fluctuating: Peak in 1988	Decreasing until 1995-97
Salmon Requirements:	Orca Community Salmon Requirements	Increasing to 1995	Decreasing
Human Predation:	Mean Number of Whale Watching Vessels Present	Increasing	Stable
Toxic Exposure:	Human Population	Increasing	Increasing
Food Resource Depletion:	Fraser River Run Estimates	Fluctuating: Peak in 1993	Decreasing since 1993
	Fraser River Commercial Catch	Fluctuating: Peak in 1989	Decreasing since 1993
	Wash, State Salmon Sport Catch	Fluctuating: Peak in 1979	Decreasing since 1993
Surface Disturbance:	Number of dedicated Whale Watching Boats	Increasing	Increasing
Underwater Noise:	Commercial Fishing Openings	Fluctuating: Peak in 1989	Decreasing
	Number of Commercial Fishing Boats	Fluctuating: Peak in 1987	Decreasing
	Shipping Traffic	Fluctuating: Peak in 1988	Stable
	Mean Number of Whale Watching Vessels Present	Increasing	Stable

population just mimic the trends in population described in number 1 (slowly increasing until a decrease in the last three years); 4) whale watching shows a steady increase over this series, with some hint of stabilizing in 1997 (confirmed with preliminary data in 1998); 5) using human population as a measure of toxic exposure suggests that there has been a steadily increasing trend in the generation of pollutants in the Salish Sea; 6) the salmon indicators show lots of fluctuating over most of the series until 1993, when all three indicators begin a steady decline; 7) surface disturbance as measured by whale watching indicators shows a steady increase that may be stabilizing in 1997; and 8) underwater noise indicators, except for whale watching, show fluctuations with peaks in the late 1980s and then finish out the sequence with a) decreases in commercial fishing indicators, b) stable conditions in ambient commercial shipping, and c) increases in potential noise associated with whale watching.

The Decadal Scale Matrix

The decadal scale perturbations from the sample mean are presented in Figure 56 and in Appendix II in Figure 60 and Table 28. In these plots all perturbations >1 SD are plotted. This plot is similar to the annual plot in exhibiting extremes in variation at either end of the series, suggesting increasing and decreasing trends. However, at this

Figure 56 Decadal Scale Matrix Plot of All Indicators



scale of two hundred years, the context is large enough for a few variables to actually go through a perturbation trend and then return to an equilibrium around the mean. In what follows first the positive and negative trends will be presented, and then the isolated perturbations will be described.

Indicators that started low and showed a continuous increasing trend include human population, and the three primary indicators of vessel traffic: commercial shipping and the two vessel-based whale watching indicators (Figure 56 & Table 28). Indicators that showed a decreasing trend over the series include: killer whale population size, and most of the salmon indicators, except for the Fraser River salmon catch; which

Table 15 Historical Context at the Decadal Scale

(1800-1990)

Historical Variable	Historical Indicator	Historical Trend	Present Trend
Orca Population Ecology:	Orca Population Size	Decreasing to 1970	Decreasing since 1990
Salmon Requirements:	Orca Food Requirements	Decreasing to 1970	Decreasing since 1990
Human Predation:	Shootings	4 Decade Impact (1940-70)	Extinguished
	Captures	2 Decade Impact (1960-70)	Extinguished
Toxic Exposure:	DDT	8 Decade Increase to 1980	Decreasing since 1980
	PCBs	8 Decade Increase to 1980	Decreasing since 1980
	Mercury (Hg)	8 Decade Increase to 1980	Decreasing since 1980
	Human Population	Increasing	Increasing > 2 SD
Food Resource Depletion:	Fraser River Run Estimates	Decreasing to 1920	Increasing since 1970
	Fraser River Catch	Increasing 1840-1900	Increasing again since 1970
	Subsistance Catch	Decreasing 1840-1960	Decreasing again since 1980
Surface Disturbance:	Number of dedicated Whale Watching Boats	Increasing from 1970	Increasing > 2 SD
	Mean Number of Whale Watching Boats	Increasing from 1970	Increasing > 2 SD
Underwater Noise:	Shipping Traffic	Increasing to 1980	Stable since 1980
	Number of Commercial Fishing Boats	Increasing 1850-1900	Decreasing since1970
	Mean Number of Whale Watching Boats	Increasing from 1970	Increasing > 2 SD

started low before European settlement, increased, then declined, and is now showing an increase again at the end of the century.

The indicators that went through a clear perturbation cycle and then returned to mean values were: shootings, captures, and the three toxic chemicals. Shootings werenon-existent until the 1850s, reached a high from the 1940s-60s and then dropped below expectation to being currently non-existent. At this scale captures were a relatively short lived phenomena over the 1960s and 1970s that immediately followed the era of shootings. However, when combined over the 40 year period, the effects of these events are likely what is responsible for the low population size of this killer whale community when photo-identification records began (1974).

Salish Sea sedimentation of the three toxic chemicals plotted in this study begin exhibiting perturbations above the sample mean in the 1950s, peak in the 60s, and are back to within 1 SD of the 20 decade mean by the 1980s. The deposition of these toxics begins with mercury in the 1850s, and PCBs and DDT after the turn of the century; after which all three exhibit a rapid increase that maximizes in the 1960s and 1970s (Figures 45 and 56; MacDonald and Crecelius, 1994).

In Table 15 the trends for the seven variables examined at the decadal time scale are summarized: 1) decreasing population size; 2) decreasing food requirements; 3) extinguished human predation; 4) decreasing toxic exposure after the 1980s (but still present); 5) decreasing salmon resources after 1900 (except for the Fraser River since the 1970s); 6) increasing surface disturbance from whale watching; and 7) increasing underwater noise after 1900 with: a) commercial fishing noise decreasing after the 1970s, b) commercial shipping traffic stabilizing after the 1980s, and c) underwater noise associated with whale watching increasing steadily since it first appears in the 1970s.

DISCUSSION

A Diachronic Assessment of Southern Resident Killer Whales

The purpose of the present chapter has been to provide a systematic index of the historical ecology of a specific population of killer whales. This has been undertaken within the conceptual framework originally presented at the beginning of the dissertation in Figures 1 and 2 (after Duffus and Dearden, 1990). First the ecological domain was addressed by compiling current information on the ecology of the management unit in order to identify three appropriate indicators of its longitudinal status (Chapter 2). In

Chapter 3 current information on the human domain was compiled to identify fifteen appropriate longitudinal indicators of human influences (Appendix I), and to compare their potential for combined effects. In the results just described, empirical data, and estimates of these indicators, were plotted at different time scales in order to determine the depth of trends, and to identify the qualities of influences that are revealed when historical contexts are shifted between scales.

These last two aspects of the historical ecology: 1) the depth of trends and 2) the qualities of influences, are summarized in Table 16 and provide the basis for assessing the "cumulative impact of this population's specific ecological history" (p. 4-1). These qualitative characteristics are revealed by identifying which influences are new, and conversely, which ones have been around for several generations, or have completely disappeared from the present environment, but still might be exhibiting residual effects. This historical context also identifies which potential impacts are acute, and which ones might have cumulative effects only being expressed now. Finally, the history provides clues to the current drop in growth rate, and consequentially, the basis for estimating what a healthy population might have been.

In a diachronic analysis such as this, the objective is to gain insights through a comparison of the historical interplay between two or more processes (Wells, 1920; Toynbee, 1972; Ingersol, 1994; Diamond, 1997). In the present study this has been applied by comparing the longitudinal interplay of different influences upon a single management unit. The next stage in a diachronic analysis would be a longitudinal comparison of the historical ecology of the management unit with another equivalent management unit and its historical ecology; a "control" population (Popper, 1959; Brown and Downhower, 1988).

This requires knowing the historical conditions that have lead to the differences between the two populations, as well as the differences in their present conditions. In this study so far, I have attempted to identify and review past and present conditions just for the Southern Resident population. The Northern Resident Community has only been mentioned in passing. In the next section the vectors of human influence on the carrying capacity of the Southern Resident Community identified in this study will be reviewed in terms of both: a) their historical characteristics, and b) the magnitude of potential impacts relative to what is generally known about the historical ecology of the Northern Residents (Spong *et al.*, 1970; Bigg *et al.*, 1976; 1987; 1990a; Jacobson, 1986; 1990; Duffus, 1988; Waite, 1988; Ford 1989; 1990; Bain, 1989; Hoyt, 1990; Morton 1990; Olesiuk *et al.*, 1990; Kruse, 1991; Barrett-Lennard, 1992; Duffus and Dearden, 1993; Ford *et al.*, 1994; 1995; 1998; Rose, 1992; Kriete, 1995; Nichol and Shackleton, 1996).

In Table 16 the context of six of the potential vectors of human influence identified in the present study are compared in a matrix composed of historical attributes. Each potential vector of human influence is assessed according to: 1) the primary human activities that provide the source of these impacts, 2) whether the potential impact has a historical presence, 3) whether it is acute and/or cumulative, 4) short term and/or *Long-term*, and 5) its most recent annual trend. Additionally, each vector for the Southern Resident Community is considered relative to the estimated degree of impact experienced by the Northern Resident pod community.

Table 16.
Historical Human Impact Matrix for Southern Resident Killer Whales with Reference to the Northern Resident Community

Vector of Influence on the Orcas	Human Source(s) of Influence	Type of Influence (Acute &/or Cumulative)	Historically Present ?	Duration of Influence (Long &/or Short-Term)	Most Recent Trend (5 yrs.)	Southern Residents Relative to Northern Residents
Human Predation	Shootings and captures	Acute	Yes	Short-term	Non-existant	Higher exposure
Surface Disturbance	Vessel-based whale watching	Both	Yes	Short-term	Increasing	Higher exposure
Underwater Noise	Vessel-based whale watching	Both	Yes	Short-term	Increasing	Higher exposure
Food Resource Deplet.	Salmon habitat destruction / over fishing.	Cumulative	No	Long-term	Increasing	Higher exposure
Toxic Exposure	Un-regulated marine pollution	Both	Yes	Both	Decreasing	Higher exposure
Disease	Acceleration of viral & bacterial evolution / lowered immunity from toxic exposure.	Acute	Unknown	Both	Unknown	Unknown

A quick review of the vectors of impact delineated in this study, indicates that some human influences have long histories with the population, and some are completely new impacts (Table 16). Obviously, impacts that have historically been a part of the killer whale's environment at equivalent or higher levels than they are at present, are less of a management concern than impacts that have never occurred historically, or that involve new types of environmental stress that the whales have never had to adapt to before. Hence, the first management result from assembling a historical ecology, is to be able to objectively prioritize potential management concerns for the population, once the vectors of interference with their biology have been inventoried and historically tracked.

In Table 16 it can be seen that human predation is now non-existent, but its past impact is still present in respect to the small size of the surviving breeding population. Toxic exposure is decreasing, but the effects of past decades are still accumulating in the food resources and tissues of the killer whales. Despite the lower levels of toxins currently being released into the marine environment (Levings and Thom, 1994; Crecelius *et al.*, 1995), chronic toxic exposure will continue to exist for this population into the foreseeable future, especially if seasonally low salmon resources force the killer whales to prey-shift, and increase the percentage of their diet that includes bottom fish and marine mammals that accumulate higher toxic loads than salmon (Calambokidis and Baird, 1994; Baird, 1999).

As repeatedly alluded to in earlier chapters, human influences that promote disease outbreaks in killer whales are unknown, either in terms of any empirical evidence of a disease outbreak ever occurring in Eastern North Pacific killer whales, or in terms of a conclusive link to a specific human influence that promotes epidemics in marine mammals. But disease outbreaks in several other marine mammal populations, including other odontocetes, have been documented in recent decades (Kennedy, 1996). The Southern Resident killer whales have such a small breeding population, that they could be extirpated if they experienced an epidemic of any sizable proportion. Furthermore, their close proximity to human activities, and high levels of existing toxic contamination (Calambokidis *et al.*, 1990; Calambokidis and Baird, 1994; Calambokidis, 1995; Jarmen *et al.*, 1996; Ross *et al.*, in press), makes them the most likely killer whale population in the world to experience an anthropogenically facilitated disease outbreak (Ross *et al.*, in press). In Table 16 it is the one potential vector of human influence for which indicators were unable to be developed, but it is included because of its "potential" to suddenly emerge as an overriding ecological factor and influence on the history of this population.

Food resource depletion, surface disturbance, and underwater noise are the three areas of environmental resistance on these whales that are presently still increasing. In terms of food resources, it is not at all clear how much these killer whales are being stressed by the decline in salmon stocks. In the summer the Fraser River runs still provide a stable abundance of salmon that more than covers the energetic requirements of this killer whale population. During the rest of the year it is possible the killer whales are being salmon-deprived, because that is when the currently most diminished salmon runs were historically more abundant. The unanswered questions in this issue that are in need of further research include: 1) how much of this killer whale population's diet truly is dependent upon salmon?, 2) how inclined towards prey shifting are Southern Resident killer whales? and 3) how abundant are the other prey the killer whales eat, the ones they would need to shift to?

Fortunately the protection and restoration of Salish Sea salmon resources has recently been receiving extensive attention by both the U.S. (Washington State, 1999), and Canadian governments (DFO, 1999), and serious efforts are optimistically underway to stop any further salmon habitat destruction, and to begin rebuilding the smaller seasonal stocks of chinook and coho salmon that the killer whales appear to have historically depended on in the winter and spring. If these salmon stocks can be restored soon, then the whole issue of prey shifting in this population may only be temporary, or never be forced to occur at all.

The last two variables in Table 16 that are potentially of management concern because they are currently increasing, are surface disturbance and underwater noise. Presently the primary source of both of these influences comes from the increase in vessel-based whale watching (Osborne 1991; 1998; Duffus and Dearden, 1993; Duffus and Baird, 1995; Burgen and Otis, 1995). This short-term impact, can be both acute and cumulative in terms of its influences upon the killer whales.

Surface disturbance comes from vessels and their gear blocking the surfacing/breathing area of the whales. This impact is basically an acute, short-term influence, but when it occurs chronically it would be expected to accumulate long-term influences upon behavior and detrimental exposure to toxic chemicals released in the immediate vicinity of the vessels. Historically these impacts occurred in respect to commercial fishing operations, where both surface disturbance (to the degree of being shot at), and underwater noise (motorized operations) were a regular part of this killer whale population's environment for decades. This source has diminished significantly in recent years and been replaced by a new source of surface disturbance and underwater noise that has one important differences from commercial fishing, this disturbance follows the killer whales themselves, not just their prey. The killer whales do not have an easy choice about whether they want to remain exposed to whale watching boats. In the case of commercial fishing, the killer whales could choose to feed on the periphery of the sources of disturbance, and they were rarely if ever pursued. In the case of whale watching, the disturbance pursues them, they would have to abandon normal activities and put out an extreme amount of effort to get away from the disturbance. It significantly removes their ability to exercise a choice in being exposed to these potential disturbances. Presently whale watching is the only vector of human interaction in Table 16 that is not already being managed towards reduction of the potential impact by existing authorities.

"Southern Residents" Relative to "Northern Residents".

A good method for assessing impacts on Southern resident killer whales also potentially exists in comparisons with the Northern Resident Population; which has shown healthy population growth since the capture era and is potentially approaching historical levels of population size (Bigg *et al.*, 1987; Bain, 1989; Hoyt, 1990; Olesiuk *et al.*, 1990; Ford *et al.*, 1994). Hence, a straight forward strategy for managers is to inventory Southern habitat conditions relative to Northern Resident habitat, and implement programs to mimic "northern" conditions in the Salish Sea.

By compiling a historical inventory for one population the ground work for a comparative analysis has been completed. Similarities and differences provide the basis for identifying causes underlying the Southern Resident population's diminished population growth as compared to the Northern Residents over the last 25 years. This potentially also allows habitat conditions in the north to provide a benchmark for habitat conservation and restoration in the south. In Table 16 every human influence potentially impacting the Southern Resident Community is seen to have occurred for the Northern Resident Community, except at a lower degree of exposure. Unfortunately this "across-the-board" comparison does not narrow down the number of potential impacts that may be contributing to the lower productivity of the Southern Resident population, but it does make it clear that habitat conditions in the north for any of these variables would be a viable initial benchmark for managers.

CONCLUSIONS

Humans presently appear to be the source of almost all the over-riding environmental influences for these killer whales. The nature of human impacts is very different from normal environmental stress on an organism because rather than a single steady or catastrophic extreme, human impacts are often just as chronic or catastrophic, but can also be subtle, specific, and numerous; interfering with the ecology of a management unit in a multifaceted way (Botkin, 1990; Allen and Hoekstra, 1992; Ulanowicz, 1997). The downside of this lies in the complexity of potential outcomes that result from human influences, the upside is that sometimes a whole suite of impacts can be reduced or eliminated with a small modification in human behavior (Leopold, 1949; Holling, 1978; Botkin, 1990; Allen and Hoekstra, 1992).

Human impacts have therefore affected the killer whales in a multitude of ways over time and to varying degrees up to the present. Over the last 100 years these killer whales have had to adapt to changes as quickly as human culture changes, and in a complex patchwork of effects that can unpredictably work synergistically with each other. From a historical perspective it is not realistic to expect that clear cause and effect results for any single variable would ever exist. There are just too many variables. However, in the largest contexts, the history of ecological adaptation for this population of killer whales provides valuable insights on their unique historical predicament.

Chapter 5

Management Options for Salish Sea Resident Killer Whales in the Context of Their Historical Ecology

INTRODUCTION

When managers attempt to redirect human behavior so that ecological conditions for the management unit are more sustainable, it is critical to have some understanding of the management unit's adaptive resiliency. This can be determined from a qualitative understanding of the condition the management unit is in now relative to the conditions it has persisted through in the past. A purely quantitative assessment of the present has no context in terms of time, so it can not fully account for adaptive resiliency. How the management unit will respond to intervention, and which interventions will be most effective, is therefore critically tied to historical context.

Chapter 1 stated that the pragmatic objective for constructing a historical ecology for this population of killer whales is to use the findings to formulate management options that account for their resiliency. The four characteristic types of resiliency that will be the focus of the present discussion were also introduced in this chapter. Chapter 2 developed three indicators of the ecological status of this killer whale population, and in Chapter 3, five vectors of potential human impacts were identified. In Chapter 4 basic trends in a set of twenty indicators of potential human influences were then examined at different time scales to provide a historical context for the whales. In this chapter I place this history in a framework that assesses the resiliency of the management unit and identifies management options that account for this resiliency.

Using Historical Ecology to Assess "Resiliency"

"*Resiliency*", as defined by Holling (1986, p. 296), "*is the ability of a system to maintain its structure and patterns of behavior in the face of disturbance.*" Hardesty defines *resilience* as, "*Processes that act to keep an ecological system from self-destructing, that is, to assure persistence even in the face of fluctuations* (Hardesty, 1977, p. 299)." From these definitions it follows that the history of adaptations by an ecological system, or management unit, is essentially the record of its resiliency (its "persistence"). Embedded in that history, however, are two characteristics that are fundamental to assessing the management unit's overall resiliency: 1) the levels, or scale of adaptive mechanisms employed by the management unit (i.e. various combinations of genetic, physiological, immunological, behavioral and cultural mechanisms), and 2) the cumulative condition of the management unit ("wear and tear" and "wisdom"). The findings of this study do not provide evidence capable of conclusively addressing these aspects of resiliency, but in formulating management options for this killer whale population, these two aspects of resiliency should be given consideration to the degree that they are understood.

Scale of Adaptation

For the present study *adaptation* is defined as: *anything that is changed or changes so as to become suitable to a new or special use, or situation* (after Bonner, 1980). In this definition adaptation is by nature a historical process that accumulates complexity as a result of building upon itself over time (Bertalanffy, 1968; Miller, 1978; Bonner, 1980;

Maynard-Smith, 1988; Kuppers, 1990; Ulanowicz, 1997). Any specific adaptation event can be seen to have a definite "before" and "after"; conditions before the change, conditions of the change, and adapted conditions after the change (Bateson, 1963; 1968; Botkin and Sobel, 1975; Huberman, 1989; Eldridge and Grene, 1992). The conditions before the change are entrained adaptive responses that provide the raw material for the new adaptation.

The way adaptive responses are acquired by a management unit (genetic, physiological, behavioral, cultural, or some combination) makes a difference in the speed and scope of adaptive response the management unit is capable of (Allen and Hoekstra, 1992). This capacity for adaptation will also vary depending upon the type of management unit (population, community, habitat) and the type of environmental change being adapted to (over-harvesting, toxic exposure, behavioral disturbance). Thus, fundamental to any assessment of resiliency, the appropriate scale(s) of adaptive responses for the management unit should be identified for each impact as much as possible (Allen and Hoekstra, 1992; Ingerson, 1994; Winterhalder, 1994).

The suite of adaptive capacities for the Southern Resident population of killer whales is poorly understood at most levels, as indicated by the review in Chapter 2. So, except where there is evidence to the contrary, it will be assumed these killer whales exhibit all the basic physiological, immunological, and behavioral adaptive mechanisms typical for mammals as a Class (Eisenberg, 1981). What is potentially different for killer whales relative to most other mammal species, is their behavioral and cultural capacities for adaptation (Bain, 1989; Osborne, 1990; Whitehead, 1998; Heimlich-Boran and Heimlich-Boran, 1999).

Cultural Adaptation

Bonner defines "culture" as, "*the transfer of information by behavioral means, most particularly by the process of teaching and learning* (Bonner, 1980, pg. 10)." The information transferred in this cultural context generally falls within the realm of guidelines for behavior, and is stored as behavioral traditions within the living social group (Bateson, 1979; Bonner, 1980; Maynard-Smith, 1988; Cavalli-Sforza and Feldman, 1981).

For the present discussion, killer whales are considered to be operating with the capacity for cultural adaptation due to their long life span (Olesiuk *et al.*, 1990), superior learning and memory capacity (Herman, 1991; Hoyt, 1990; 1992b), and apparent social complexity (Norris and Dohl, 1980; Osborne, 1986; S.L. Heimlich-Boran, 1986; Eisenberg, 1986; Waite, 1988; Rose, 1992; Whitehead, 1998; Heimlich-Boran and Heimlich-Boran, 1999). Another attribute of killer whales that has recently been suggested as further indication that they are operating at the cultural scale of adaptation, is the fact they exhibit low diversity of their mitochondrial DNA (Whitehead, 1998). Whitehead's findings on this phenomena in matrilineal odontocetes is the first non-human example of this cultural characteristic, and may further bolster the case for cultural adaptation being important for interpretations of resiliency in the Southern Resident killer whale population.

From a management perspective, beyond potentially providing the management unit with rapid and behaviorally complex adaptive responses, cultural adaptation can also be deceptive because overt behavior will not necessarily be a clear indicator of disturbances. For example, if due to a cultural tradition these killer whales continued to use areas of their habitat despite excessive vessel traffic, sewage, or underwater noise, their adherence to tradition could potentially over-ride what would otherwise be avoidance of noxious environmental conditions. Or, if as a result of their cultural plasticity, the killer whales prey-shift from salmon to, even more toxic, bottomfish, the consequences on their resiliency would also be detrimental.

This potential for some traditions to dominate or over-ride a more resilient adaptation is important for interpreting the killer whale's response to human influences. It is not just a matter of "approach or avoidance" to human impacts, but also includes the killer whale's cultural experience with the impact, and whether overriding traditions in some other sphere motivate them to ignore the impact until it reaches threatening proportions.

Unfortunately, the lack of empirical evidence to test cultural influences in the adaptive responses of these killer whales, or even to conclusively prove they have culture, doesn't leave the manager much to work with. However, to ignore the potential of these characteristics of cultural adaptation in interpretations of resiliency in this killer whale population could be a greater fallacy. Pragmatically, it means the manager should interpret adaptive responses with more caution than they might with non-cultural species, and that they should be open to considering management options that might include cultural adaptation on the part of the management unit.

Cumulative Ecological Condition

The second qualitative characteristic of history that must be accounted for in an assessment of a management unit's resiliency, is its cumulative ecological condition. What is the "wear and tear" on the management unit? Are population levels, or age structure in a state to sustain the population, or to withstand a random catastrophic event such as a Tsunami, an oil spill, a mass stranding, or a disease outbreak? Has the management unit historically adapted to impacts that have now been replaced by ones that appear serious, but are actually less threatening than impacts they survived for decades in the past? In the case of these killer whales this latter example appears to be the case relative to vessel traffic (Chapter 4). It can be seen that these perspectives are potentially critical for accurately assessing the management unit's resiliency, and can only be answered by knowing its history. To Winterhalder (1994, p.40),

> "...knowledge of the history of natural systems is an indispensable part of their scientific analysis. The structural and functional properties of organisms, communities, and ecosystem must be sought in their history because they are only partly revealed in their extant form."

In Chapter 4 the review of trends in available historical information on these killer whales indicates they have withstood major reductions in their population and have acquired a mosaic of human impacts over the last century. It strongly suggests that this threatened* population was well below their historical carrying capacity for decades prior to the capture era. Yet, if interpreted only in terms of the present, the recent population drop that has led to these whales being listed as "threatened", instead indicates a recent impact as the cause of the current decline, and cautiously underestimates the beginning population at less than 150 (Olesiuk *et al.*, 1990).

* Committee on the Status of Endangered Wildlife in Canada (22, April, 1999).

This example clearly demonstrates the importance of a historical perspective, especially if a government mandated management regime is implemented to increase the population of these killer whales so that they are no longer classified as a threatened stock. In what follows, resiliency-based management options and recommendations for this killer whale population will be presented in an attempt to avoid the limited perspective of only considering extant conditions. It is proposed that by drawing upon the historical context developed in Chapter 4, a more robust management approach will be provided for the protection of this threatened stock.

METHODS

In Chapter 1 the objective of adaptive management was identified as: 1) improving the management unit's resiliency for adapting to change, rather than a specifically prescribed stable condition, and 2) maintaining flexible management strategies that are modified depending upon how the system behaves (after: Holling, 1978; 1986; Bateson, 1972; Botkin and Sobel, 1975; Walters, 1986; Duffus and Dearden, 1990; Allen and Hoekstra, 1992; Winterhalder, 1994). To quote Winterhalder (1994, p.40) again:

> "The concept of adaptive management captures some of the policy implications of a scientific commitment to historical ecology. It is an attempt to formulate development and policy tactics that recognize (1) the importance of ecosystem history, (2) uncertainties in our ability to predict ecosystem behavior, and (3) the desirability of focusing on change and resilience rather than attempting to guarantee stability."

Using this framework the current objective is to undertake the first part of this adaptive management process, by identifying the management options within the context of the management unit's historical resiliency.

The four types of historical characteristics of resiliency that were introduced in Chapter 1 (Figure 5), are directly applied to the killer whales in this chapter. These historical characteristics are: 1) *relic impacts,* which are potential impacts that are no longer present, but may account for present conditions; 2) *adapted impacts,* which are potential impacts that have been around long enough for the management unit to have adapted to them; 3) *cumulative impacts,* which are potential impacts that accumulate slowly in the environment or life history of the management unit before exerting environmental resistance; and 4) *new impacts*, potential impacts with which the management unit has not had previous experience. It will be demonstrated that with these four historical characteristics accounted for, the manager can better assess the resiliency of the management unit, focus upon the most critical potential impacts for present conditions, and more specifically identify the most effective scales of management for restorative intervention.

In Table 17 the four categories for the resiliency assessment are listed relative to three sets of characteristics: 1) seven of the primary potential human impacts that were identified and defined in previous chapters, 2) in terms of resiliency-based management benchmarks, and 3) recommended strategies for each of the potential human impacts.

The categories identified in Table 17 are compared in the results as part of two matrices. The first matrix (Table 18) is an assessment based upon the findings presented in Chapter 4. In this table each of the seven potential human impacts are described in terms of the four categories of historical resiliency. The second matrix (Table19) provides

Table 17. Categories for Assessing Southern Resident Killer Whale Resiliency in Relation to Potential Human Impacts

Potential Human Impacts:	Resiliency Assessment	Management Implications
Shootings	Relic Impacts	Proposed Measurable Benchmarks
Captures	Adapted Impacts	Recommended Management Strategies
Toxic Exposure	Cumulative Impacts	
Salmon Depletion	New Impacts	
Secondary Food Depletion		
Surface Disturbance		
Underwater Noise		

recommended benchmarks and management strategies for each of the seven impact categories that follow from the conclusions listed in Table 18.

RESULTS

Resiliency of Southern Resident Killer Whales

In Table 18 seven categories of potential human impact used in this study are described in terms of having *relic* effects, *adapted* effects, *cumulative* effects, or being *new* potential impacts with which the killer whales have not had previous experience. The findings will be presented by following the matrix from left to right for each category of potential human impact.

Shootings and Captures

For shooting and captures the potential *relic impacts* include shootings and resultant killings associated with commercial salmon fisheries from the 1930s to the 1960s, and repeated captures that removed a minimum of 46 individuals from 1964 to 1973 (Olesiuk *et al.*, 1990; Hoyt, 1990). However, perhaps the biggest single impact to these whales came in the 1940s, when local pods were the subjects of military aircraft target practice (Olesiuk *et al.*, 1990), and where whole pods could have been eliminated at

Table 18. An Assessment of the Historical Resiliency of Salish Sea Resident Orcas:

Potential Human Impact	Relic Impacts	Adapted Impacts	Cumulative Impacts	New Impacts
Shootings:	Regularly shot 1930s to mid-1970s. Military target practice (WWII) = reduced population.	Experienced humans killing them with guns from the air, from boats and from shore.	Reduced orca reproductive potential due to small population size and uneven age distribution.	Absent
Captures:	Multiple Captures, est. 48 individuals removed (1962-1973)= reduced population.	Experienced humans capturing them in shallow bays and removing their offspring.	Reduced orca reproductive potential due to small population size and uneven age distribution.	Absent
Toxic Exposure:	Increasing from 1900; military dumping 1940s - 1970s; maximum levels from sediments in the '70s.	Unknown	Toxic loads are still being accumulated at levels that are historical highs, and will continue with the present generations of living orcas.	There is a trend towards source reduction, but the cumulative effects of a life-time of toxic loading are still being added to.
Salmon Depletion:	Nothing that likely impacted their annual salmon intake.	Adjusted feeding strategies to account for seasonally extinct and depleted runs.	The cumulative loss of salmon resources would only recently have started to seasonally affect the orcas, if at all.	Salmon depletion is reaching levels that are potentially affecting their food intake in the winter & spring.
Secondary Food Resource Depletion:	Nothing that likely impacted their annual food intake.	Adjusted feeding strategies to account for seasonally extinct and depleted food patches?	The cumulative loss of secondary fish species reduces the prey options of the orcas when salmon are not avaialable.	Secondary food resources may also be depleted * forcing even more extreme shifts in "prey choice."
Surface Disturbance:	Historically intensive gill net & seiner fishing and a century of increasing vessel traffic.	Learned to manuver through fishing gear, and whale watching traffic without fatal accidents.	Increasing seasonal interference with feeding, resting and socializing behaviors of the orcas.	Vessel density in the immediate vicinity of the orcas is at a historical high, and potentially a stress.
Underwater Noise:	Sporadic military and scientific testing: 1930s to present= interferance w/ senses & comm. ? - hearing loss?	Experienced active military test sites, and oceanographic vessels during acoustic tests.	Cumulative hearing loss, cumulative loss of acuity in communication and echolocation?	Underwater noise in the immediate vicinity of the orcas is at a historical high, and potentially a stress.

* a petition to list Salish Sea herring, hake, ling cod and 2 species of rockfish as "threatened" under the U.S. Endangered Species Act is currently under consideration.

Table 19. Historically Implicated Management Options for Salish Sea Resident Orcas:

Potential Human Impact	Proposed Benchmark	Recommended Management Strategy
Shootings:	No records of shootings.	status quo
Captures:	No records of captures.	status quo
Toxic Exposure:	Elimination of toxic emmissions into the environment..	* Continue to reduce toxic levels in the marine environment. * Longitudinally monitor toxic loads in the orcas by sex and age class from biopsy samples (sample secondary foods).
Salmon Depletion:	Restoration of sustainable year-round wild salmon runs that allow limited human harvest, in addition to the share consumed by the orcas and other wildlife.	* Concentrate on salmon habitat recovery for all exisiting runs. * Focus recovery on salmon runs with winter/spring returns.
Secondary Food Resource Depletion:	Restoration and enhancement of primary ecosystem functions in the Salish Sea as measured by stable trends in species diversity and other ecological indicators.	(Needs more basic research to identify key species)
Surface Disturbance:	Establishment of a 100 meter buffer around around the orcas by all wildlife viewing traffic, and the establishment of larger buffer zones in key locations of the core whale watching areas.	* Reduce surface impacts of vessel-based whale watching. * Cap vessel speeds in narrow channels.
Underwater Noise:	Establishment of a 100 meter buffer around around the orcas, reduce measurable engine noise by all wildlife viewing traffic, and establish quiet zones in key locations.	* Reduce noise impacts of vessel-based whale watching. * Cap allowable ambient noise and work towards future reductions.

once*. The relic impact of all this is a reduced population for up to six decades, with diminished reproductive resiliency, and without a buffer for natural mortality events or additional human impacts.

Adapted impacts relative to shootings and captures could conceivably have included the killer whales making the connection between human shootings and potentially fatal wounds. There is no evidence, however, to suggest the killer whales vigorously avoided being shot at by fisherman. In terms of captures, it was observed that the resident pods avoided being herded into shallow bays for three years after 1973 (D. Goldsberry, pers. com.; author's observation 1975-76), suggesting that they had adapted to avoiding captures without leaving their Salish Sea habitat zones.

The *cumulative* impacts of shootings and captures are a reduced population size that has not exhibited overall growth for almost three decades (Ginnekin and Ellifrit, 1999; Figures 12, 17, and 28-31), and is potentially too small to effectively survive any major mortality events that might be associated with a random catastrophic environmental perturbation. The Southern Resident killer whale pods have been reduced to the point that the breeding population appears unable to sustain growth under the current carrying capacity of their environment. However in terms of *new* impacts, shootings and captures are now non-existent, and not likely to occur again in the foreseeable future.

Toxic Exposure

The *relic* impacts of toxic exposure include nearly 100 years of toxic dumping into the Salish Sea, that peaked in the early 1970s, and has been slowly diminishing over the last two decades (Crecelius *et al.*, 1995; Ross *et al.*, in press; Table 18). However, present toxic dumping in the Salish Sea continues at levels that still pose a potential threat to upper trophic level consumers such as killer whales (Addison, 1989; Calambokidis and

* actual records of the number of whales shot at and killed do not exist, all that is documented is that killer whales were the
targets, and that they were successfully encountered and shot at in Georgia Strait (Olesiuk et al., 1990)..

Baird, 1994; Calambokidis, 1995; Johnston *et al.*, 1996; Reijnders, 1996), and will remain circulating in the marine environment for decades (Ward and Sullivan, 1980; Lyons, 1989; PSWQA, 1992; Crecelius *et al.*, 1995; PSWQAT, 1998). In addition to building up in the environment, individual killer whales who have been alive during the peak of toxic dumping in the Salish Sea will be more likely to be carrying maximally accumulated toxic loads that could start contributing to increased mortalities for decades to come (Addison, 1989; Reijnders, 1996; Ross pers. com.; Ross *et al.*, in press).

Presently there is no information on how killer whales may be physiologically or immunologically adapted to impacts of toxic exposure. Behavioral adaptations to toxic exposure would be negligible, outside of the killer whales consciously rejecting a particularly cancerous bottomfish, or avoiding acute high toxic concentration sites in response to noxious sensory cues.

As mentioned above, *cumulative impacts* from toxic exposure are potentially severe for this killer whale population, because the killer whales feed at high trophic levels where toxic chemicals tend to accumulate and concentrate (Calambokidis *et al.*, 1985; 1990; Addison, 1989; Calambokidis and Baird, 1994; Reijnders, 1996; Baird, in press). Individual killer whales born prior to the mid-1970s presently have the highest body loads of toxic chemicals in the population, and through bio-accumulation these loads will only increase during what remains of their lifetimes, especially for males (Calambokidis, 1995; Ross *et al.*, in press).

Female marine mammals have been demonstrated to dump a large proportion of their fat soluble toxic load into their offspring through gestation and lactation (Addison, 1989; Reijnders, 1996). Consequently, if there are toxic physiological effects on reproductive hormones, digestion, or sensory systems, these impacts would be expected to have accumulated the highest in males alive during the maximum historical levels of toxic dumping (1940-1980). If levels reach the point that they cause fatalities, reduced lifespans, or contribute to reproductive failure, then a period of decline might be expected for this population in the near or immediate future, and it would not be expected to end for several decades (Ross *et al.*, in press.).

New impacts from toxic exposure come from the chemicals that are still being released into the Salish Sea environment, albeit along a decreasing trend (PSWQAT, 1998), and the hundreds of new synthetic chemicals still being manufactured and released into the environment with presently unknown effects (Segal *et al.*, 1980; Lyons, 1989; PSWQAT, 1998). Individual killer whales with the highest historical loads are still adding to their lifetime compliment, and will continue to do so until the release of toxic chemicals into the Salish Sea is virtually eliminated. In terms of resiliency, Southern Resident killer whales are seriously threatened by continued toxic exposure, and their population size is likely not resilient enough to withstand conditions of reduced fertility and increased mortality that might be associated with toxic poisoning.

Food Resource Depletion

Based upon estimates of the historical biomass of the Salish Sea (Kruckeberg, 1991; Levings and Thom, 1994), the historical abundance of salmon (Roos, 1990; Schmitt *et al.*, 1994), and the energetic requirements of the killer whales (Kriete, 1995; Chapter 2), Southern Resident killer whales have not been stressed in terms of access to preferred food resources until very recently, if at all. There are no *relic impacts* in terms of food resource depletion (Table 18). However, over the last century the seasonal abundance of salmon has varied significantly some years (McKervill, 1967; Roos, 1990; Schmitt *et al.*, 1994), and the extinction of specific runs has undoubtedly required the killer whales to adjust their feeding strategies at times. These *adapted impacts* have probably increased with time as Salish Sea salmon resources have diminished; especially in the winter and early spring (Simenstad *et al.*, 1982; Schmitt *et al.*, 1994; Wash. State, 1999). These adaptations have potentially improved the resiliency of this population by providing them with increasing practice at adjusting their feeding strategies to accommodate the loss of traditional food resources, without threatening them with starvation.

Similar to salmon, secondary food species such as bottom fish, Pacific tomcod, and hake, have probably only recently become difficult for the killer whales to find in traditional sites (Schmitt *et al.*, 1994; WDFW, 1999). Given the secondary status of these food resources, it is unlikely there are any *relic impacts* or *adapted impacts*, and it follows that there has not been enough time for any *cumulative impacts* to be experienced by the killer whales. However, the cumulative irreversible loss of habitat that supports salmon and other Salish Sea fish species, signals a potential food resource crisis for these whales that is in the making.

Food resource depletion is a condition that represents a *new potential impact* for these whales (Table 18). Although summer resources of sockeye and pink salmon have been generally increasing over-all in recent years* (Schmitt *et al.*, 1994; 1995; Pacific Salmon Commission, 1995-98), most of the seasonal wild salmon runs of Chinook, coho and chum have been on a steady decline since the mid-1980s (Schmitt *et al.*, 1994; 1995), and several winter-spring stocks have recently been listed as "threatened" under the U.S. Endangered Species Act (Wash. State, 1999). This indicates that the killer whales may now be finding it harder to maintain a steady salmon diet in some seasons, requiring them to rely more on secondary food species. Yet, most other species of marine fishes in the Salish Sea are also declining (Schmitt *et al.*, 1994; 1995; WDFW, 1999), limiting the prey options for the killer whales, and potentially being in amounts insufficient to replace the nutritional requirements previously provided by salmon.

In terms of resiliency, the behavioral and cultural flexibility of these killer whales, and the wide variety of food types the species is capable of consuming, should mean they

* The summer sockeye and pink runs in 1999 are a current exception to this, they are at less than 60% of their estimate on what was not supposed to be a particularly large run, making it the lowest catch on record since 1889 (Pacific Salmon Commission, 1999).

are resilient in the face of food resource depletion. However, that is not to suggest that they would not be stressed during times when they are shifting to new prey items. During these periods of adaptation the population becomes more vulnerable to other stresses, such as disease or toxic poisoning, which their current population size is not at a level to easily withstand. For the Southern Resident killer whales this situation of multiple effects would be increased if they shifted to more resident and/or bottom dwelling species of fish, which have been documented with consistently higher loads of toxic chemicals than resident salmon (Calambokidis *et al.*, 1985; Calambokidis and Baird, 1994; Casillas *et al.*, 1995; West *et al.*, 1995).

Surface Disturbance and Underwater Noise

The primary anthropogenic source of both surface disturbance and underwater noise for Southern Resident killer whales is motorized vessel traffic. Motorized vessel traffic has been increasing slowly for these killer whales since the turn of the century. Other *relic impacts* of surface disturbance included intensive commercial fishing with gillnets at the turn of the century, that leveled off to about half the number of boats after the 1940s, and has been dropping steadily over the last decade (Figures 54 & 56). Rarely were there any historical reports about the killer whales becoming entangled in fishing gear, or avoiding areas where fishing operations were under way, even when the killer whales were being shot at.

Relic impacts from underwater noise, other than those associated with vessel traffic, potentially include extreme periods of insonification associated with military testing, and scientific seismic surveys. Close exposure to these activities could theoretically have resulted in hearing loss in some individuals (Richardson *et al.*, 1995), but no historical records exist to support this, and recent studies suggest clear impacts from these intense sound sources are not readily measurable (Miller and Willis, 1997; Bain, 1999).

In terms of *adapted impacts* (Table 18), although there is not a sufficient baseline to directly compare past and present conditions, it can be argued that all the killer whales alive today have lived with vessel impacts of surface disturbance and underwater noise their entire lives. Current observations on the behavior of these killer whales supports the idea that they are behaviorally well adapted to vessel activities (Osborne, 1991; Phillips and Baird, 1993; Burgen and Otis, 1995; Williams, 1998). Historically, the lack of reported incidents of killer whales getting entangled in gear or interacting with vessels (Scheffer and Slipp, 1948), indicates they have apparently learned how to avoid collisions, entanglements, and painful noise thresholds without noticeably altering their use of traditional habitat areas. Their persistence despite intensive commercial fishing operations and vessel traffic patterns is a testament to their resilience in this area of behavioral adaptation.

Potential *cumulative impacts* from surface disturbance and underwater noise include increasing seasonal interference with feeding, resting and socializing behaviors in relation to whale watching traffic in recent years (Table 18). Potential *cumulative impacts* from underwater noise include hearing loss, and interference with echolocation and social communication (Myerberg, 1990; Bain and Dahlheim, 1993; Richardson *et al.*, 1995; Reeves *et al.*, 1996; Gordon and Moscrop, 1996; Miller and Willis, 1997; Bain,1999). These are impacts that could become worse as a result of the killer whales behaviorally adapting to these activities, because they might be physiologically habituating to the disturbance levels, and inadvertently exposing themselves to hearing damage and loss of foraging and reproductive efficiency (Richardson *et al.*, 1995; Reeves *et al.*, 1996). In terms of present findings however, these potential impacts are purely theoretical, and preliminary findings would suggest that the whales are very resilient in this arena, and are not exhibiting any indications of cumulative impact (Miller and Willis, 1997; Bain,1999).

The *new impacts* associated with surface disturbance and underwater noise are all the result of the recent increase in vessel-based whale watching (Table 18, Figures 53 to 56). Presently whale watching has created historical maximums in vessel density around the whales (Osborne, 1991; 1998; Figures 53 to 56), leading to potential surface disturbance and underwater noise at sustained levels not previously experienced by these whales. Although their apparent resiliency for these human impacts appears high historically, empirical evidence of impacts on these whales is still severely lacking at this point (Miller and Willis, 1997; Bain,1999). From a management perspective surface disturbance and underwater noise are therefore good candidates for precautionary management and further research.

Management Options for Southern Resident Killer Whales

In Table 19 the same seven categories of potential human impacts described in Table 18, are reviewed in relation to management options. First each category is described in terms of a potentially measurable benchmark that can be used as an indicator that the impact is being reduced or eliminated (Table 19). Then the management strategy recommended in order to reach the benchmark is proposed relative to the historical assessment presented so far.

For shootings and captures the benchmark is a complete absence of any shootings or captures, which is simply a continuation of the status quo (Table 19). The benchmark for toxic exposure is the elimination of measurable toxic emissions into the Salish Sea environment, and the recommended management strategy is to continue to reduce toxic emissions and to monitor the whales and their food resources to determine when the accumulation of further toxic substances has stopped (Calambokidis and Baird, 1994; Baird, 1999; Ross *et al.*, in press).

The benchmarks for food resource depletion are measurable increases in year round salmon resources, and other indicator species of the food web that supports the killer whales (Table 19). The management recommendations are to continue to reduce harvest, and concentrate on restoration of salmon habitat, with a focus on wild runs that return to the inland waters in the Winter and Spring when the whales appear to need them the most (Figure 15). In terms of secondary food resources, management must first concentrate on improving the basic understanding about which species are actually involved, and in what proportion of their diet, and then establish programs to facilitate the protection and enhancement of these species.

The benchmarks for surface disturbance and underwater noise are all related to whale watching, and focus upon measurable implementation of existing guidelines for 100 meter buffers around the whales at all times. Both benchmarks also call for the existence of small marine protected areas. To mitigate surface disturbances, geographic areas along coastlines where no vessel-based whale watching is allowed are proposed as a means of providing the killer whales with a refuge from the boat traffic. Similarly for mitigating underwater noise, marine protected areas that are "quiet zones" would be established, where boats must be stationary with their engines off. The degree to which the whales use these areas after they are established can be compared with the baseline data on movements (Figures 22, 24 and 34; and Olson, 1998), allowing these marine protected areas to potentially serve as an experimental demonstration of just how disturbing these proposed impacts are.

Beyond enforcing the 100 meter/yard buffer around whales currently in the Canadian/U.S. whale watching guidelines, and establishing special protection zones, these impacts can also be addressed through more general management of their ambient sources (Table 19). In the case of surface disturbance, implementing speed limits of vessels in certain zones could reduce the likelihood of collisions*, and a limit on the number of boats allowed in close proximity for whale watching could reduce crowding around the killer whale's breathing space at the surface. In the case of underwater noise, industry standards could be established that require quieter water-based transportation, and whale watching boats could be encouraged to reduce the amount of time they leave their engines running during whale watching.

DISCUSSION

The Hidden Effects of Cumulative Experience

Logically, if individual killer whales carry a lifetime of memories of their contacts with humans, then this may affect the way they behave in subsequent encounters. Extreme changes in one-on-one contacts between individual killer whales and humans, from being shot at and captured to being mobbed by whale watchers, should lead to change in habitat use at some level. How much individual experiences are then integrated into the behavior of the group as a whole is unknown, though many of the killer whales currently living in the study area have been alive long enough to have experienced large transitions in the nature of one-on-one interactions with people.

A 70 year old killer whale matriarch born in the early 1930s (e.g. the individual killer whale known as J-8; Ford *et al.*, 1994; Center for Whale Research, 1998), would have started her life during the early domination of modern North American culture upon the Salish Sea marine ecosystem (Kruckeberg, 1991; Yates, 1992; Levings and Thom, 1994). As suggested by the historical assessment presented here, the human impacts during this era amounted to occasional encounters with small numbers of deadly humans,

* Unpublished data collected by The Whale Museum's Whale Hotline and Soundwatch Boater Education Program have documented up to 10 minor incidents of whale watching boat collisions, (i.e. "bumpings") with the orcas since the 1980s. In no case were there any indications of injuries to either boats or whales.

but the habitat provided sufficient salmon and pristine water quality. Over J-8's life time came more frequent deadly encounters with larger numbers of hostile humans, including military target practice when J-8 was a juvenile, regular shooting encounters over the next two decades, culminating in a third decade of repeated captures and the removal of what were possibly some of her offspring.

As the findings in Chapter 4 suggest, these acute impacts would have been accented by an underlying condition of slowly increasing toxic exposure from sites of chronic point source pollution, increasing ambient noise pollution, and the gradual elimination of favored salmon runs. During the last two decades, except for hostility from humans, all these variables have increased in influence or leveled off at a historical extreme. Now the predatory hostility from humans has been replaced with predatory curiosity from whale watchers. This has logically increased the noise pollution, and disturbances associated with vessels crowding around the immediate surfacing habitat of the killer whales; such as engine exhaust, and the need to engage in collision avoidance.

But what has been J-8's response to all this? In no instance is it clear how the killer whales have actually adapted to these historical changes in their environment. Even when the impacts on the killer whales can be specifically identified (e.g. shootings, captures, acute high density vessel traffic) the adaptive responses of the whales do not appear to be overtly exhibited in terms of surface behavior or lack of site tenacity. The persistence of these pods in their seasonal return to the same areas, and continued tolerance of zones of high human activity, provides no observable basis for concluding they are being impacted, with the exception of their mortality and fertility rates. This lack of clear response in the behavior of the killer whales to logical impacts is more likely a testament to their adaptive "resiliency", as opposed to a lack of adaptive response, but without measurable evidence it must remain as speculation.

The details of the killer whale's behavioral response have potentially hidden the adaptations that undoubtedly have occurred, so until those details are made accessible to historians and managers, the substance of killer whale behavioral/cultural adaptations will remain elusive. The next challenge for research into the resiliency of this killer whale population is therefore, to assess the capacities of the communication system that mediates their behavior.

CONCLUSIONS

The present study has attempted to describe the historical relationship of the Southern Resident Community of killer whales with their habitat and with the humans of the Salish Sea, and from this history, to develop a systematic list of management options that account for the current resiliency of this population of whales (Tables 18 and 19). Returning to the conceptual framework for this dissertation that was outlined in Chapter 1 (Figures, 1 and 2), the next step in an adaptive management scenario is to actually begin manipulating environmental variables (mostly human) towards sustainability of the management unit, and to do so using flexible management strategies that are modified according to the outcomes of management interactions (Holling, 1978; 1986; 1992; Duffus and Dearden, 1990; Allen and Hoekstra, 1992; Winterhalder, 1994; Ulanowicz, 1997). This next phase, however, is beyond the scope of this dissertation and remains as the task ahead, but will hopefully be more effectively undertaken as the result of the contributions provided by this study.

Short of actually implementing adaptive management programs, a primary objective of this dissertation was to demonstrate that the Southern Resident Community of killer whales are an ideal model for applying historical ecology in an adaptive management context. It has been repeatedly suggested in this study that an important aspect of the applicability of historical ecology for assessing the management of this particular species is due to their ecological characteristics of being generalist social predators, with a long lifetime of learning, and the inter-generational influences of cultural adaptation. Further detailed research on their adaptive capacities, especially in terms of social communication, should provide an important opportunity to examine the evolution of mammalian cultural adaptive mechanisms in general, and especially in relation to how human communication may be unique relative to other mammals.

From the perspective of adaptive resiliency associated with culture, it can be seen that the killer whale's behavioral adaptive response to environmental resistance must be sophisticated, and so it is logical to assume that they would easily accommodate things like whale watching, fishing gear entanglement, and prey shifting. However, this also indicates that most of the behavioral adaptations undertaken by these killer whales will more often involve modifications to deep socio-cultural patterns about behavior that are without overtly measurable responses. The implications for this potential cultural phenomena is that, except in the case of acute catastrophic impacts, it is probably invalid to try and measure overt behavior as a reliable indicator of environmental impacts in these whales. Instead, managers should stick to basic biological measures such as recruitment to evaluate management success, and manage potential behavioral impacts, such as vessel traffic, in a precautionary fashion that does not attempt to set behavioral benchmarks.

In this study it has also been shown that without a historical perspective, the types of management decisions applied to these killer whales could differ significantly; resulting in widely varying outcomes and allocations of management resources. Consideration must be given to the historical context in terms of how experience builds preparedness in the management unit, and how historical circumstances may have reduced resiliency. In Table 20 these management considerations for the Southern Resident Community killer whales are enumerated. In terms of management each one of the points in Table 20 has implications for pragmatic strategies that would help protect and restore this killer whale population, and suggests that the differences between "Northern" and "Southern" resident communities can serve as a preliminary benchmark for what needs to be minimally improved in the Salish Sea.

First, the lack of predation and attack upon humans, means that these killer whales pose no direct threat to us, and are behaviorally capable of adapting to direct human

Table 20. Management Considerations for Southern Resident Killer Whales in the Context of their Historical Ecology

1) Southern Resident killer whales are not a threat to humans as a predator.

2) Southern Resident killer whales are very site tenacious, and will tolerate a high amount of human activities without leaving the area.

3) Southern Resident killer whales have had a low population size for at least several decades.

4) Southern Resident killer whales are susceptible to the accumulation of toxic levels of persistent pollutants in the marine environment, and may only now be exhibiting mortalities and reproductive failures associated with long-term bioaccumulation.

5) Southern Resident killer whales appear tolerant of commercial fishing operations, vessel traffic and underwater noise, but present levels of exposure are apparently at a historical maximum.

6) The predominant food resource of Southern Resident killer whales is year-round salmon, indicating:
   a) that the continuous take of salmon by the killer whales needs to be accounted for in any management plans aimed at protecting and restoring salmon stocks.
   b) that salmon recovery programs will significantly enhance habitat quality for the killer whales.

contact. Second, the traditional site tenacity of these killer whales means the Salish Sea is important habitat for them, and it can not be assumed the killer whales will indicate stress by slowly disappearing, or that they will seek resources very far out of their range to replace the resources of the Salish Sea. Third, their low population size and unstable population growth, means they probably are in need of protection if they are to survive as a breeding population. This means that environmental restoration and enhancement in any of the vectors of environmental resistance identified in this dissertation should improve their chances for survival.

The fourth, fifth, and sixth findings listed above, provide the areas where Northern and Southern residents presently exhibit their major differences in habitat conditions in terms of degree of anthropogenic influence. The levels of persistent toxic chemicals in the Salish Sea, particularly in terms of bottomfish, are historically higher for the Southern residents (Calambokidis, 1995; Jarmen *et al.*, 1996; Ross *et al.*, in press). The levels of whale watching vessel traffic (Osborne, 1991; Burgen and Otis, 1995; Baird *et al.*, 1998) and the loss of year-round salmon runs (Appleby and Doty, 1995; Wash. State, 1999) are also higher in the Salish Sea. In the latter case, the reduction in salmon increases the likelihood of seasonal consumption of bottom fish (Calambokidis and Baird, 1994; Baird, 1999), which would likely increase the exposure of the killer whales to higher levels of persistent toxic chemicals due to the higher levels in these more resident food species (Lyons, 1989; Crecelius *et al.*, 1995; Johnson *et al.*, 1995; Casillas *et al.*, 1995; West and O'Neill, 1995).

To manage these three conditions in favor of the Southern Resident Community, and using relative conditions for the Northern Resident Community as a model, three basic management strategies are apparent: 1) further reduce the release of persistent toxic chemicals into the Salish Sea (which has been happening over the last two decades);

2) increase the year-round abundance of salmon (which is very recently a major mandate of government programs in both the U.S. and Canada); and 3) reduce the levels of vessel traffic and underwater noise associated with whale watching (which has been seeing active attention from community-based adaptive management programs; Baird *et al.*, 1998; Osborne, 1998).

The high levels of vessel traffic around the killer whales is the only salient difference between habitat conditions for the "Northern" and "Southern" residents that presently does not have an existing regulatory management program aimed at directing habitat conditions in the South to be more like those in the North. However, new programs recently initiated by the Canadian Department of Fisheries and Oceans (DFO; Malcolm, 1999) are moving in the direction of implimenting community generated regulations. Whale watching vessel traffic is the only area of potential impact that is not already in the process of reduction, though the whale watching user groups are at the forefront of precautionary, cooperative, self-regulation (Osborne, 1991; 1998). Hence, whale watching is an obvious place to initially focus adaptive management.

The Southern Resident Community may be unfortunate in being the most urban extant population of killer whales in the world, but they are under the care of two of the most wealthy and technologically advanced nations in history. If they can't survive as urban killer whales in the Salish Sea, the long-term prospects for their species on a more densely human-populated planet are not promising. With their apparent cultural capacities, however, these killer whales should theoretically be one of the species with behavioral resiliency that is capable of withstanding global anthropogenic change; as long as they can physiologically survive the present era of toxic exposure and low food supply. From this perspective, if society is really committed to having the Southern Resident Killer Whale Community survive, then over the next two decades these whales should be afforded all the protection possible, and societal changes aimed at restoring resiliency to the Salish Sea ecosystem as a whole must be initiated and followed through with.

Literature Cited:

Addison, R.F., 1989.
Organochlorines and Marine Mammal Reproduction. CANADIAN JOURNAL OF FISHERIES AND AQUATIC SCIENCES, 46:360-368.

Allen, T.F.H., and T.B. Starr, 1982.
HIERARCHY: PERSPECTIVES FOR ECOLOGICAL COMPLEXITY. Chicago, Univ. Chicago Press.

Allen, T.F.H., and T.W. Hoekstra, 1992.
TOWARDS A UNIFIED ECOLOGY. New York, Columbia University Press.

Amante-Helweg, V., 1996.
Ecotourists' Beliefs and Knowledge About Dolphins and the Development of Cetacean Ecotourism, AQUATIC MAMMALS, 22.2:131-40.

Andrews, J.T., P.T. Davis, W.N. Mode, H. Nichols, and S.K. Short, 1981.
Relative Departures in July Temperatures in Northern Canada for the Past 6,000 yr. NATURE, 289:164-167.

Appleby, A.E., and D.C. Doty, 1995.
Status and Trends in the Survival and Distribution of Resident Coho and Chinook Salmon in Puget Sound, Washinton. In: PUGET SOUND RESEARCH '95 PROCEEDINGS VOL. 2., Olympia, WA, Puget Sound Water Quality Authority, pp.882-892.

Aronoff, S., 1989.
GEOGRAPHIC INFORMATION SYSTEMS: A MANAGEMENT PERSPECTIVE. Ottawa, WDL Publications.

Ayers, R.U., 1994.
INFORMATION, ENTROPY, AND PROGRESS: A NEW EVOLUTIONARY PARADIGM. New York, American Institute of Physics Press.

Bain, D.E., 1986.
Acoustic Behavior of *Orcinus*: Sequences, Periodicity, Behavioral Correlates and an Automated Technique for Call Classification. In: B.C. Kirkevold and J.S. Lockard (Eds.), BEHAVIORAL BIOLOGY OF KILLER WHALES, New York, A.R. Liss, pp. 335-371.

Bain, D.E., 1989.
AN EVALUATION OF EVOLUTIONARY PROCESSES: STUDIES OF NATURAL SELECTION, DISPERSAL, AND CULTURAL EVOLUTION IN KILLER WHALES (*Orcinus orca*). Ph.D. Thesis, University of California Santa Cruz, Santa Cruz, CA.

Bain, D.E., 1999.
Effects of Airgun Noise on Marine Mammals: Responses as a Function of Received Sound Level and Distance. Addendum to USGS/MMS Draft Report on the S.H.I.P.S. Project.

Bain, D.E., B. Kriete, and M. Dahlheim, 1993.
Hearing Abilities of Killer Whales (*Orcinus orca*). JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, 94(2):1829.

Bain, D.E., and M.E. Dahlheim, 1994.
Effects of Masking Noise on Detection Thresholds of Killer Whales. In: T.R. Loughlin, (Ed.), MARINE MAMMALS AND THE EXXON VALDEZ, New York, Academic Press, pp. 243-256.

Baird, R.W., 1994.
FORAGING BEHAVIOUR AND ECOLOGY OF TRANSIENT KILLER WHALES (*Orcinus orca*). Ph.D. Thesis, Simon Fraser University, Burnaby, B.C.

Baird, R.W., 1999.
Status of Killer Whales in Canada. Contract report to the COMMITTEE ON THE STATUS OF ENDANGERED WILDLIFE IN CANADA (C.O.S.E.W.I.C), Ottawa.

Baird, R.W., In Press.
The Killer Whale - Foraging Specializations and Group Hunting. In: J. Mann, R. Connor, P. Tyack and H. Whitehead (Eds.), CETACEAN SOCIETIES: FIELD STUDIES OF DOLPHINS AND WHALES, Chicago, Univ. Chicago Press.

Baird, R.W., and P.J. Stacey, 1988.
Variation in Saddle Patch Pigmentation in Populations of Killer Whales (Orcinus orca) frpm British Columbia, Alaska snd Washington State. CANADIAN JOURNAL OF ZOOLOGY, 66:2582-2585.

Baird, R.W., P.A. Abrams, and L.M. Dill, 1992.
Possible Indirect Interactions Between Transient and Resident Killer Whales: Implications for the Evolution of Foraging Specializations in the Genus *Orcinus*. OECOLOGIA, 89:125-132.

Baird, R.W., and L.M. Dill, 1996.
Ecological and Social Determinants of Group Size in *Transient* Killer Whales. BEHAVIORAL ECOLOGY, 7:408-416.

Baird, R.W., L.M. Dill, and M.B. Hanson, 1998.
Diving Behavior of Killer Whales. Abstract of a paper presented at the WORLD MARINE MAMMAL CONFERENCE, Monaco, January, 1998.

Baird, R.W., R.E. Otis and R.W. Osborne, 1998.
Killer Whale Watching Off Southern Vancouver Island. Abstract of a paper presented at the Whale Watching Research Workshop, WORLD MARINE MAMMAL CONFERENCE, Monaco, January, 1998.

Baird, R.W. and H. Whitehead, In Prep.
The Link Between Social Organization and Ecology: Association Patterns of Mammal-Eating Killer Whales Off Vancouver Island. Unpublished draft manuscript.

Baker, R. G., 1983.
Holocene vegetational history of the western United States. In: H.E. Wright (Ed.), LATE-QUATERNARY ENVIRONMENTS OF THE UNITED STATES, VOL. 2: THE HOLOCENE, Minneapolis, University of Minnesots Press, pp. 109-127.

Balcomb, K.C., 1995.
Orca Survey 1995 Final Report. Unpublished report to EARTH WATCH, Boston, MA.

Balcomb, K.C., 1997.
Orca Survey 1997 Final Report. SPIRIT OF THE SOUND, Vol. 10, No. 3-4.

Balcomb, K.C., J.R. Boran, R.W. Osborne, and N.J. Haenel, 1980.
Observations of Killer Whales (*Orcinus orca)* in Greater Puget Sound, State of Washington, NTISPB80-224728, U.S. DEPT. OF COMMERCE, Springfield, VA.

Balcomb, K.C., and M.A. Bigg, 1986.
Population Biology of the Three Resident Killer Whale Pods in Puget Sound and off Southern Vancouver Island. In: B.C. Kirkevold and J.S. Lockard (Eds.), BEHAVIORAL BIOLOGY OF KILLER WHALES, New York, A.R. Liss, pp. 85-96.

Barrett-Lennard, L. 1992.
ECHOLOCATION IN WILD KILLER WHALES (*Orcinus orca*). M.Sci. Thesis, University of British Columbia, Vancouver, B.C.

Barrett-Lennard, L. , J.K.B. Ford, and K.A. Heise, 1996.
The Mixed Blessing of Echolocation: Differences in Sonar Use by Fish-Eating and Mammal-Eating Killer Whales. ANIMAL BEHAVIOR, 51:553-565.

Barrows, H.H., 1923.
Geography as Human Ecology. ANNALS OF THE ASSOCIATION OF AMERICAN GEOGRAPHERS, 13:1-14.

Bateson, G., 1963.
The Role of Somatic Change in Evolution, JOURNAL OF EVOLUTION, 17:529-39.

Bateson, G. 1966.
Problems in Cetacean and Other Mammalian Communication. In: K.S. Norris (Ed.), WHALES, DOLPHINS AND PORPOISES, Berkeley, CA, University of California Press, pp.569-599.

Bateson, G., 1968.
Effects of Conscious Purpose on Human Adaptation. Reprinted in: G. Bateson (1972), STEPS TO AN ECOLOGY OF MIND, New York, Chandler Publishing Company, pp. 440-447.

Bateson, G., 1972.
The Logical Categories of Learning and Communication. In: G. Bateson, STEPS TO AN ECOLOGY OF MIND, New York, Chandler Publishing Company, pp. 279-308.

Bateson, G., 1974.
Observations of a Cetacean Community. In: J.McIntyre (Ed.), MIND IN THE WATERS, New York, Charles Scribner's Sons, Sierra Club Books, 146-165.

Bateson, G., 1979.
MIND AND NATURE: A NECESSARY UNITY. New York, E.P. Dutton.

Beamish, R.J., and D.R. Bouillon, 1993.
Pacific Salmon Production Trends in Relation to Climate. CANADIAN JOURNAL OF FISHERIES AND AQUATIC SCIENCES, 50: 1002-1016.

Beamish, R.J., and B. Riddell, 1995.
Factors Affecting the Production of Chinook and Coho Salmon in the Strait of Georgia. PUGET SOUND RESEARCH '95 PROCEEDINGS VOL. 2., Olympia, WA, Puget Sound Water Quality Authority, pp. 891-892.

Bertalaniffy, L. von, 1968.
GENERAL SYSTEM THEORY: FOUNDATIONS, DEVELOPMENT, APPLICATIONS. New York, George Braziller.

Bigg, M.A., 1982.
An Assessment of Killer Whales (*Orcinus orca*) off Vancouver Island, British Columbia. REPORT OF THE INTERNATIONAL WHALING COMMISSION, 32:655-666.

Bigg, M.A., and A.A. Wolman, 1975.
Live Capture Killer Whale (*Orcinus orca*) Fishery in British Columbia and Washington. JOURNAL OF THE FISHERIES RESEARCH BOARD OF CANADA, 32:1213-1222.

Bigg, M.A., I.B. MacAskie, and G. Ellis, 1976.
Abundance and Movements of Killer Whales off Eastern and Southern Vancouver Island with Comments on Management. Unpublished report, St. Anne de Bellevue, Quebec, ARCTIC BIOLOGICAL STATION.

Bigg, M.A., G.M. Ellis, J.K.B. Ford, and K.C. Balcomb, 1987.
KILLER WHALES: A STUDY OF THEIR IDENTIFICATION, GENEALOGY, AND NATURAL HISTORY. Nanaimo, B.C., Phantom Press and Publishers.

Bigg, M.A., P.F. Olesiuk, G.M. Ellis, J.K.B. Ford, and K.C. Balcomb, 1990a.
Social Organization and Genealogy of Resident Killer Whales (*Orcinus orca*) in the Coastal Waters of British Columbia and Washington State. In: P.S. Hammond, S.A. Mizroch, and G.P. Donovan (Eds.), Individual Recognition of Cetaceans: Through the Use of Photoidentification and Other Techniques to Estimate Population Parameters, REPORT OF THE INTERNATIONAL WHALING COMMISSION, SPECIAL ISSUE 12, Cambridge,U.K., pp. 383-406.

Bigg, M.A., G.M. Ellis, J.K.B. Ford, and K.C. Balcomb, 1990b.
Feeding Habits of the Resident and Transient Forms of Killer Whale in British Columbia and Washington State. Abstract of a paper given at the THIRD INTERNATIONAL ORCA SYMPOSIUM, Victoria, British Columbia.

Bigler, B.S., D.W. Welch, and J.H. Helle, 1996.
A Review of Size Trends Among North Pacific Salmon (*Oncorhynchus spp.*). CANADIAN JOURNAL OF FISHERIES AND AQUATIC SCIENCES, 53: 455-465.

Bilsky, L.J., 1980.
Historical Ecology: Fundamental Factors. In: L.J. Bilsky (Ed.), HISTORICAL ECOLOGY: ESSAYS ON ENVIRONMENT AND SOCIAL CHANGE, Port Washington, NY, Kennikat Press.

Black, N.A., A. Sshulman-Janiger, R.L. Ternullo, and M. Guerro-Ruiz, 1996.
A Killer Whale Catalog for California and Western Mexico. NATIONAL MARINE FISHERIES SERVICE, SOUTHWEST FISHERIES CENTER/NOAA, Contract No. 40JGNF500356.

Blane, J.M., and R. Jaackson, 1996.
The Impact of Ecotourism Boats on the St. Lawerence Beluga Whales. ENVIRONMENTAL CONSERVATION, 21(3):267-269.

Boesch, C., 1996.
The Emergence of Cultures Among Wild Chimpanzees. In: W.G. Runciman, J. Maynard-Smith, and R.I.M. Dunbar (Eds.), EVOLUTION OF SOCIAL BEHAVIOR PATTERNS IN PRIMATES AND MAN, Oxford, Oxford University Press.

Bonner, J.T., 1980.
THE EVOLUTION OF CULTURE IN ANIMALS. Princeton, N.J., Princeton University Press.

Borden, C.E., 1968.
Prehistory of the Lower Mainland. In: A.H. Siemens (Ed.), Lower Fraser Valley: Evolution of a Cultural Landscape, Vancouver, B.C., GEOGRAPHICAL SERIES, 9:9-26.

Botkin, D.B., 1990.
DISCORDANT HARMONIES: A NEW ECOLOGY FOR THE TWENTY-FIRST CENTURY. New York, Oxford University Press.

Botkin, D.B., and M.J. Sobel, 1975.
Stability in Time-Varying Ecosystems, AMERICAN NATURALIST, 109:.625-46.

Box, G.E.P., and G.M. Jenkins, 1976.
TIME-SERIES ANALYSIS: FORECASTING AND CONTROL. Oakland, CA, Holden-Day.

Brault, S., and H. Caswell, 1993.
Pod-Specific Demography of Killer Whales (*Orcinus orca*). ECOLOGY, 74:1444-1454.

Brown, L, and J.F. Downhower, 1988.
ANALYSES IN BEHAVIORAL ECOLOGY. Saunderland, MA, Sinauer Assoc., Inc.

Burgner, R.L., 1991.
Life History of Sockeye Salmon (*Oncorhynchus nerka*) In: C. Groot and L. Margolis (EDs.), PACIFIC SALMON LIFE HISTORIES, Vancouver, B.C., UBC Press, pp. 1-117.

Burgen, M. and R.E. Otis, 1995.
The Behavior of Boats Around Killer Whales (*Orcinus orca*) in Haro Strait, WA. Abstract of a paper presented at the ELEVENTH BIENNIAL CONFERENCE ON THE BIOLOGY OF MARINE MAMMALS, Orlando, FL.

Butler, R.W., 1980.
The Concept of a Tourist Area Cycle of Evolution: Implications for Management of Resources. CANADIAN GEOGRAPHER, 24:5-12.

Butzer, K.W., 1982.
ARCHAEOLOGY AS HUMAN ECOLOGY. Cambridge, Cambridge University Press.

Calambokidis, J,. 1995.
Contaminants in Puget Sound Marine Mammals: Temporal, Spatial, and Species-Related Patterns. In: PUGET SOUND RESEARCH '95 PROCEEDINGS VOL. 2., Olympia, WA, Puget Sound Water Quality Authority, pp. 901-908.

Calambokidis, J., and R.W. Baird, 1994.
Status of Marine Mammals in the Strait of Georgia, Puget Sound and the Juan de Fuca Strait and Potential Human Impacts. CANADIAN TECHNICAL REPORTS IN FISHERIES AND AQUATIC SCIENCES, 1948:282-300.

Calambokidis, J., G.H. Steiger, J.C. Cubbage, and R.L. DeLong, 1985.
Biology of Puget Sound Marine Mammals and Marine Birds: Population Health and Evidence of Pollution Effects. NOAA TECHNICAL MEMORANDOM NOS, OMA 18.

Calambokidis, J., K.M. Langelier, P.J. Stacey, and R.W. Baird, 1990.
Environmental Contaminants in Killer Whales from Washington, British Columbia and Alaska. Abstract of a paper presented at the THIRD INTERNATIONAL ORCA SYMPOSIUM, Victoria, B.C.

Canada , Ministry of Industry, 1996.
CANADA YEARBOOK 97, Ottawa.

Carl, G.C., 1946.
A School of Killer Whales Stranded at Estevan Point. B.C. PROVINCIAL MUSEUM OF NATURAL HISTORY AND ANTHROPOLOGY REPORT (1945). pp. 21-28.

Carl, G.C., 1959.
Albinistic Killer Whales in British Columbia. B.C. PROVINCIAL MUSEUM OF NATURAL HISTORY AND ANTHROPOLOGY REPORT (1959). pp. 29-36.

Capra, F., 1982.
THE TURNING POINT: SCIENCE, SOCIETY AND THE RISING CULTURE. New York, Bantum Books.

Caro, T.M., and M.D. Hauser, 1992.
Is There Teaching in Non-Human Animals? QTLY. REV. BIOL. 67:151-174.

Casillas, E., M.R. Arkoosh, E. Clemons, T. Hom, D. Misitano, T.K. Collier, J.E. Stein, and U. Varanasi, 1995. Chemical Contaminant Exposure and Physiological Effects in Outmigrant Juvenile Chinook Salmon from Urban Estuaries of Puget Sound, Washington. In: PUGET SOUND RESEARCH '95 PROCEEDINGS VOL. 2., Olympia, WA, Puget Sound Water Quality Authority, pp. 657-665.

Cavalli-Sforza, L.L., and M.W. Feldman, 1981.
CULTURAL TRANSMISSION AND EVOLUTION: A QUANTITATIVE APPROACH. Princeton, N.J., Princeton University Press.

Cavanagh-Ford, 1984.
Culture and nature on the Northwest Coast. WATERS, 7:6-14.

Center for Whale Research, 1998.
FIELD GUIDE TO THE ORCAS OF THE PACIFIC NORTHWEST. Center for Whale Research, Friday Harbor, WA.

Chasen, D.J., 1981.
THE WATER LINK: A HISTORY OF PUGET SOUND AS A RESOURCE. Seattle, Univ. Wash. Press.

Cherfas, J., 1990.
The Fringe of the Ocean - Under Siege from Land. SCIENCE, 248(4952):163-165.

Clark, C.W., 1985.
BIOECONOMIC MODELING AND FISHERIES MANAGEMENT. New York, Wiley-Interscience.

Costanza, R., 1991.
Goals, Agenda and Policy Recommendations for Ecological Economics. In: R. Costanza (Ed.), ECOLOGICAL ECONOMICS: THE SCIENCE AND MANAGEMENT OF SUSTAINABILITY, New York, Columbia University Press, pp. 1-21.

C.O.S.E.W.C., 1999.
Status of Killer Whales (Orcinus orca) in Canada. Report of the Committee on the Status of Endangered Wildlife in Canada, April, 1999.

Cox, C.B., and P.D. Moore, 1985.
BIOGEOGRAPHY: AN ECOLOGICAL AND EVOLUTIONARY APPROACH, Fourth Edition, Oxford, Blackwell Scientific Publications.

Crecelius, E.A., N.S. Bloom, and G. Massoth, 1983.
Sediment Mass Balance for the Main Basin of Puget Sound. EARTH AND OCEAN SCIENCES, TRANSACTIONS OF THE AMERICAN GEOPHYSICAL UNION, 64:1104.

Crecelius, E.A., V.I. Cullinan, L.F. Lefkovitz, and C. Peven, 1995.
Historical Trends in the Accumulation of Chemicals in Puget Sound. In: PUGET SOUND RESEARCH '95 PROCEEDINGS VOL. 2., Olympia, WA, Puget Sound Water Quality Authority, pp. 825-831.

Cronon, W., 1983.
CHANGES IN THE LAND: INDIANS, COLONISTS, AND THE ECOLOGY OF NEW ENGLAND. New York, Hill and Wang.

Crumley, C.L., 1994.
Historical Ecology: A Multidimensional Ecological Orientation. In: C.L. Crumley (Ed.), HISTORICAL ECOLOGY: CULTURAL KNOWLEDGE AND CHANGING LANDSCAPES, Sante Fe NM, School of American Research Press, (Seattle, Univ. Wash. Press distrb.) pp. 1-16.

Dahlheim, M.E., 1997.
A Photographic Catalog of Killer Whales, *Orcinus orca*, from the Central Gulf of Alaska to the Southeastern Bering Sea. NOAA TECHNICAL REPORT, NMFS 131.

Dahlheim, M.E., and C.O. Matkin, 1994.
Assessment of Injuries to Prince William Sound Killer Whales. In: T.R. Loughlin (Ed.), MARINE MAMMALS AND THE EXXON VALDEZ, San Diego, Academic Press.

Dahlheim, M.E., D.K. Ellifrit, and J.D. Swenson, 1997.
Killer Whales of S.E. Alaska: A Catalog of Photo-Identified Individuals. Seattle, Day Moon Press.

DeFran, R.H., and K. Pryor, 1980.
The Behavior and Training of Cetaceans in Captivity. In: L.M. Herman (ed.), CETACEAN BEHAVIOR: MECHANISMS AND FUNCTIONS, New York, John Wiley and Sons, pp. 319-362.

DFO, 1997.
B.C. Lighthouse Station Sea Surface Temperature Data. Institute of Ocean Sciences, Fisheries and Oceans, Canada: *http://www.ios.bc.ca/ios/sos/bcsop/lights.htm*.

DFO, 1999.
AN ALLOCATION POLICY FOR PACIFIC SALMON: A NEW DIRECTION, The Fourth in a Series of Papers from Fisheries and Oceans, Canada.

DOE, 1998.
Vessel Entries and Transits for Washington Waters: VEAT '98. WDOE 99-251.

Diamond, J., 1997.
GUNS, GERMS, AND STEEL: THE FATES OF HUMAN SOCIETIES. New York, W.W. Norton & Co.

Downton, M.W., and K.A. Miller, 1998.
Relationships Between Alaskan Salmon Catch and North Pacific Climate in Interannual and Interdecadal Time Scales. CANADIAN JOURNAL OF FISHERIES AND AQUATIC SCIENCES, 55: 2255-2265.

Drucker, P., 1965.
CULTURES OF THE NORTH PACIFIC COAST. Scranton, PA, Chandler Publishing, Co.

Duffus, D.A., 1988.
NON-CONSUMPTIVE USE AND MANAGEMENT OF CETACEANS IN BRITISH COLUMBIA COASTAL WATERS. Ph.D. Thesis, University of Victoria, Victoria, B.C., 339 p.

Duffus, D.A., and P. Dearden, 1990.
Non-Consumptive Wildlife-Oriented Recreation: A Conceptual Framework. BIOLOGICAL CONSERVATION, 53:213-231.

Duffus, D.A., and P. Dearden, 1992.
Whales, Science and Protected Area Management in British Columbia, Canada. GEORGE WRIGHT FORUM , 9(3-4):79-87.

Duffus, D.A., and P. Dearden, 1993.
Recreational Use, Valuation, and Management, of Killer Whales (*Orcinus orca*) on Canada's Pacific Coast. ENVIRONMENTAL CONSERVATION, 20:149-156.

Duffus, D.A., and R.W. Baird, 1995.
Killer Whales, Whalewatching and Management: A Status Report. WHALEWATCHER, 29(2):14-17.

Dumond, D.E., 1978.
Alaska and the Northwest Coast. In: J.D. Jennings (Ed.), ANCIENT NATIVE AMERICANS, San Francisco, W.H. Freeman and Company, pp. 43-94.

Durning, 1991.
Asking How Much Is Enough. In: L.R. Brown (Ed.) STATE OF THE WORLD 1991. New York, W.W. Norton & Co., pp. 153- 169.

Ehrlich, P.R., A.H. Ehrlich, and J.P. Holdren, 1977.
ECOSCIENCE: POPULATION, RESOURCES, ENVIRONMENT. San Francisco, CA, W.H. Freeman and Company.

Eisenberg, J.F., 1981.
THE MAMALIAN READIATIONS: AN ANALYSIS OF TRENDS IN EVOLUTION, ADAPTATION AND BEHAVIOR. Chicago, The University of Chicago Press.

Eisenberg, J.F., 1986.
Dolphin Behavior and Cognition: Evolutionary and Ecological Aspects. In: R.J. Schusterman, J.A. Thomas, and F.G. Wood (Eds.), DOLPHIN COGNITION AND BEHAVIOR: A COMPARATIVE APPROACH, Lawerance Erlbaum Assoc., Hillsdale, N.J., pp. 261-270.

Eldridge, N., and M. Grene, 1992.
INTERACTIONS: THE BIOLOGICAL CONTEXT OF SOCIAL SYSTEMS. New York, Columbia University Press.

Fagan, B.M., 1987.
THE GREAT JOURNEY: THE PEOPLING OF ANCIENT AMERICA. New York, Thames and Hudson, Inc.

Felleman, F.L., J.R. Heimlich-Boran, and R.W. Osborne, 1991.
Feeding Ecology of the Killer Whale, (*Orcinus orca*). In: K.W. Pryor and K.S. Norris (Eds.), DOLPHIN SOCIETIES:DISCOVERIES AND PUZZLES, Berkeley, University of California Press, 113-147.

Fleming, R.H., 1977.
Time and Change in Puget Sound: The Study, Use and Management of Puget Sound. WASHINGTON SEA GRANT, Seattle, WA.

Ford, J.K.B., 1984.
CALL TRADITIONS AND DIALECTS OF KILLER WHALES (*Orcinus orca*) IN BRITISH COLUMBIA. Ph.D. Thesis, Vancouver, University of British Columbia.

Ford, J.K.B., 1989.
Acoustic Behaviour of Resident Killer Whales (*Orcinus orca*) Off Vancouver Island, British Columbia. CANADIAN JOURNAL OF ZOOLOGY, 67:727-745.

Ford, J.K.B., 1990.
Vocal Traditions Among Resident Killer Whales (*Orcinus orca*) in Coastal Waters of British Columbia. CANADIAN JOURNAL OF ZOOLOGY, 69:1454-1483.

Ford, J.K.B., and A.B. Morton, 1990.
Vocal Behavior and Dialects of Transient Killer Whales in Coastal Waters of British Columbia, California, and Southeast Alaska. Abstract of the THIRD INTERNATIONAL ORCA SYMPOSIUM, Victoria, B.C.

Ford, J.K.B., G.M. Ellis, and L.M. Nichol, 1992.
KILLER WHALES OF THE QUEEN CHARLOTTE ISLANDS: A PRELIMINARY STUDY OF THE ABUNDANCE, DISTRIBUTION, AND POPULATION IDENTITY OF *Orcinus orca* IN THE WATERS OF HAIDA GWAII. South Moresby/Gwaii Haana National Park Reserve, Queen Charlotte City, B.C., Canadian Park Service.

Ford, J.K.B., G.M. Ellis, and K.C. Balcomb, 1994.
KILLER WHALES: THE NATURAL HISTORY AND GENEALOGY OF *ORCINUS ORCA* IN BRITISH COLUMBIA AND WASHINGTON STATE. Vancouver, UBC Press.

Ford, J.K.B., G.M. Ellis, and A.B. Morton, 1995.
Diet Specialization of Resident and Transient Killer Whales in Coastal British Columbia and Adjacent Waters. Abstract ELEVENTH BIENNIAL CONFERENCE ON THE BIOLOGY OF MARINE MAMMALS, Orlando, FL.

Ford, J.K.B., G.M. Ellis, L.G. Barrett-Lennard, A.B. Morton, R.S. Palm, and K.C. Balcomb, 1998. Dietary Specialization in Two Sympatric Populations of Killer Whales (*Orcinus orca*) in Coastal British Columbia and Adjacent Waters. CANADIAN JOURNAL OF ZOOLOGY, 76(8): 1456-1471.

Ford, J.K.B., and G.M. Ellis, 1999.
TRANSIENTS: MAMMAL HUNTING KILLER WHALES. Vancouver, U.B.C. Press.

Francis and Hare, 1994.
Decadal-Scale Regime Shifts in the Large Marine Ecosystems of the Northeast Pacific: A Case for Historical Science. FISHERIES OCEANOGRAPHY, 3(4):279-291.

Garrett, H., 1995.
ORCAS IN OUR MIDST. Friday Harbor, WA, Center for Whale Research.

Ginneken, A.M. van, D.K. Ellifrit, and R.W. Baird, 1998.
ORCA SURVEY FIELD GUIDE TO TRANSIENTS OF THE HARO STRAIT REGION. Friday Harbor, WA., Center for Whale Resarch.

Ginneken, A.M. van, and D.K. Ellifrit, 1999.
OFFICIAL ORCA SURVEY FIELD GUIDE: ORCAS OF THE PACIFIC NORTHWEST, THE SOUTHERN RESIDENT COMMUNITY (Summer 1999 Edition). Friday Harbor, WA., Center for Whale Research.

Ginneken, A.M. van, D.K. Ellifrit, and K.C. Balcomb, in preparation.
THE ALL WHALE CATALOG OF THE SOUTHERN RESIDENTCOUMMUNITY OF ORCAS. Friday Harbor, WA, Center for Whale Research.

Goodwin, R.L., 1982.
RECREATONAL BOATING IN WASHINGTON'S COASTAL ZONE: THE MARKET FOR MOORAGE. Economics of Marine Recreation (R/CZ-8), Seattle, Washington Sea Grant, Institute for Marine Studies, University of Washington.

Gordon, J, and A. Moscrop, 1996.
Underwater Noise Pollution and Its Significance for Whales and Dolphins. In: M.P. Simmonds and J.D. Hurchinson (Eds.), THE CONSERVATION OF WHALES AND DOLPHINS, New York, John Wilely & Sons, Inc., pp. 281-320.

Gould, S.J., 1977
ONTOGENY AND PHYLOGENY. Cambridge MA, Harvard University Press.

Gregson, H., 1970.
A HISTORY OF VICTORIA. Vancouver, B.C., J.J. Douglas, LTD.

Griffin, E.I., 1982.
NAMU: QUEST FOR THE KILLER WHALE. Seattle, Gryphon West.

Groerner, S.J., 1993.
CHAOS AND THE EVOLVING ECOLOGICAL UNIVERSE: A STUDY IN THE SCIENCE AND HUMAN IMPLICATIONS OF A NEW WORLD HYPOTHESIS. New York, Gordon and Breach.

Groot, C., and L. Margolis, 1991.
Preface. In: C. Groot and L. Margolis (EDs.), PACIFIC SALMON LIFE HISTORIES, Vancouver, B.C., UBC Press, pp. IX-XI.

Haenel, N.J., 1986.
General Notes on the Behavioral Ontogeny of Puget Sound Killer Whales and the Occurrence of Allomaternal Behavior. In: B.C. Kirkevold and J.S. Lockard (Eds.), BEHAVIORAL BIOLOGY OF KILLER WHALES, New York, A.R. Liss, pp. 285-301.

Hardesty, D.L., 1977.
ECOLOGICAL ANTHROPOLOGY. New York, John Wiley & Sons.

Hardin, G, 1986.
Cultural Carrying Capacity: A Biological Approach to Human Problems. BIOSCIENCE, 36:599-606.

Hardy, J.T., and L. Antrim, 1988.
Distribution and Biological Eggects of Sea-Surface Contaminants in Puget Sound. PROCEEDINGS: FIRST ANNUAL MEETING ON PUGET SOUND RESEARCH, Vol. 2, Seattle, WA, Puget Sound Water Quality Authority, p. 400-408.

Hassan, F.A., 1994.
Population Ecology and Civilization in Ancient Egypt. In: C.L. Crumley (Ed.), HISTORICAL ECOLOGY: CULTURAL KNOWLEDGE AND CHANGING LANDSCAPES, Sante Fe, NM, School of American Research Press, (Seattle, Univ. Wash. Press distrb.) pp. 155-82.

Hayner, N.S., 1929.
Ecological Succession in the San Juan Islands. PUBLICATIONS OF THE AMERICAN SOCIOLOGICAL SOCIETY, Vol. 23:81-92.

Healey, M.C., 1991.
Life History of Chinook Salmon (*Oncorhynchus tshawytcha*). In: C. Groot and L. Margolis (EDs.), PACIFIC SALMON LIFE HISTORIES, Vancouver, B.C., UBC Press, pp. 311-393.

Heard, W.R., 1991.
Life History of Pink Salmon, (*Oncorhynchus gorbuscha*) In: C. Groot and L. Margolis (EDs.), PACIFIC SALMON LIFE HISTORIES, Vancouver, B.C., UBC Press, pp. 119-229.

Heimlich-Boran, J.R., 1986.
Fishery Correlation's with the Occurrence of Killer Whales in Greater Puget Sound. In: B.C. Kirkevold and J.S. Lockard (Eds.), BEHAVIORAL BIOLOGY OF KILLER WHALES, New York, A.R. Liss, pp. 113-131.

Heimlich-Boran, J.R., 1988.
Behavioral Ecology of Killer Whales (*Orcinus orca*) in the Pacific Northwest, CANADIAN JOURNAL OF ZOOLOGY, 66:565-579.

Heimlich-Boran, S.L., 1986.
Cohesive Relationships Among Puget Sound Killer Whales. In: B.C. Kirkevold and J.S. Lockard (Eds.), BEHAVIORAL BIOLOGY OF KILLER WHALES, New York, A.R. Liss, pp. 251-284.

Heimlich-Boran, J.R., and S.L. Heimlich-Boran, 1999.
Social Learning in Cetaceans. In: H.Box and K.Gibson (Eds.), MAMMALIAN SOCIAL LEARNING: COMPARATIVE & ECOLOGICAL PERSPECTIVES, Cambridge, Cambridge University Press.

Herman, L.M., 1986.
In: R.J. Schusterman, J.A. Thomas, and F.G. Wood (Eds.), DOLPHIN COGNITION AND BEHAVIOR: A COMPARATIVE APPROACH, Hillsdale, N.J., Lawerance Erlbaum Assoc., pp. 221-252.

Herman, L.M., 1991.
What the Dolphin Knows, or Might Know, in its Natural World. In: K.W. Pryor and K.S. Norris (Eds.), DOLPHIN SOCIETIES:DISCOVERIES AND PUZZLES, Berkeley, University of California Press, pp. 349-363.

Herman, L.M., and W.M. Tavolga, 1980.
The Communication Systems of Cetaceans. In: L.M. Herman (Ed.), CETACEAN BEHAVIOR: MECHANISMS AND FUNCTIONS, New York, John Wiley and Sons, pp.149-209.

Heyning, J.E., 1988.
Presence of Solid Food in a Young Calf Killer Whale (*Orcinus orca*). MARINE MAMMAL RESEARCH, 4:68-71.

Heyning, J.E., and M.E. Dahlheim, 1988.
Orcinus orca. MAMMALIAN SPECIES (Journal of Mammalogy), 304:1-9.

Hoelzel, A.R., 1993.
Foraging Behaviour and Social Group Dynamics in Puget Sound Killer Whales. ANIMAL BEHAVIOUR, 45:581-591.

Hoelzel, A.R., and R.W. Osborne, 1986.
Killer Whale Call Characteristics: Implications for Cooperative Foraging Strategies. In: B.C. Kirkevold and J.S. Lockard (Eds.), BEHAVIORAL BIOLOGY OF KILLER WHALES, New York, A.R. Liss, pp. 373-403.

Hoelzel, A.R., and G.A. Dover, 1991.
Genetic Differentiation Between Sympatric Killer Whale Populations. JOURNAL OF HEREDITY, 66:191-195.

Hoelzel, A.R., M.E. Dahlheim, and S.J. Stern, 1998.
Genetic variation among killer whales (Orcinus orca) in the Eastern North Pacific, and genetic differentiation between foraging specialists. JOURNAL OF HEREDITY, 89:121.

Holling, C.S., 1973.
Resilience and Stability of Ecological Systems. ANNUAL REVIEW OF ECOLOGY AND SYSTEMATICS, 4:1-23.

Holling, C.S., 1978.
Overview and Conclusions. In: C.S. Holling (Ed.), ADAPTIVE ENVIRONMENTAL ASSESSMENT AND MANAGEMENT, Chichister, John Wiley & Sons.

Holling, C.S., 1986.
The Resilience of Terrestrial Ecosystems: Local Surprise and Global Change. In: W.C. Clark and R.E. Munn (Eds.), SUSTAINABLE DEVELOPMENT OF THE BIOSPHERE. Cambridge, Cambridge University Press, pp. 292-317.

Holling, C.S., 1992.
Cross-scale Morphology, Geometry, and Dynamics of Ecosystems. ECOLOGICAL MONOGRAPHS, 62(4):447-502.

Holt, S.J., 1969.
The Food Resources of the Ocean. SCIENTIFIC AMERICAN, 221(3): 178-194.

Holt, S.J. and L.M. Talbot, 1978.
New Principals for the Conservation of Wild Living Resources. WILDLIFE MONOGRAPHS, No. 59, 33 p.

Horner, R.R., 1995.
Overview of the Puget Sound Wetlands and Stormwater Management Research Program. In: PUGET SOUND RESEARCH '95 PROCEEDINGS VOL. 2., Olympia, WA, Puget Sound Water Quality Authority, pp. 141-145.

Hoyt, E., 1981.
THE WHALE CALLED KILLER. Canada, Camden House.

Hoyt, E., 1990.
ORCA: THE WHALE CALLED KILLER, 3rd Edition. Canada, Camden House.

Hoyt, E., 1992a.
Whale Watching Around the World, INTERNATIONAL WHALE BULLETIN, No. 7.

Hoyt, E., 1992b. THE PERFORMING ORCA - WHY THE SHOW MUST STOP. England, Whale and Dolphin Consrvation Society.

Hoyt, E., 1995.
THE WORLDWIDE VALUE AND EXTENT OF WHALE-WATCHING:1995. Bath, U.K., Whale and Dolphin Conservation Society.

Huberman, B.A., 1989.
The Adaptation of Complex Systems. In: B. Goodman and P. Saunders (Eds.), THEORETICAL BIOLOGY: EPIGENETIC AND EVOLUTIONARY ORDER FROM COMPLEX SYSTEMS, Edinburgh, U.K., Edinburg University Press.

Ingerson, A.E., 1989.
The Uses of History by Ecologists. JOURNAL OF FOREST HISTORY, 33 Special Issue, 114p.

Ingerson, A.E., 1994.
Tracking and Testing the Nature/Culture Dichotomy in Practice. In: C.L. Crumley (Ed.), HISTORICAL ECOLOGY: CULTURAL KNOWLEDGE AND CHANGING LANDSCAPES, Sante Fe, NM, School of American Research Press, (Seattle, Univ. Wash. Press distrb.) pp. 43-66.

Innes, S., D.M. Lavigne, W.M. Earle and K.M. Kovacs, 1987.
Feeding Rates of Seals and Whales. J.ANIMAL ECOLOGY, 56:115-130.

Jacobson, J.K., 1986.
The Behavior of Orcinus orca in the Johnstone Strait, British Columbia. In: B.C. Kirkevold and J.S. Lockard (Eds.), BEHAVIORAL BIOLOGY OF KILLER WHALES, New York, A.R. Liss, pp. 135-186.

Jacobson, J.K., 1990.
ASSOCIATIONS AND SOCIAL BEHAVIORS AMONG KILLER WHALES (*Orcinus orca*) IN THE JOHNSTONE STRAIT, BRITISH COLUMBIA, 1979-1986. M.A. Thesis, Humbolt State University.

Janik, V.M., and P.J.B. Slater, 1997.
Vocal Learning in Mammals. ADVANCES IN THE STUDY OF BEHAVIOR, 26:59-99.

Jarman, W.M., R.J. Norstrom, D.C.G. Muir, B. Rosenberg, M. Simon, and R.W. Baird, 1996. Levels of Organochlorine Compounds, Including PCDDs and PCDFs, in Blubber Of Cetaceans from the West Coast of North America. MARINE POLLUTION BULLITEN, 32:425-435.

Jefferson, T.A., P.J. Stacey, and R.W. Baird, 1991.
A Review of Killer Whale Interactions with Other Marine Mammals: Predation to Co-Existence. MAMMAL REVIEW, 21:151-180.

Jefferson, T.A., B. Wursig, and D. Fertl, 1992.
Cetacean Detection and Responses to Fishing Gear. In: J.A. Thomas, R.A. Kastelein, and P.E. Nachtigall (eds.), MARINE MAMMAL SENSORY SYSTEMS, New York, Plenum Press.

Jerison, H.J., 1973.
EVOLUTION OF THE BRAIN AND INTELLIGENCE. New York, Academic Press.

Jerison, H.J., 1986.
The Perceptual Worlds of Dolphins. In: R.J. Schusterman, J.A. Thomas, and F.G. Wood (Eds.), DOLPHIN COGNITION AND BEHAVIOR: A COMPARATIVE APPROACH, Hillsdale, N.J., Lawerance Erlbaum Assoc., pp. 141-166.

Johnson, L.L., J.T. Landahl, K. Kardong, and B.H. Horness, 1995.
Chemical Contaminants, Fishing Pressure, and Population Growth of Puget Sound English Sole (*Pleuronectes vetulus*). In: PUGET SOUND RESEARCH '95 PROCEEDINGS VOL. 2., Olympia, WA, Puget Sound Water Quality Authority, pp. 686-698.

Johnston, R.J., 1987.
GEOGRAPHY AND GEOGRAPHERS: ANGLO-AMERICAN HUMAN GEOGRAPHY SINCE 1945, Third Edition. London, Edward Arnold, 304 p.

Johnston, P.A., R.L. Stringer, and D. Santillo, 1996.
Cetaceans and Environmental Pollution: The Global Concerns. In: M.P. Simmonds and J.D. Hurchinson (Eds.), THE CONSERVATION OF WHALES AND DOLPHINS, New York, John Wiley & Sons, Inc., pp. 219-262.

Kastelein, R.A., and N. Vaughan, 1989.
Food Consumption, Body Measurements and Weight Changes of a Female Killer Whale (*Orcinus orca*). AQUATIC MAMMALS, 15:18-21.

Kennedy, S., 1996.
Infectious Disseases of Cetacean Populations. In: M.P. Simmonds and J.D. Hurchinson (Eds.), THE CONSERVATION OF WHALES AND DOLPHINS, New York, John Wiley & Sons, Inc., pp.333-353.

Kimerling, A.J., and P.L. Jackson, 1985.
ATLAS OF THE PACIFIC NORTHWEST, Seventh Edition. Corvalis, OR, Oregon State University Press.

Kirkevold, B.C., and J.S. Lockard (Eds.), 1986.
BEHAVIORAL BIOLOGY OF KILLER WHALES., New York, Alan R. Liss, Inc.

Knox, J.C., 1983.
Responses of River Systems to Holocene Climates. In: H.E. Wright (Ed.), LATE-QUATERNARY ENVIRONMENTS OF THE UNITED STATES, VOL. 2: THE HOLOCENE, Minneapolis, University of Minnesots Press, pp. 26-41.

Kormondy, E.J., 1969.
CONCEPTS OF ECOLOGY. Engelwood Cliffs, N.J., Prentice-Hall, Inc.

Kriete, Birgit, 1995.
BIOENERGETICS IN THE KILLER WHALE, *ORCINUS ORCA*. Ph.D. Thesis, Department of Animal Science, University of British Columbia, Vancouver, B.C.

Kruckeberg, A.R. 1991.
THE NATURAL HISTORY OF PUGET SOUND COUNTRY. Seattle, University of Washington Press.

Kruse, S., 1991.
The Interactions Between Killer Whales and Boats in Johnstone Strait, B.C. In: K.W. Pryor and K.S. Norris (Eds.), DOLPHIN SOCIETIES:DISCOVERIES AND PUZZLES, Berkeley, University of California Press.

Kuppers, B-O, 1990.
INFORMATION AND THE ORIGIN OF LIFE. Cambridge, MA, The MIT Press.

Leopold, A., 1949.
A SAND COUNTY ALMANAC. London, Oxford University Press.

Leopold, L.B., 1971.
A PROCEDURE FOR EVALUATING ENVIRONMENTAL IMPACT. U.S. Geological Survey Circular 645, Wash., D.C., U.S. Govt. Print. Off.

Leopold, L.B., 1974.
The Use of Data in Environmental Impact Assessment. In: T.G. Dickert, and K.R. Domeny (Eds.), ENVIRONMENTAL IMPACT ASSESSMENT:GUIDELINES AND COMMENTARY, Berkeley, CA, Univ. Calif. Press.

Levings, C.D., and R.M. Thom, 1994.
Habitat Changes in Georgia Basin: Implications for Resource Management and Restoration. In: R.C.H. Wilson, R.J. Beamish, F.A. Aitkens and J. Bell (Eds.), Review of the Marine Environment and Biota of the Strait of Georgia, Puget Sound and Juan de Fuca Strait. CANADIAN TECHNICAL REPORTS IN FISHERIES AND AQUATIC SCIENCES, No. 1948, p. 330-351.

Lockard, J.S., 1986.
Research Status of Orcinus orca: What Is Not Known About Its Behavioral Biology. In: B.C. Kirkevold and J.S. Lockard (Eds.), BEHAVIORAL BIOLOGY OF KILLER WHALES, New York, A.R. Liss, pp. 407-442.

Loomis, J.B., and R.G. Walsh, 1986.
Assessing Wildlife and Environmental Values in Cost-Benefit Analysis: State of the Art, JOURNAL OF ENVIRONMENTAL MANAGEMENT, 22:125-31.

Lyons, B., 1989.
DIRE STRAITS: POLLUTION IN THE STRAIT OF GEORGIA, BRITISH COLUMBIA, CANADA. Vancouver, B.C., Greenpeace.

MacAskie, I. B., 1966.
Unusual Example of Group Behavior by Killer Whales (*Orcinus rectipinna*). MURRELET, 47(2): 38.

Macdonald, R.W., and E.A. Crecelius, 1994.
Marine Sediments in the Strait of Georgia, Juan de Fuca Strait and Puget Sound: What can They Tell us about Contamination? In: R.C.H. Wilson, R.J. Beamish, F.A. Aitkens and J. Bell (Eds.), Review of the Marine Environment and Biota of the Strait of Georgia, Puget Sound and Juan de Fuca Strait. CANADIAN TECHNICAL REPORTS IN FISHERIES AND AQUATIC SCIENCES, No. 1948, p.101-134.

Mangel, M., 1985.
DESCISION AND CONTROL IN UNCERTAIN RESOURCE SYSTEMS. New York, Academic Press.

Mangel, M., and C.W. Clark, 1988.
DYNAMIC MODELING IN BEHAVIORAL ECOLOGY. Princeton, N.J., Princeton University Press.

Mantua, N.J., S.R. Hare, Y. Zang, J.M. Wallace and R.C. Francis, 1997.
A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production. BULLETIN OF THE AMERICAN METEOROLOGICAL SOCIETY, 78:1069-1079.

Margalef, R., 1969.
Diversity and Stability: A Practical Proposal and a Model of Interdependence. BROOKHAVEN SYMPOSIUM IN BIOLOGY, 22:25-37.

Marquardt, W.H., 1994.
The Role of Archaeology in Raising Environmental Consciousness: An Example from Southwest Florida. In: C.L. Crumley (Ed.), HISTORICAL ECOLOGY: CULTURAL KNOWLEDGE AND CHANGING LANDSCAPES, Sante Fe, NM, School of American Research Press, (Seattle, Univ. Wash. Press distrb.) pp. 203-222.

Marsh, G.P., 1864 (reprinted: 1965).
MAN AND NATURE: OR PHYSICAL GEOGRAPHY AS MODIFIED BY HUMAN NATURE, D. Lowehthal (Ed.) 1965 Edition, Oxford, Oxford University Press.

Martinez, D.R., and E. Klinghammer, 1970.
The Behavior of the Killer Whale, Orcinus orca: A Review of the Literature. ZEITSCHRIFT FUR TIERPSYCHOLOGIE, 27:828-839.

Matkin, C.O., and S. Leatherwood, 1986.
General Biology of the Killer Whale, *Orcinus orca*: A Synopsis of Knowledge. In: B.C. Kirkevold and J.S. Lockard (Eds.), BEHAVIORAL BIOLOGY OF KILLER WHALES, New York, A.R. Liss, pp. 35-68.

Matkin, C.O., G.M. Ellis, M.E. Dahlheim, and J. Zeh, 1994.
Status of Killer Whales in Prince William Sound, 1985-1992. In: T.R. Loughlin (Ed.), MARINE MAMMALS AND THE EXXON VALDEZ, New York, Academic Press, pp. 141-162.

May, R. M., 1973.
STABILITY AND COMPLEXITY IN MODEL ECOSYSTEMS. Princeton, Princeton University Press.

Maynard Smith, J., 1988.
Evolutionary Progress and Levels of Selection. In: M.H. Nittecki (Ed.), EVOLUTIONARY PROGRESS, Chicago, Univ. Chicago Press, pp. 219-230.

Mayo, C., R. Bowman, R.W. Osborne, W.J. Richardson, P. Tyack, and G.Vequist, 1989.
Report of the Panel on the Effects of Whale Watching. In: N. Atkins and S.L. Swartz (Eds.), PROCEEDINGS OF THE WORKSHOP TO REVIEW AND EVALUATE WHALE WATCHING PROGRAMS AND MANAGEMENT NEEDS Washington D.C., U.S. National Marine Fisheries Service, NOAA and the Center for Marine Conservation, pp 20-24.

McKervill, H.W., 1967.
THE SALMON PEOPLE: THE STORY OF CANADA'S WEST COAST SALMON FISHING INDUSTRY. Vancouver, B.C., Gray's Publishing, LTD.

McMillan, A.D., 1988.
NATIVE PEOPLES AND CULTURES OF CANADA: AN ANTHROPOLOGICAL OVERVIEW. Vancouver, Douglas & McIntyre.

McNeill, W.H., 1971.
A WORLD HISTORY. Oxford, Oxford University Press.

Merilees, W., 1985.
The Humpback Whale in Georgia Strait. WATERS, Vol. 8.

Miller, J.G., 1978.
LIVING SYSTEMS. New York, McGraw-Hill Book Company.

Miller, P.J., and P.M. Willis, 1997.
MONITORING THE EFFECTS OF THE HARO STRAIT FRONTAL DYNAMICS EXPERIMENT ON MARINE MAMMAL ABUNDANCE, DISTRIBUTION, AND BEHAVIOR, INCLUDING RESULTS OF THE MITIGATION PROGRAM. Unpublished Preliminary Report to the National Marine Fisheries Service, Seattle, 20 p.

Mitchell, B., 1989.
GEOGRAPHY AND RESOURCE ANALYSIS, 2nd Edition. New York, John Wiley and Sons.

Morton, A.B., 1990.
A Quantitative Comparison of the Behaviour of Resident and Transient Forms of the Killer Whale off central British Columbia coast In: P.S. Hammond, S.A. Mizroch, and G.P. Donovan (Eds.), Individual recognition of Cetaceans: Through the Use of Photoidentification and Other Techniques to Estimate Population Parameters, Cambridge,U.K., REPORT OF THE INTERNATIONAL WHALING COMMISSION, SPECIAL ISSUE 12, pp. 245-24.

Moss, C.W., 1988.
ELEPHANT MEMORIES: THIRTEEN YEARS IN THE LIFE OF AN ELEPHANT FAMILY. New York, William Morrow.

Myrberg, A.A., Jr., 1990.
The Effects of Man-Made Noise on the Behavior of Marine Animals. ENVIRONMENT INTERNATIONAL, 16:575-586.

Nasser, C., 1992.
Beyond the Border: Environmental Management in British Columbia and Washington. U.S. Environmental Protection Agency, TECHNICAL REPORT OF THE ENVIRONMENTAL PROTECTION AGENCY. EPA 910/9-91-038.

Nebergall, W.H., H.F. Holtzclaw, Jr., and W.R. Robinson, 1980.
GENERAL CHEMISTRY, 6th Edition. Lexington, MA., D.C. Heath and Co.

Nehlsen, W., J.E. Williams, and J.A. Lichatowich, 1991.
Pacific Salmon at the Crossroads: Stocks at Risk from California, Oregon, Idaho, and Washington. FISHERIES, 15(2):4-21.

Newton, J.A., 1995.
El Nino weather conditions reflected in Puget Sound temperatures and salinities. PUGET SOUND RESEARCH '95: PROCEEDINGS, VOL. 2, Olympia, WA, Puget Sound Water Quality Authority, pp. 979-991.

Nichol, L.M., and D.M. Shackleton, 1996.
Seasonal movements and foraging behavior of notrhern resident killer whales (*Orcinus orca*) in relation to the inshore distribution of salmon (Oncorhynchus spp.) in British Columbia. CANADIAN JOURNAL OF ZOOLOGY, 74:983-991.

Norris, K.S., 1974.
THE PORPOISE WATCHER. New York, W.W. Norton.

Norris, K.S., and T.P. Dohl, 1980.
The Structure and Function of Cetacean Schools. In: L.M. Herman (ed.), CETACEAN BEHAVIOR: MECHANISMS AND FUNCTIONS, New York, John Wiley and Sons, pp. 211-261.

NWAFC, NOAA, 1977.
Mean Caloric Values of Eastern North Pacific Food Fish. Food Sciences Exhibit report, Northwest and Alaska Fisheries Center, NMFS, NOAA, DOC.

Odum, E.P., 1963.
THE FUNDAMENTALS OF ECOLOGY, Philadelphia, W. Saunders.

Odum, E.P., 1969.
The Strategy of Ecosystem Development. SCIENCE 164:262-270.

Odum, H.T., 1988.
Self-Organization, Transformity, and Information. SCIENCE, 242-1132-1139.

Olesiuk, P.F., M.A. Bigg, and G.M. Ellis, 1990.
Life History and Population Dynamics of Resident Killer Whales (Orcinus orca) in the Coastal Waters of British Columbia and Washington State. In: P.S. Hammond, S.A. Mizroch, and G.P. Donovan (Eds.), Individual recognition of Cetaceans: Through the Use of Photoidentification and Other Techniques to Estimate Population Parameters, Cambridge, U.K REPORT OF THE INTERNATIONAL WHALING COMMISSION, SPECIAL ISSUE 12.

Olson, Jean M., 1998.
TEMPORAL AND SPATIAL DISTRIBUTION PATTERNS OF SIGHTINGS OF SOUTHERN COMMUNITY AND TRANSIENT ORCAS IN THE INLAND WATERS OF WASHINGTON AND BRITISH COLUMBIA. M.S. Thesis, Huxley College of Environmental Studies, Western Washington University, Bellingham, WA.

O'Riordan, T., 1971.
PERSPECTIVES ON RESOURCE MANAGEMENT., London, Pion.

Osborne, R.W., 1986.
A Behaviour Budget of Puget Sound Orca, In: B.C. Kirkevold and J.S. Lockard (Eds.), BEHAVIORAL BIOLOGY OF KILLER WHALES. New York, Alan R. Liss, Inc., pp. 211-250.

Osborne, R.W., 1990.
A Review of Potential Cultural Adaptations Documented in Killer Whales (*Orcinus orca)*. Abstract of a paper given at the THIRD INTERNATIONAL ORCA SYMPOSIUM, Victoria, B.C.

Osborne, R.W., 1991.
Trends in Killer Whale Movements, Vessel Traffic, and Whale Watching in Haro Strait. PROCEEDINGS OF PUGET SOUND RESEARCH '91, Seattle, WA., Puget Sound Water Quality Authority, pp.672-688.

Osborne, R.W., 1996.
Preliminary Assesment of Potential Impacts of Personal Water-Craft ("Jet Skis") on Marine Wildlife in the San Juan Islands. Unpublished report to the San Juan County Board of County Commissioners, The Whale Museum, Friday Harbor, WA.

Osborne, R.W., 1998.
Whale Watching in the Boundary Straits: Growth Trends and Cooperative Self-Management. Abstract of a paper presented at PUGET SOUND RESEARCH 98, Puget Sound Water Quality Action Team.

Osborne, R.W., and J.W. Sundsten, 1981.
Preliminary Observations on Thirteen Killer Whale Cranial Volumes, CETUS 3:(5)12-13.

Osborne, R.W., J. Calambokidis, and E.M. Dorsey, 1988.
A GUIDE TO THE MARINE MAMMALS OF GREATER PUGET SOUND. Anacortes, WA, Island Publishers / The Whale Museum.

Pacific Salmon Commission, 1985-1998.
ANNUAL REPORTS OF THE PACIFIC SALMON COMMISSION (Vols. 1-13), Vancouver, B.C. Canada. Pacific Salmon Commission, 1999.

Parker and Folland, 1989.
Worldwide Surface Temperature Trends Since the Mid-Nineteenth Century. In: PROCEEDINGS OF THE US DOE WORKSHOP ON GREENHOUSE GAS INDUCED CLIMATE CHANGE, Amherst, MA.

Philander, S.G., 1990.
EL NINO, LA NINA AND THE SOUTHERN OSCILLATION. San Diego, CA, Academic Press.

Phillips, N.E., and R.W. Baird, 1993.
Are Killer Whales Harassed by Boats?. THE VICTORIA NATURALIST, 50(3):10-11.

Pierson, E.A., and R.M. Turner, 1998.
An 85-Year Study of Saguaro (*Carnegiea gigantea*) Demography. ECOLOGY, 79(8): 2676-2693.

Pike, G.C., and I.B. MacAslie, 1969.
Marine Mammals of British Columbia. FISHERIES RESEARCH BOARD OF CANADA, BULLETIN, 171: 19-23.

Popper, K.R., 1959.
THE LOGIC OF SCIENTIFIC DISCOVERY. London, Hutchinson and Co.

Popper, K.R., 1982.
THE OPEN UNIVERSE: AN ARGUMENT FOR INDETERMINISM. Totowa, N.J., Rowman and Littlefield..

Popper, K.R., 1990.
A WORLD OF PROPENSITIES. Bristol, U.K., Thoemmes.

Port of Seattle, 1995.
1995 MARINE CARGO FORECAST TECHNICAL REPORT. Seattle, Washington Public Ports Association and Washington State D.O.T.

Prigogine, I., and I. Stengers, 1984.
ORDER OUT OF CHAOS: MAN'S NEW DIALOGUE WITH NATURE. New York, Bantam Books.

P.S.W.Q.A., 1988.
STATE OF THE SOUND 1988 REPORT. Olympa, WA, Puget Sound Water Quality Authority.

P.S.W.Q.A., 1992.
STATE OF THE SOUND 1992 REPORT. Olympa, WA, Puget Sound Water Quality Authority.

P.S.W.Q.A., 1995.
1994 PUGET SOUND WATER QUALITY MANAGEMENT PLAN. Olympia WA., Puget Sound Water Quality Authority.

P.S.W.Q.A.T., 1998.
1998 PUGET SOUND UPDATE: SIXTH REPORT OF THE PUGET SOUND AMBIENT MONITORING PROGRAM. Olympia, WA., Puget Sound Water Quality Action Team.

Ray, R.D., M.L. Carlson, T.M. Carlson, and J.D. Upson, 1986.
Behavioral and Respiratory Synchronization Quantified in a Pair of Captive Killer Whales. In: B.C. Kirkevold and J.S. Lockard (Eds.), BEHAVIORAL BIOLOGY OF KILLER WHALES, New York, A.R. Liss, pp. 187-210.

Reèkie, K., 1962.
Fisherman Shoot Whale in Skirmish. THE BELLINGHAM HERALD. Sep. 6th, 1962, pp. 1, 5.

Reeves, R.R., R.J. Hoffman, G.K. Silber, and D. Wilkinson, 1996.
Acoustic Deterrence of Harmful Marine Mammal Fishery Interactions: Proceedings of a Workshop held in Seattlr, Washington, 20-22 March 1996. NOAA TECHNICAL MEMORANDUM NMFS-OPR-10.

Reijnders, P.J.H., 1996.
Organohalogen and Heavy Metal Contamination in Cetaceans: Observed Effects, Potential Impact and Future Prospects. In: M.P. Simmonds and J.D. Hurchinson (Eds.), THE CONSERVATION OF WHALES AND DOLPHINS, New York, John Wilely & Sons, Inc., pp. 205-218.

Reinhold, B., 1987.
Weather Regimes: The Challenge in Extended-Range Forecasting. SCIENCE, 235:437-441.

Richardson, W.J., C.R. Greene Jr., C.I. Malme, and D.H. Thomson, 1995.
MARINE MAMMALS AND NOISE, Academic Press, New York.

Richerson, P.J., and R. Boyd, 1989.
A Darwinian Theory for the Evolution of Symbolic Cultural Traits. In: M. Freilich (Ed.), THE RELEVANCE OF CULTURE, Boston, MA, Bergin and Garvey, pp. 121-42.

Richerson, P.J., and R. Boyd, 1992.
Cultural Inheritance and Evolutionary Ecology. In: E.A. Smith and B. Winterhalder (Eds.), EVOLUTIONARY ECOLOGY AND HUMAN BEHAVIOR, Hawthorn, N.Y., Aldine de Gruyter, Inc.

Ricklefs, R.E., 1979.
ECOLOGY, Second Edition. New York, Chiron Press.

Ridgway, S.H., 1986.
Physiological Observations on Dolphin Brains. In: R.J. Schusterman, J.A. Thomas, and F.G. Wood (Eds.), DOLPHIN COGNITION AND BEHAVIOR: A COMPARATIVE APPROACH, Lawerance Erlbaum Assoc., Hillsdale, N.J., pp. 31-60.

Roberts, N., 1989.
THE HOLOCENE: AN ENVIRONMENTAL HISTORY. Oxford, Basil Blackwell.

Robinson, W.L., and E.G. Bolen, 1989.
WILDLIFE ECOLOGY AND MANAGEMENT, Second Edition. Macmillan Publishers, New York.

Roos, J.F., 1990.
RESTORING FRASER RIVER SALMON: A HISTORY OF THE INTERNATIONAL PACIFIC SALMON COMMISSION 1937-1985. Pacific Salmon Commission, Vancouver, B.C.

Rose, N. A., 1992.
THE SOCIAL DYNAMICS OF MALE KILLER WHALES, *Orcinus orca*, IN JOHNSTONE STRAIT, BRITISH COLUMBIA. Ph.D. Thesis, University of California Santa Cruz.

Ross, P.S., G.M. Ellis, M.G. Ikonomou, L.G. Barrett-Lennard, and R.F. Addison, (in press). High PCB Concentrations in Free-Ranging Pacific Killer Whales, *Orcinus orca*: Effects in Terms of Age, Sex and Dietary Preference, MARINE POLLUTION BULLETEN, (accepted 17, Oct. 1999).

Salden, D.R., 1979.
Supplementary Observations Concerning an Ethogram of the Killer Whale. CARNIVORE, 2:16-18.

Salo, E.O., 1991.
Life History of Chum Salmon (*Oncorhynchus keta*). In: C. Groot and L. Margolis (EDs.), PACIFIC SALMON LIFE HISTORIES, Vancouver, B.C., UBC Press, pp. 231-309.

Sandercock, F.K., 1991.
Life history of coho salmon (*Oncorhynchus kisutch*). In: C. Groot and L. Margolis (EDs.), PACIFIC SALMON LIFE HISTORIES, Vancouver, B.C., UBC Press, pp. 395-445.

Sauer, C.O., 1925 (in Mitchel, 1989).
The Morphology of Landscape. UNIVERSITY OF CALIFORNIA PUBLICATIONS IN GEOGRAPHY, 2: 19-53.

Sauer, C.O., 1941.
Forward, in Historical Geography. ANNALS OF THE AMERICAN ASSOCIATION OF GEOGRAPHERS, 31: 1-24.

Scheffer, V.B., and J.W. Slipp, 1948.
The Whales and Dolphins of Washington State With a Key to the Cetaceans of the West Coast of North America. AMERICAN MIDLAND NATURALIST, 39:257-337.

Schmidt. P.R., 1994.
Historical Ecology and Landscape Transformation in Eastern Equatorial Africa. In: C.L. Crumley (Ed.), HISTORICAL ECOLOGY: CULTURAL KNOWLEDGE AND CHANGING LANDSCAPES, Sante Fe NM, School of American Research Press, (Seattle, Univ. Wash. Press distrb.) pp. 99-126.

Schmitt, C., J. Schweigert, and T.P. Quinn, 1994.
Anthropogenic Influences on Fish Populations of the Georgia Basin. In: R.C.H. Wilson, R.J. Beamish, F.A. Aitkens and J. Bell (Eds.), Review of the Marine Environment and Biota of the Strait of Georgia, Puget Sound and Juan de Fuca Strait. CANADIAN TECHNICAL REPORTS IN FISHERIES AND AQUATIC SCIENCES, No. 1948, p. 630-637.

Schmitt, C.C., S.J. Jeffries, and P.J. Gearin, 1995.
Pinniped Predation on Marine Fish in Puget Sound. PUGET SOUND RESEARCH 95, Olympia, WA, Puget Sound Water Quality Authority.

Schwantes, C.A.,1996.
THE PACIFIC NORTHWEST: AN INTERPRETIVE HISTORY. Lincoln NB, University of Nebraska Press.

Segel, E., K.S. Kamlet, B. Clark, W. Veraska, and J. Lowe, 1980.
THE TOXIC SUBSTANCES DILEMMA: A PLAN FOR CITIZEN ACTION. Washington, D.C., The National Wildlife Federation and U.S. Environmental Protection Agency, U.S. Govt. Printing Office: 620-228/4089.

Sheail, J., 1980.
HISTORICAL ECOLOGY: THE DOCUMENTARY EVIDENCE. Cambridge, Inst. of Terrestrial Ecology.

Siemens, A.H., 1966.
The process of settlement in the Lower Fraser Valley. In: A.H. Siemens (ed.), In: Lower Fraser Valley: Evolution of of a Cultural Landscape. B.C. GEOGRPHICAL SERIES No. 9, Vancouver, B.C.

Simenstad, C.A., B.s Miller, C.F. Nyblade, K. Thornburgh, and L.J. Bledsoe, 1979.
FOOD WEB RELATIONSHIPS OF NORTHERN PUGET SOUND AND THE STRAIT OF JUAN DE FUCA: A SYNTHESIS OF KNOWLEDGE. Washington, D.C., Officie of Environmental Engineering and Technology, and Office of Research and Development, U.S. Environmental Protection Agency.

Simenstad, C.A., K.L. Fresh, and E.O. Salo, 1982.
The role of Puget Sound and Washington coastal estuaries in the life history of Pacific salmon. In: V.S. Kennedy (Ed.), ESTUARINE COMPARISONS, New York, Academic Press, 343-364.

Simmons, I.G., 1979.
BIOGEOGRAPHY: NATURAL AND CULTURAL. London, Edward Arnold Ltd.

Singleton, R.C., and T.C. Poulter, 1967.
Spectral Analysis of the Call of the Male Killer Whale. IEEE TRANSACTIONS OF AUDIO AND ELECTRONIC ACOUSTICS, 15:104-113.

Soule, M.E., and K.A. Kohm (Eds.), 1989.
RESEARCH PRIORITIES FOR CONSERVATION BIOLOGY. Wash. D.C., Island Press.

Smith, J.C. , R.W. Osborne, and K. Balcomb-Bartok, in prep.
THE L-25 SUBPOD OF KILLER WHALES (*Orcinus orca*) IN DYES INLET, WASHINGTON. Unpublished draft manuscript (Center for Whale Research / The Whale Museum, Friday Harbor, WA).

Spong, P., J. Bradford, and D. White, 1970.
Field Studies of the Behavior of the Killer Whale (Orcinus orca). PROCEEDINGS OF THE 7TH ANNUAL CONFERANCES ON THE BIOLOGY OF DIVING MAMMALS, Menlo Park, CA, Stanford Research Institute.

Stenzel, F., 1975.
JAMES MADISON ALDEN: YANKEE ARTIST OF THE PACIFIC COAST, 1854-1860. Fort Worth, TX., Amon Carter Museum.

Steward, J.H., 1955.
THEORY OF CULTURE CHANGE. Urbana, IL., University of Illinois Press.

Street, J., 1969.
An Evaluation of the Concept of Carrying Capacity. PROFESSIONAL GEOGRAPHER, 21:104-107.

Strickland, R.M., 1983.
THE FERTILE FJORD: PLANKTON IN PUGET SOUND. Seattle, WA, Univ. Wash. Press.

Stuiver, M., and G.W. Pearson, 1986.
High-Precision Calibration of the Radiocarbon Time Scale, AD 1950-500BC. RADIOCARBON, 28(2B):805-838.

Tanami, R., 1984.
A Killer Whale Legacy. WATERS, 7:15-20.

Thomas, G.L., and F.L. Felleman, 1988.
Acoustic Measurement of the Fish Assemblage Beneath Killer Whale Pods in the Pacific Northwest. RIT. FISKIDVELDER, 11:276-284.

Thomas, D.H., 1976.
FIGURING ANTHROPOLOGY. New York, Holt, Rinehart and Winston.

Thomas, D.H., 1989.
ARCHAEOLOGY, Second Edition. New York, Holt, Rinehart and Winston.

Thomson, R.E., 1981.
Oceanography of the British Columbia Coast. CANADIAN SPECIAL PUBLICATIONS IN FISHERIES AND AQUATIC SCIENCES, No. 56.

Thomson, R.E., 1994.
Physical Oceanography of the Strait of Georgia-Puget Sound-Juan de Fuca Strait System. In: R.C.H. Wilson, R.J. Beamish, F.A. Aitkens and J. Bell (Eds.), Review of the Marine Environment and Biota of the Strait of Georgia, Puget Sound and Juan de Fuca Strait. CANADIAN TECHNICAL REPORTS IN FISHERIES AND AQUATIC SCIENCES, No. 1948, p. 36-100.

Tomasello, M., and J. Call, 1997.
PRIMATE COGNITION. New York, Oxford University Press.

Toynbee, A. 1972.
A STUDY OF HISTORY. New York, Oxford University Press.

Turner, B.L., 1990.
THE EARTH AS TRANSFORMED BY HUMAN ACTION: GLOBAL AND REGION CHANGES OVER THE LAST 300 YEARS. Cambridge, Cambridge University Press.

Ulanowicz, R.E., 1986.
GROWTH AND DEVELOPMENT: ECOSYSTEMS PHENOMENOLOGY. New York, Springer-Verlag.

Ulanowicz, R.E., 1997.
ECOLOGY, THE ASCENDENT PERSPECTIVE. New York, Columbia University Press.

Urquhart, M.C., and K.A.H. Bukley, 1965.
HISTORICAL STATISTICS OF CANADA. Toronto, The Macmillan Co. of Canada, LTD.

U.S. Coast Guard, VTS data, 1984-89;
U.S. Coast Guard, VTS records for tankers, freighters, tug-barge combinations, ferries and cruise ships 1984-89, Seattle, U.S Coast Guard 13th District.

Vance, J.E., Jr., 1990.
THE CONTINUING CITY: URBAN MORPHOLOGY IN WESTERN CIVILIZATION. Baltimore, MD, Johns Hopkins University Press.

Verhulst, P.F., 1838.
Notice sur la loi que la population pursuit dans son accroissement. CORRESPONDENCE IN MATHIMATICS AND PHYSICS, 10: 113-121.

Voget, F.W., 1975.
A HISTORY OF ETHNOLOGY. New York, Holt, Rinehart and Winston.

Waite, J.M., 1988.
ALLOPARENTAL CARE IN KILLER WHALES (*Orcinus orca*). M.A. Thesis, University of California, Santa Cruz.

Waldichuk, M., 1983.
Pollution in the Strait of Georgia: A Review. CANADIAN JOURNAL OF FISHERIES AND AQUATIC SCIENCES, 40:1142-1167.

Walker, L.A., L. A. Cornell, K.D. Dahl, N.M. Czekala, C.M. Dargen, B. Joseph, A.J.W. Hsueh, and B.L. Lasley, 1988. Urinary Concentrations of Ovarian Steroid Hormone Metabolites and Bioactive Follicle-Stimulating Hormone in Killer Whales (*Orcinus orca*) Duriing Ovarian Cycles and Pregnancy. BIOLOGY OF REPRODUCTION.39: 1013-1020.

Walters, C.J., 1986.
ADAPTIVE MANAGEMENT OF RENEWABLE RESOURCES. New York, Macmillan Publishers.

Walters, E.L., R.W. Baird, and T.J. Guenther, 1992.
New Killer Whale "Pod" Discovered Near Victoria. VICTORIA NATURALIST, 49(3): 7-8.

Ward, A.B., abd D.L. Sullivan, 1980.
A REVIEW OF EXISTING AND HISTORICAL OCEAN DUMPSITES IN THE PACIFIC REGION. Regional Program Report: 80-5, Environmental Protection Service, Environment Canada, Pacific Region.

Washington State Historical Society, 1941 (1950 Edition).
THE NEW WASHINGTON: A GUIDE TO THE EVERGREEN STATE, Washington Writers' Project, Revised Edition. Portland, OR, Binfords & Mort Publishers.

Wash. State Department of Finance, 1995.
WASHINGTON DATA BOOK 95. Forecasting Division, Olympia, WA.

Wash. State, Governor's Salmon Recovery Office, 1999.
DRAFT STATEWIDE STRATEGY TO RECOVER SALMON: EXTINCTION IS NOT AN OPTION, Volume 2. Olympia, WA, State of Washington Governor's Salmon Recovery Office.

Wash. St., Office of Marine Safety, 1993-1997.
VEAT '93- VEAT'97: Vessel Entries and Transits for Washington Waters. Olympia, WA, Office of Marine Safety.

Watkins, W.A., 1986.
Whale Reactions to Human Activities in Cape Cod Waters, MARINE MAMMAL SCIENCE, 24(4):25-62.

Watt, K.E.F., 1962.
Use of Mathematics in Population Ecology. ANNUAL REVIEW OF ENTOMOLOGY, 7:243-252.

WDFW, 1996.
WASHINGTON STATE SPORT SALMON CATCH STATISTICS (1967-95). Unpublished data provided by L. Swope-Lysistrata in 1995 and 1996, WDFW, Olympia, WA.

WDFW, 1997.
WASHINGTON STATE COMMERCIAL SALMON LICENSES AND OPENING STATISTICS (1993-97). Unpublished summary data , WDFW, Olympia, WA.

Wells, H.G., 1921.
THE OUTLINE OF HISTORY, Third Edition, New York, The Macmillan Co.

West, J.E., 1997.
Protection and Restoration of Marine Life in the Inland Waters of Washington State. PUGET SOUND/GEORGIA BASIN ENVIRONMENTAL REPORT SERIES, No. 6.

West, J.E., and S.M. O'Neill, 1995.
Accumulation of Mercury and Polychlorinated Biphenyls in Quilback Rockfish (*Sebastes maliger*) from Puget Sound, Washington. In: PUGET SOUND RESEARCH '95 PROCEEDINGS VOL. 2., Olympia, WA, Puget Sound Water Quality Authority, pp. 666-677.

White, L., Jr., 1967.
The Historical Roots of our Ecologic Crisis. SCIENCE, 155:1203-1207.

Whitehead, H., 1998.
Cultural Selection and Genetic Diversity in Matrilineal Whales. SCIENCE, 282:1708-1711.

Whitehead, H., and R.W.Baird, (in prep. DRAFT).
The Link Between Social Organization and Ecology: Association Patterns of Mammal-Eating Killer Whales Off Vancouver Island (Biology Dept., Dalhousie University).

Williams, R., 1998.
BEHAVIOURAL RESPONSES OF KILLER WHALES TO WHALE WATCHING: OPPORTUNISTIC OBSERVATIONS AND EXPERIMENTAL APPROACHES. M.S., Thesis, Dept. Zoology, University of Bristish Columbia, Vancouver.

Winterhalder, B.P., 1994.
Concepts in Historical Ecology: The View from Evolutionary Theory. In: C.L. Crumley (Ed.), HISTORICAL ECOLOGY: CULTURAL KNOWLEDGE AND CHANGING LANDSCAPES, Sante Fe NM, School of American Research Press, (Seattle, Univ. Wash. Press distrb.) pp. 17-42.

Worster, 1979.
DUST BOWL: THE SOUTHERN PLAINS IN THE 1930S. New York, Oxford University Press.

Worster, D., 1984.
History as Natural History: An Essay on Theory and Method. PACIFIC HISTORICAL REVIEW, 53:1-9.

Worster, D., 1988.
The Vulnerable Earth: Toward a Planetary History, and Appendix: Doing Environmental History. In: D. Worster (Ed.), THE ENDS OF THE EARTH: PERSPECTIVES ON MODERN ENVIRONMENTAL HISTORY, Cambridge, Cambridge University Press, pp. 289-307.

Worster, D., 1990.
The Ecology of Order and Chaos. ENVIRONMENTAL HISTORY REVIEW, 14:1-18.

Yates, S. 1992.
ORCAS, EAGLES AND KINGS: GEORGIA STRAIT AND PUGET SOUND. Boca Raton, FL., Primavera Press.

Zar, J.H., 1996.
BIOSTATISTICAL ANALYSIS, 3rd Edition. Englewood Cliffs, N.J., Prentice-Hall, Inc.

* * *

APPENDIX I

Data Sources

Data Sources

In Appendix I the data sources and parameters for each historical indicator are presented. These tables are divided between indicator variables for the killer whales (Table 21) and indicator variables for human impacts on the killer whales (Table 22). Each variable is specifically identified in terms of the scale in which it is plotted, the sample size for the plot, percent of the sample that was estimated, Sample Mean, Standard Deviation, figures in which the data is plotted, and citations for the sources. In the methods section of Chapter 4 each variable is also defined in narrative form so that the reasoning behind their use as an indicator, and any procedures for deriving estimates, are made clear.

Estimates were used 100% for plots at the century and millennial scales, and not at all for the 240 month scale, where all data was empirical. At the annual and decadal scales a combination of estimates and partial estimates were used in a mix with empirical data in order to produce some of the plots (Figure 57).

Figure 57 **Percentage of Estimated Data at the Annual and Decal Scales**

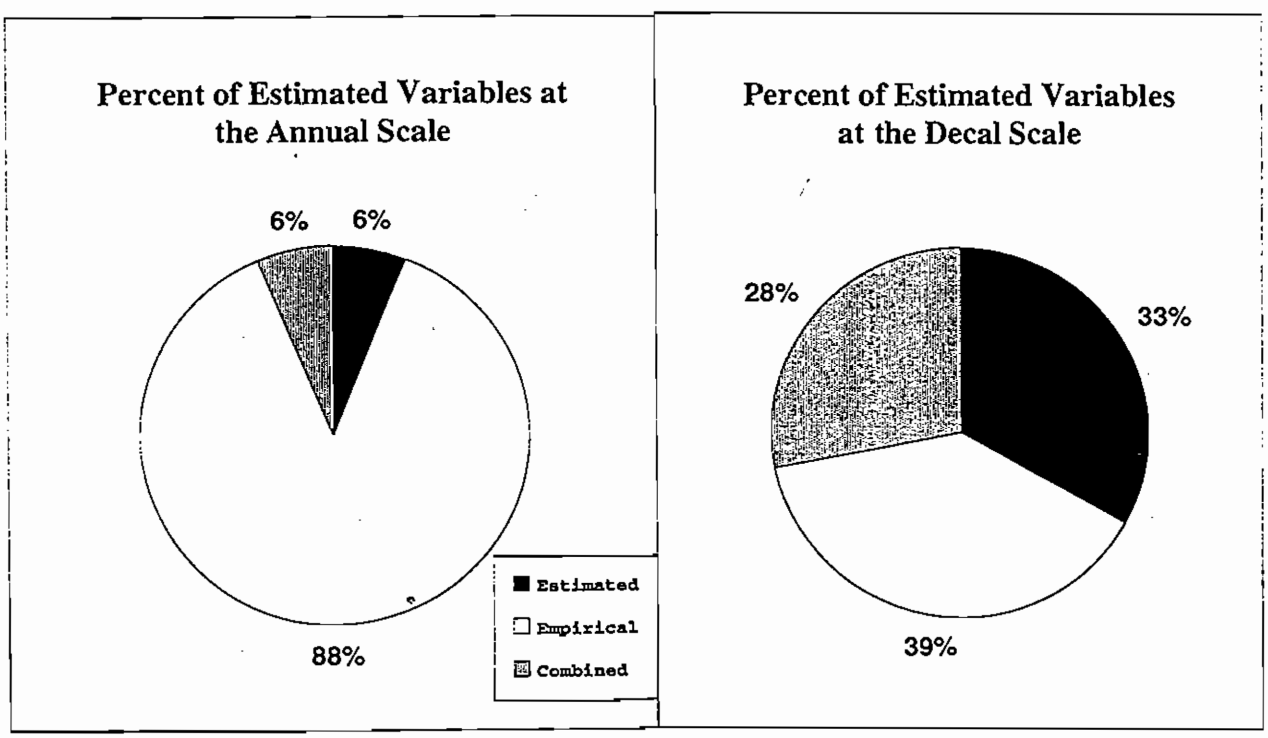


Table 21 Data Sources for Historical Killer whale Plots

Ecological Indicator:	Variables that are Plotted	Scale	Units	Sample Size	% Author Estimated	Sample Mean	Stnd.Dev.	Data Sources
Orca Population Size	Photo-ID Census	Years	Individuals	N= 20	0%	86	7.32	Center for Whale Research, 1998; Ford et al, 1994; Olesiuk et al, 1990.
	Photo-ID, and Estimates	Decades	Individuals	N=20	85%	229.9	92.35	Center for Whale Research, 1998; Olesiuk et al, 1990; AUTHOR ESTIMATES.
	Estimates	Centuries	Individuals	N=20	99%	291.35	42.72	AUTHOR ESTIMATES.
	Estimates	Millenia	Individuals	N= 10	99%	258.33	69.60	AUTHOR ESTIMATES.
Orca Feeding	Energetic Estimate/Population Size	Years	Individuals	N= 20	0%	779,947.37	71,292.44	Kriete, 1995; Center for Whale Research, 1998.
Requirements	Energetic Estimate/Population Size	Decades	Individuals	N= 20	85%	1,821,806.25	789,772.64	Kriete, 1995; Olesiuk et al, 1990; AUTHOR ESTIMATES.
Orca Habitat-Use	Days/Month Orcas Detected Zone 1	Months	Days	N= 240	0%	10.90	8.80	Osborne, 1991, Osborne, unpublished data, 1991-97a; Olson, 1998.
	Days/Month Orcas Detected Zone 2	Months	Days	N=240	0%	2.94	3.14	Osborne, 1991, Osborne, unpublished data, 1991-97a; Olson, 1998.
	Days/Month Orcas Not Deteced in Zones 1 or 2	Months	Days	N=240	0%	16.61	8.55	Osborne, 1991, Osborne, unpublished data, 1991-97a; Olson, 1998.
	Days/Year Orcas Detected Zone 1	Years	Days	N= 20	0%	10.56	2.43	Osborne, 1991, Osborne, unpublished data, 1991-97a; Olson, 1998.
Climate	El Nino/Southern Oscillation Index	Months	Mean Variation	N=240	0%	N.A.	N.A.	Institute of Ocean Sciences, DFO, 1997a.
	Mean Monthly Sea Surface Temp. at Active Pass	Months	Degrees Celsius	N= 240	0%	11.22	3.31	Institute of Ocean Sciences, DFO, 1997b.
	Mean Annual Sea Surface Temperature at Active Pass	Years	Degrees Celsius	N= 20	0%	11.22	0.47	Institute of Ocean Sciences, DFO, 1997b.
	Mean Decal Sea Surface Temp. at Departure Bay	Decades	Degrees Celsius	N=8	0%	11.04	0.37	Institute of Ocean Sciences, DFO, 1997b.
	Mean 5 Century July Temperatues in Arctic North America	Millennia	Degrees Celsius	N=13	0%	1.85	1.64	Andrews et.al., 1981.

Table 22 Data Sources for Historical Plots of Human Vectors

Indicator:	Variables that are Plotted	Scale	Units	Sample Size	% Estimated	Sample Mean	Stnd.Dev.	Data Sources
Predation	Recorded Shooting Incidents	Years	Incidents	N= 20	0%	0.15	0.37	The Whale Museum, unpublished records 1976-97.
	Annual Number Commercial Whale Watch Boats	Years	Boats	N= 20	0%	23.00	21.47	Osborne, 1991; Osborne, unpublished data 1990-97b.
	Mean Number of Whale Watch Boats w/Whales	Years	Boats	N= 20	0%	14.55	7.93	The Whale Museum, Soundwatch, unpublished data 1991-1997.
	Recorded Capture Incidents	Decades	Captures	N= 20	0%	0.45	1.39	Olesiuk et al, 1990; Hoyt, 1990.
	Estimated & Recorded Shooting Incidents	Decades	Incidents	N= 20	99%	14.52	23.88	Olesiuk et al, 1990; Hoyt, 1990; Scheffer and Slipp, 1948; AUTHOR ESTIMATES.
	Mean Number of Dedicated Whale Watch Boats	Decades	Boats	N= 20	0%	2.80	9.95	Osborne, 1991; Osborne, unpublished data 1991-97.
	Estimated Capture Incidents	Centuries	Incidents	N= 20	0%	0.45	2.01	AUTHOR ESTIMATES
	Estimated Shooting/Killing Incidents	Centuries	Incidents	N= 20	100%	11.75	45.75	AUTHOR ESTIMATES
	Mean Number of Dedicated Whale Watch Boats	Centuries	Boats	N= 20	0%	0.28	1.25	Osborne, 1991; Osborne, unpublished data 1991-97; AUTHOR ESTIMATES.

(continued on next page)

(Table 22 continued)

Indicator:	Variables that are Plotted	Scale	Units	Sample Size	% Estimated	Sample Mean	Stnd.Dev.	Data Sources
Food	Wash. St. Salmon Sport Catch in Zone 1	Months	Individuals	N= 156	0%	1,707.62	1,900.30	WDFW, 1996; Haines,1995.
Resource	Wash. St. Salmon Sport Catch in Zone 2	Months	Individuals	N= 156	0%	10,654.90	10,196.23	WDFW, 1996; Haines,1995.
Depletion	Relative Frequency of Salmon Sport Catch in Zone 1	Months	Individuals	N= 156	0%	1,707.62	1,900.30	WDFW, 1996; Haines,1995.
	Relative Frequency of Salmon Sport Catch in Zone 2	Months	Individuals	N= 156	0%	10,654.90	10,196.23	WDFW, 1996; Haines,1995.
	Fraser River Pink & Sockeye Salmon Est. Escapment	Years	Individuals	N= 20	0%	17,598,290.79	10,967,615.84	Pacific Salmon Commission, Annual Reports, 1985-1997.
	Fraser River Pink & Sockeye Salmon Est. Catch	Years	Individuals	N= 20	0%	12,005,212.79	7,445,582.08	Pacific Salmon Commission, Annual Reports, 1985-1997.
	Fraser River Native Subsistance Catch	Years	Individuals	N=19	0%	566,223.47	258,468.21	Pacific Salmon Commission, Annual Reports, 1985-1997.
	Wash. State Sport Catch (all inland waters)	Years	Individuals	N=19	0%	237,495.26	103,716.55	Haines, 1995; Schmitt et al, 1995; Pacific Salmon Commisiion, Annual Report, 1997.
	Fraser River Pink & Sockeye Salmon Est. Escapment	Decades	Individuals	N= 20	60%	24,238,648.34	16,906,205.77	Roos, 1990.
	Fraser River Pink & Sockeye Salmon Est. Catch	Decades	Individuals	N= 20	60%	8,081,024.88	4,131,559.45	Roos, 1990.
	Est. Salish Sea Subsistance & Sports Catch	Decades	Individuals	N= 20	85%	1,172,100.00	1,157,740.22	Roos, 1990; AUTHOR ESTIMATES.
Disease	(same as toxic exposure)	N.A.	N.A.	N.A.	N.A.		N.A.	N.A.
Toxic	Estimated Salish Sea Human Population	Years	Individuals	N= 20	0%	5,530,487.00	656,684.16	Wash. State Office Financial Mgmt., 1995; Canada, Ministry of Industry, 1996.
Exposure	Estimated Salish Sea Human Population	Decades	Individuals	N= 15	50%	1,710,963.08	1,865,486.07	Urquhart and Bukley, 1965; Wash. State Office Financial Mgmt., 1995; Canada, Ministry of Industry, 1996.
	DDT (mg/kg)	Decades	ug/mg	N=15	0%	1.72	2.96	Macdonald and Crecelius, 1994.
	PCBs (mg/kg	Decades	ug/mg	N=15	0%	10.18	103.64	Macdonald and Crecelius, 1994.
	Mercury (Hg)mg/g	Decades	ug/mg	N= 15	0%	109.85	12,067.38	Macdonald and Crecelius, 1994.
	Estimated Salish Sea Human Population	Centuries	Individuals	N= 20	90%	337,500.00	1,332,867.41	Urquhart and Bukley, 1965; Wash. State Office Financial Mgmt., 1995; Canada, Ministry of Industry, 1996.
	Estimated Salish Sea Human Population	Milennia	Individuals	N=9	90%	375,555.56	995,538.31	Drucker, 1965; McKervill, 1967; Wash. State Office Financial Mgmt., 1995; Canada, Ministry of Industry, 1996.
Surface	Mean Annual Whale Watching Traffic Around Orcas	Years	Boats	N= 8	0%	14.55	7.93	Burgen and Otis, 1995; Otis, 1990-1997; The Whale Museum, Soundwatch Program, 1991-97.
Disturbance	Annual Number Commercial Whale Watch Boats	Years	Boats	N=20	0%	23.00	21.47	Osborne, 1991; The Whale Museum, Soundwatch Program, unpublished data 1991-97.
	Annual Number of Commercial Salmon Fishing Licenses in Zor	Years	Boats	N=20	0%	94.10	20.66	WDFW, 1996; WDFW, 1997.
	Annual Number of Commercial Salmon Fishing Days in Zone 1	Years	Days	N-10	0%	61.40	40.64	WDFW, 1997.
	Estimated Number of Dedicated Whale Watching Boats	Decades	Boats	N=15	0%	7.05	21.95	Osborne, 1991; Osborne, unpublished data, 1991-97.
	Annual Number of Commercial Salmon Fishing Boats	Decades	Boats	N=15	86%	1,155.00	1,247.56	WDFW, 1996; WDFW, 1997.
Underwater	Commercial Shipping Traffic in Haro Strait	Years	Boats	N=10	0%	191,273.00	63,682.79	U.S. Coast Guard, VTS data, 1984-89; Osborne 1991; Wash. St., DOE, Office of Marine Safety, 1993-97.
Noise	Estimated Commercial Shipping Traffic	Decades	Boats	N=15	86%	78,329.12	78,641.50	AUTHOR ESTIMATE
	Estimated Number of Motorized Commercial Salmon Fishing B	Decades	Boats	N=15	86%	1,296.80	1,216.76	Roos, 1990; WDFW, 1996; WDFW, 1997.
	Mean Number of Dedicated Whale Watch Boats	Decades	Boats	N=15	0%	3.73	11.43	The Whale Museum, Soundwatch Program, unpublished data, 1990-97.

References for Appendix I

Andrews, J.T., P.T. Davis, W.N. Mode, H. Nichols, and S.K. Short, 1981.
Relative departures in July temperatures in northern Canada for the past 6,000 yr. NATURE, 289:164-167.

Burgen, M. and R.E. Otis, 1995.
The Behavior of Boats Around Killer Whales (*Orcinus orca*) in Haro Strait, WA. Abstract of a paper presented at the ELEVENTH BIENNIAL CONFERENCE ON THE BIOLOGY OF MARINE MAMMALS, Orlando, FL.

Canada , Ministry of Industry, 1996.
CANADA YEARBOOK 97, Ottawa.

Center for Whale Research, 1998.
FIELD GUIDE TO THE ORCAS OF THE PACIFIC NORTHWEST. Center for Whale Research, Friday Harbor, WA.

Drucker, P., 1965.
CULTURES OF THE NORTH PACIFIC COAST. Scranton, PA, Chandler Publishing, Co.

Ford, J.K.B., G.M. Ellis, and K.C. Balcomb, 1994.
KILLER WHALES: THE NATURAL HISTORY AND GENEALOGY OF *ORCINUS ORCA* IN BRITISH COLUMBIA AND WASHINGTON STATE. Vancouver, UBC Press.

Hoines, Lee, 1995.
1992 FISHERIES STATISTICAL REPORT. Washington State Department of Fish and Wildlife, Spring, 1995, Olympia, WA.

Hoyt, E., 1990.
ORCA: THE WHALE CALLED KILLER, 3rd Edition., Canada, Camden House.

Institute of Ocean Sciences, DFO, 1997a.
LISTING OF THE SOUTHERN OSCILLATION INDEX. INTERNET Web Site: www.ios.bc.ca/projects/elnino/s-osc.

Institute of Ocean Sciences, DFO, 1997b.
B.C. LIGHHOUSE DATA. INTERNET Web Site: www.ios.bc.ca/ios/sos/bcsop/lights.

Kriete, Birgit, 1995.
BIOENERGETICS IN THE KILLER WHALE, *ORCINUS ORCA*. Doctoral Dissertation, Department of Animal Science, University of British Columbia, Vancouver, B.C.

Macdonald, R.W., and E.A. Crecelius, 1994.
Marine Sediments in the Strait of Georgia, Juan de Fuca Strait and Puget Sound: What can They Tell us about Contamination? In: R.C.H. Wilson, R.J. Beamish, F.A. Aitkens and J. Bell (Eds.), Review of the Marine Environment and Biota of the Strait of Georgia, Puget Sound and Juan de Fuca Strait. CAN. TECH. RPT. FISH. AQUAT. SCI., No. 1948, p.101-134.

McKervill, H.W., 1967.
THE SALMON PEOPLE: THE STORY OF CANADA'S WEST COAST SALMON FISHING INDUSTRY. Vancouver, B.C., Gray's Publishing, LTD.

Olesiuk, P.F., M.A. Bigg, and G.M. Ellis, 1990.
Life History and Population Dynamics of Resident Killer Whales (Orcinus orca) in the Coastal Waters of British Columbia and Washington State. In: P.S. Hammond, S.A. Mizroch, and G.P. Donovan (Eds.), Individual recognition of Cetaceans: Through the Use of Photoidentification and Other Techniques to Estimate Population Parameters, Cambridge, U.K REPT. INT. WHAL.COMM., SPECIAL ISSUE 12.

Olson, Jean M., 1998.
TEMPORAL AND SPATIAL DISTRIBUTION PATTERNS OF SIGHTINGS OF SOUTHERN COMMUNITY AND TRANSIENT ORCAS IN THE INLAND WATERS OF WASHINGTON AND BRITISH COLUMBIA. M.S. Thesis, Huxley College of Environmental Studies, Western Washington University, Bellingham, WA.

Osborne, R.W., 1991.
Trends in Killer Whale Movements, Vessel Traffic, and Whale Watching in Haro Strait. PROCEEDINGS OF PUGET SOUND RESEARCH '91, Seattle, WA., Puget Sound Water Quality Authority, pp.672-688.

Osborne, 1991-97a.
Monthly sighting data from The Whale Museum's, Whale Hotline Sighting Network 1991-97. TWM data archives, The Whale Museum, Friday Harbor, WA.

Osborne, 1991-97b.
Annual commercial vessel counts (1991-1997) and industry surveys (1992 and 1994). TWM data archives, The Whale Museum, Friday Harbor, WA.

Otis, R.E., 1990-97.
Unpublished annual reports on vessel traffic at Lime Kiln Lighthouse 1990-97. TWM data archives, The Whale Museum, Friday Harbor, WA.

Pacific Salmon Commission, 1985-1997.
ANNUAL REPORTS OF THE PACIFIC SALMON COMMISSION (Vols. 1-13), Vancouver, B.C. Canada.

Puget Sound Water Quality Authority, 1992.
STATE OF THE SOUND 1992 REPORT. Olympa, WA, Puget Sound Water Quality Authority.

Roos, J.F., 1990.
RESTORING FRASER RIVER SALMON: A HISTORY OF THE INTERNATIONAL PACIFIC SALMON COMMISSION 1937-1985. Pacific Salmon Commission, Vancouver, B.C.

Scheffer, V.B., and J.W. Slipp, 1948.
The whales and dolphins of Washington State with a key to the cetaceans of the west coast of North America. AMERICAN MIDLAND NATURALIST, 39:257-337.

Schmitt, C.C., S.J. Jeffries, and P.J. Gearin, 1995.
Pinniped Predation on Marine Fish in Puget Sound. PUGET SOUND RESEARCH 95, Olympia, WA, Puget Sound Water Quality Authority.

The Whale Museum, unpublished records 1976-97.
Unpublished sighting and stranding records. TWM data archives, The Whale Museum, Friday Harbor, WA.

The Whale Museum, Soundwatch, 1990-1997.
Unpublished vessel counts of the number of whale watching boats around whales at 30 minute intervals. TWM data archives, The Whale Museum, Friday Harbor, WA.

Urquhart, M.C., and K.A.H. Bukley, 1965.
HISTORICAL STATISTICS OF CANADA. Toronto, The Macmillan Co. of Canada, LTD.

U.S. Coast Guard, VTS data, 1984-89;
U.S. Coast Guard, VTS records for tankers, freighters, tug-barge combinations, ferries and cruise ships 1984-89, Seattle, U.S Coast Guard 13th District.

WDFW, 1996.
WASHINGTON STATE SPORT SALMON CATCH STATISTICS (1967-95). Unpublished data provided by L. Swope-Lysistrata in 1995 and 1996, WDFW, Olympia, WA.

WDFW unpublished data, 1997.
WASHINGTON STATE COMMERCIAL SALMON LICENSES AND OPENING STATISTICS (1993-97). Unpublished summary data , WDFW, Olympia, WA.

Washington State Department of Finance, 1995.
WASHINGTON DATA BOOK 95. Forecasting Division, Olympia, WA.

Wash. St., Office of Marine Safety, 1993-1997.
VEAT '93- VEAT'97: Vessel Entries and Transits for Washington Waters. Olympia, WA, Office of Marine Safety.

Wash. St., Office of Marine Safety, 1997.
FIELD OPERATIONS REPORT: FEBRUARY 1997., Olympia, WA, Office of Marine Safety.

* * *

APPENDIX II

Historical Interaction Matrices

Historical Interaction Matrices

The historical interaction matrices list all variables in the study with perturbations greater than 1 SD from the sample mean. A different matrix is produced for each scale. The parameters for each sample at each of three time scales (monthly, annual, and decadal) are presented in Tables 23, 25 and 27. The matrices are arranged listing each indicator on the ordinate axis and time on the abscissa (Tables 24, 26 and 28). All standard deviation values greater or less than 1 SD from the sample mean (the extreme 32% of the sample) are recorded in the matrix cell. Values less than one standard deviation receive a score of 0, values below 1 SD are negative (16% of the sample), and above 1 SD are positive (16%). Values greater than 2 SD above or below the sample mean (< 0.02%) are marked in **bold**. These historical interaction matrices are also plotted as histograms, so that they display the cumulative perturbations for each time period (Figures58-60).

Table 23. Table of Data Parameters for Monthly Plots.

Historical Variable	Time Scale:	Mean	SD	Units	N
Orca Habitat-Use:	San Juan Gulf Islands (Zone 1)	11.51	9.04	Days	240
	Puget Sound (Zone 2)	3.00	0.71	Days	240
	Other Areas	16.58	0.71	Days	240
Food Resource Depletion:	Fraser River Run Estimates	17,598,290.79	10,967,615.84	Individuals	60
	Sport Salmon Catch in Area 7	1,707.62	1,900.30	Individuals	204
	Southern Oscilation Index	Unique Index	Unique Index	Unique Index	240
	Active Pass Sea Surface Temperature	11.22	3.31	Degrees Celcius	240

Figure 58 **Monthly Scale Cumulative Matrix Values > 1 SD**

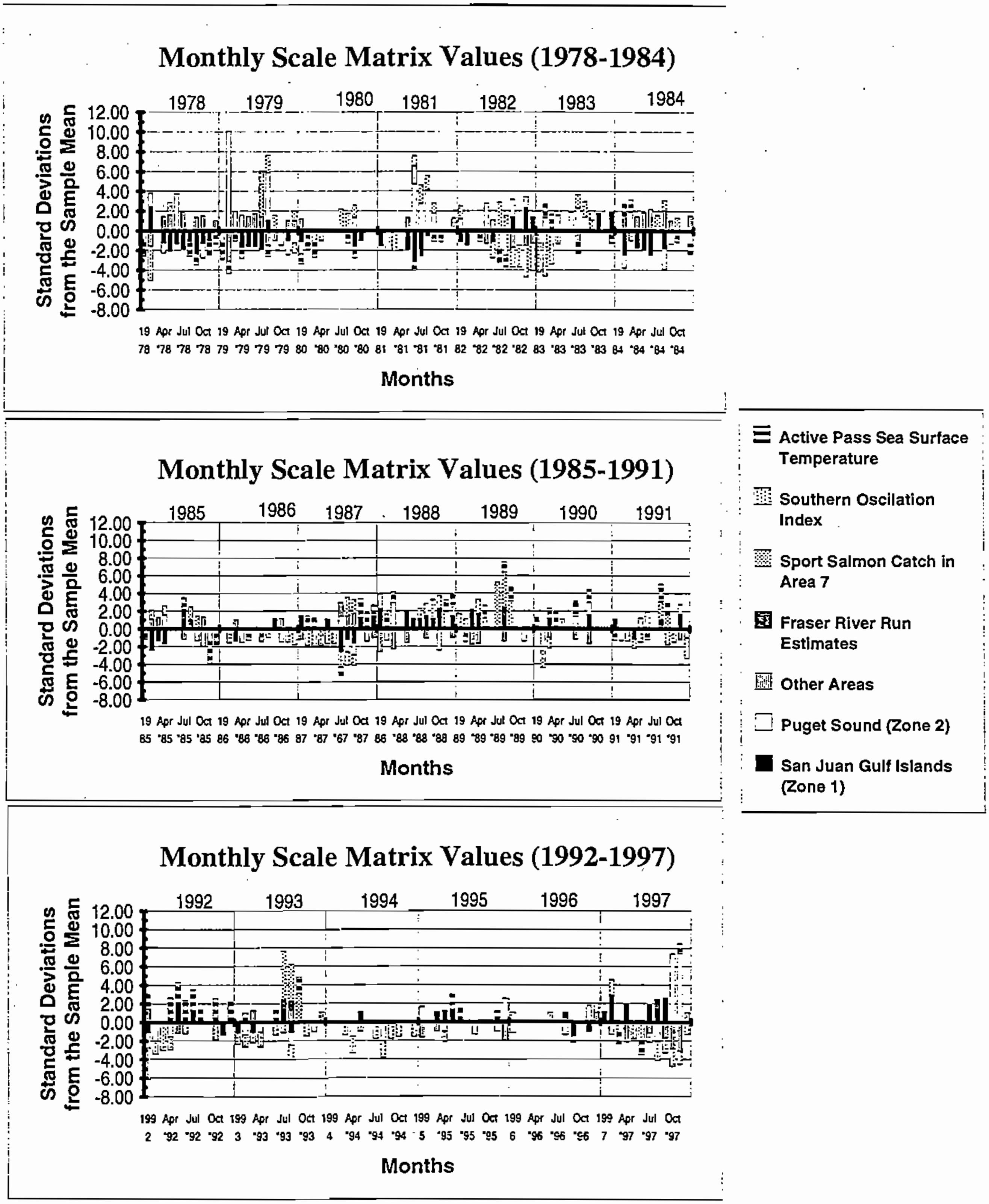


Table 24. Monthly Scale Historical Interaction Matrix.

Historical Variable	Time Scale:	1978	Feb '78	Mar '78	Apr '78
Orca Habitat-Use:	San Juan Gulf Islands (Zone 1)	0.00	**2.45**	0.00	-1.22
	Puget Sound (Zone 2)	-1.21	1.34	0.00	-1.04
	Other Areas	0.00	-1.54	0.00	1.45
Food Resource Depletion:	Fraser River Run Estimates	0.00	0.00	0.00	0.00
	Sport Salmon Catch in Area 7	0.00	0.00	0.00	0.00
Climate	Southern Oscilation Index	0.00	**-3.50**	0.00	0.00
	Active Pass Sea Surface Temperature	-1.31	0.00	0.00	0.00

Time Scale:	May '78	Jun '78	Jul '78	Aug '78	Sep '78	Oct '78	Nov '78
San Juan Gulf Islands (Zone 1)	**-2.07**	-1.32	-1.89	-1.09	**-2.11**	-1.30	-1.01
Puget Sound (Zone 2)	0.00	**3.77**	0.00	0.00	0.00	-1.47	0.00
Other Areas	1.59	0.00	1.98	0.00	1.36	1.53	0.00
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Southern Oscilation Index	1.30	0.00	0.00	0.00	0.00	0.00	0.00
Active Pass Sea Surface Temperature	0.00	0.00	0.00	-1.51	-1.37	0.00	-1.47

Time Scale:	Dec '78	1979	Feb '79	Mar '79	Apr '79	May '79	Jun '79
San Juan Gulf Islands (Zone 1)	0.00	0.00	0.00	0.00	-1.70	-1.59	-1.65
Puget Sound (Zone 2)	0.00	-1.21	**10.07**	1.94	1.56	0.00	0.00
Other Areas	1.02	0.00	**-3.07**	0.00	0.00	1.45	1.72
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Southern Oscilation Index	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Active Pass Sea Surface Temperature	-1.37	-1.72	-1.31	-1.03	-1.11	0.00	0.00

Time Scale:	Jul '79	Aug '79	Sep '79	Oct '79	Nov '79	Dec '79	1980
San Juan Gulf Islands (Zone 1)	-1.89	1.09	0.00	0.00	-1.01	0.00	-1.14
Puget Sound (Zone 2)	0.00	**4.79**	0.00	-1.47	-1.42	-1.25	-1.21
Other Areas	1.39	-1.42	-1.02	0.00	1.05	1.02	1.19
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	**3.32**	1.76	1.55	0.00	0.00	1.00	0.00
Southern Oscilation Index	1.30	0.00	0.00	0.00	0.00	-1.00	0.00
Active Pass Sea Surface Temperature	0.00	-1.20	0.00	0.00	0.00	0.00	-1.04

Time Scale:	Feb '80	Mar '80	Apr '80	May '80	Jun '80	Jul '80	Aug '80
San Juan Gulf Islands (Zone 1)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Puget Sound (Zone 2)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other Areas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	0.00	0.00	**2.16**	1.74
Southern Oscilation Index	0.00	-1.20	-1.00	0.00	0.00	0.00	0.00
Active Pass Sea Surface Temperature	-1.89	-1.53	0.00	0.00	0.00	0.00	-1.30

Time Scale:	Sep '80	Oct '80	Nov '80	Dec '80	1981	Feb '81	Mar '81
San Juan Gulf Islands (Zone 1)	-1.41	-1.04	0.00	0.00	-1.52	0.00	0.00
Puget Sound (Zone 2)	1.33	0.00	0.00	0.00	0.00	**-2.01**	0.00
Other Areas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	1.26	0.00	0.00	0.00	0.00	0.00	0.00
Southern Oscilation Index	0.00	0.00	0.00	0.00	0.00	0.00	**-2.10**
Active Pass Sea Surface Temperature	-1.37	0.00	0.00	0.00	0.00	0.00	0.00

Time Scale:	Apr '81	May '81	Jun '81	Jul '81	Aug '81	Sep '81	Oct '81
San Juan Gulf Islands (Zone 1)	0.00	-1.91	**-2.81**	**-2.59**	-0.54	0.00	0.00
Puget Sound (Zone 2)	0.00	0.00	**4.72**	**2.76**	**4.11**	1.77	0.00
Other Areas	0.00	1.32	1.88	0.00	0.00	0.00	0.00
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	1.84	1.47	1.03	0.00
Southern Oscilation Index	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Active Pass Sea Surface Temperature	0.00	0.00	-1.31	0.00	0.00	-1.11	-1.13

Time Scale:	Nov '81	Dec '81	1982	Feb '82	Mar '82	Apr '82	May '82
San Juan Gulf Islands (Zone 1)	0.00	0.00	-1.14	-1.47	0.00	0.00	0.00
Puget Sound (Zone 2)	0.00	0.00	1.21	0.00	0.00	0.00	**2.77**
Other Areas	0.00	1.28	0.00	0.00	0.00	0.00	-1.32
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Southern Oscilation Index	0.00	0.00	1.30	0.00	0.00	0.00	0.00
Active Pass Sea Surface Temperature	0.00	0.00	0.00	0.00	0.00	-1.11	0.00

Time Scale:	Jun '82	Jul '82	Aug '82	Sep '82	Oct '82	Nov '82	Dec '82
San Juan Gulf Islands (Zone 1)	-1.16	0.00	0.00	1.41	0.00	**2.36**	1.43
Puget Sound (Zone 2)	0.00	0.00	0.00	1.77	-1.47	1.06	0.00
Other Areas	1.10	0.00	0.00	-1.70	0.00	-1.50	-1.28
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	**2.85**	1.53	0.00	0.00	0.00	0.00
Southern Oscilation Index	-1.60	-1.90	**-2.50**	**-2.00**	**-2.20**	**-3.20**	**-2.80**
Active Pass Sea Surface Temperature	0.00	-1.34	-1.20	0.00	0.00	0.00	0.00

Time Scale:	1983	Feb '83	Mar '83	Apr '83	May '83	Jun '83	Jul '83
San Juan Gulf Islands (Zone 1)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Puget Sound (Zone 2)	0.00	1.34	0.00	1.56	0.00	1.89	**2.30**
Other Areas	0.00	0.00	0.00	0.00	0.00	0.00	-1.19
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	0.00	0.00	0.00	1.34
Southern Oscilation Index	**-4.20**	**-4.60**	**-3.40**	-1.30	0.00	0.00	0.00
Active Pass Sea Surface Temperature	0.00	1.40	1.71	0.00	0.00	0.00	-1.13

Time Scale:	Aug '83	Sep '83	Oct '83	Nov '83	Dec '83	1984	Feb '84
San Juan Gulf Islands (Zone 1)	0.00	0.00	1.82	0.00	1.90	0.00	**-2.45**
Puget Sound (Zone 2)	1.37	0.00	0.00	0.00	0.00	0.00	-1.34
Other Areas	0.00	0.00	0.00	0.00	0.00	0.00	1.54
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	1.59	1.07	0.00	0.00	0.00	0.00	0.00
Southern Oscilation Index	0.00	1.00	0.00	0.00	0.00	0.00	0.00
Active Pass Sea Surface Temperature	0.00	0.00	0.00	0.00	-1.23	0.00	1.21

Time Scale:	Mar '84	Apr '84	May '84	Jun '84	Jul '84	Aug '84	Sep '84
San Juan Gulf Islands (Zone 1)	0.00	-1.70	-1.91	**-2.48**	0.00	-1.81	0.00
Puget Sound (Zone 2)	1.94	0.00	0.00	0.00	0.00	**-2.05**	-1.33
Other Areas	-1.02	1.45	1.85	**2.19**	0.00	**2.06**	1.02
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	0.00	1.57	1.03	0.00
Southern Oscilation Index	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Active Pass Sea Surface Temperature	1.21	0.00	0.00	0.00	0.00	0.00	0.00

Time Scale:	Oct '84	Nov '84	Dec '84	1985	Feb '85	Mar '85	Apr '85
San Juan Gulf Islands (Zone 1)	0.00	0.00	0.00	0.00	**-2.45**	-1.36	-1.70
Puget Sound (Zone 2)	0.00	0.00	-1.25	0.00	0.00	0.00	1.56
Other Areas	0.00	0.00	1.53	0.00	1.10	1.28	0.00
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	1.31	0.00	0.00	0.00	0.00	0.00	0.00
Southern Oscilation Index	0.00	0.00	0.00	0.00	1.00	0.00	1.00
Active Pass Sea Surface Temperature	-1.13	0.00	-1.10	-1.18	0.00	0.00	0.00

Time Scale:	May '85	Jun '85	Jul '85	Aug '85	Sep '85	Oct '85	Nov '85
San Juan Gulf Islands (Zone 1)	0.00	0.00	1.18	0.00	0.00	0.00	0.00
Puget Sound (Zone 2)	0.00	0.00	0.00	0.00	-1.33	-1.96	-1.42
Other Areas	0.00	0.00	-1.19	0.00	0.00	1.34	0.00
Fraser River Run Estimates	0.00	0.00	1.00	1.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	1.49	1.44	0.00	0.00
Southern Oscilation Index	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Active Pass Sea Surface Temperature	0.00	0.00	1.36	0.00	0.00	0.00	**-2.50**

Time Scale:	Dec '85	1986	Feb '86	Mar '86	Apr '86	May '86	Jun '86
San Juan Gulf Islands (Zone 1)	0.00	0.00	0.00	-1.36	0.00	0.00	0.00
Puget Sound (Zone 2)	0.00	0.00	0.00	0.00	-1.56	0.00	0.00
Other Areas	0.00	0.00	0.00	1.02	0.00	0.00	0.00
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Southern Oscilation Index	0.00	0.00	-1.60	0.00	0.00	0.00	0.00
Active Pass Sea Surface Temperature	**-2.07**	0.00	0.00	0.00	0.00	-1.32	0.00

Time Scale:	Jul '86	Aug '86	Sep '86	Oct '86	Nov '86	Dec '86	1987
San Juan Gulf Islands (Zone 1)	0.00	0.00	1.17	0.00	0.00	0.00	1.52
Puget Sound (Zone 2)	0.00	0.00	0.00	-1.47	0.00	0.00	0.00
Other Areas	0.00	0.00	0.00	1.15	0.00	0.00	-1.19
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Southern Oscilation Index	0.00	-1.00	0.00	0.00	-1.50	-1.80	0.00
Active Pass Sea Surface Temperature	-1.45	0.00	0.00	0.00	0.00	0.00	0.00

Time Scale:	Feb '87	Mar '87	Apr '87	May '87	Jun '87	Jul '87	Aug '87
San Juan Gulf Islands (Zone 1)	0.00	0.00	0.00	1.11	0.00	**-2.59**	-1.27
Puget Sound (Zone 2)	0.00	0.00	0.00	0.00	0.00	1.38	-1.37
Other Areas	0.00	0.00	0.00	0.00	0.00	1.59	1.42
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	0.00	0.00	0.00	**2.08**
Southern Oscilation Index	-1.90	**-2.00**	-1.90	-1.70	-1.70	-1.70	-1.50
Active Pass Sea Surface Temperature	1.40	1.21	0.00	0.00	0.00	-1.03	0.00

Time Scale:	Sep '87	Oct '87	Nov '87	Dec '87	1988	Feb '88
San Juan Gulf Islands (Zone 1)	-1.64	1.30	0.00	1.43	**2.27**	0.00
Puget Sound (Zone 2)	-1.33	0.00	-1.42	0.00	1.61	-1.34
Other Areas	1.70	0.00	0.00	-1.02	**-2.63**	0.00
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	1.56	0.00	0.00	0.00	0.00	0.00
Southern Oscilation Index	-1.20	0.00	0.00	0.00	0.00	0.00
Active Pass Sea Surface Temperature	0.00	**2.07**	1.93	1.26	0.00	1.60

Time Scale:	Mar '88	Apr '88	May '88	Jun '88	Jul '88	Aug '88	Sep '88
San Juan Gulf Islands (Zone 1)	0.00	0.00	**2.07**	1.16	1.18	1.45	1.17
Puget Sound (Zone 2)	**2.91**	0.00	0.00	0.00	0.00	0.00	0.00
Other Areas	**-2.30**	0.00	-1.59	0.00	0.00	-1.11	0.00
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Southern Oscilation Index	0.00	0.00	0.00	0.00	1.10	1.40	**2.10**
Active Pass Sea Surface Temperature	1.21	0.00	0.00	0.00	0.00	0.00	0.00

Time Scale:	Oct '88	Nov '88	Dec '88	1989	Feb '89	Mar '89	Apr '89
San Juan Gulf Islands (Zone 1)	**2.34**	0.00	1.43	0.00	0.00	**2.18**	1.70
Puget Sound (Zone 2)	**-2.45**	0.00	0.00	0.00	0.00	0.00	0.00
Other Areas	0.00	0.00	-1.02	0.00	0.00	-1.79	-1.69
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Southern Oscilation Index	1.40	1.90	1.30	1.70	1.10	0.00	1.60
Active Pass Sea Surface Temperature	0.00	1.34	1.12	0.00	-1.50	0.00	0.00

Time Scale:	May '89	Jun '89	Jul '89	Aug '89	Sep '89	Oct '89	Nov '89
San Juan Gulf Islands (Zone 1)	0.00	0.00	0.00	1.45	0.00	0.00	0.00
Puget Sound (Zone 2)	0.00	0.00	0.00	0.00	0.00	0.00	-1.42
Other Areas	0.00	0.00	0.00	-1.42	0.00	0.00	0.00
Fraser River Run Estimates	0.00	0.00	0.00	1.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	**5.24**	**3.94**	**3.12**	0.00	0.00
Southern Oscilation Index	1.20	0.00	0.00	0.00	0.00	0.00	0.00
Active Pass Sea Surface Temperature	1.42	0.00	0.00	1.12	1.55	0.00	0.00

Time Scale:	Dec '89	1990	Feb '90	Mar '90	Apr '90	May '90	Jun '90
San Juan Gulf Islands (Zone 1)	0.00	0.00	0.00	1.09	0.00	0.00	0.00
Puget Sound (Zone 2)	0.00	0.00	**-2.01**	0.00	0.00	0.00	0.00
Other Areas	0.00	0.00	0.00	-1.02	0.00	0.00	0.00
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Southern Oscilation Index	0.00	0.00	**-2.40**	-1.20	0.00	1.10	0.00
Active Pass Sea Surface Temperature	0.00	1.27	0.00	1.21	1.95	0.00	0.00

Time Scale:	Jul '90	Aug '90	Sep '90	Oct '90	Nov '90	Dec '90	1991
San Juan Gulf Islands (Zone 1)	0.00	0.00	1.64	0.00	0.00	0.00	1.14
Puget Sound (Zone 2)	1.38	0.00	1.33	0.00	0.00	0.00	0.00
Other Areas	-1.19	0.00	-1.70	0.00	0.00	0.00	0.00
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Southern Oscilation Index	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Active Pass Sea Surface Temperature	1.67	0.00	1.46	0.00	0.00	0.00	-1.31

Time Scale:	Feb '91	Mar '91	Apr '91	May '91	Jun '91	Jul '91	Aug '91
San Juan Gulf Islands (Zone 1)	0.00	0.00	-1.22	0.00	0.00	0.00	0.00
Puget Sound (Zone 2)	-1.34	0.00	0.00	1.19	1.89	0.00	0.00
Other Areas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	0.00	0.00	0.00	**2.08**
Southern Oscilation Index	0.00	-1.40	-1.00	-1.50	0.00	0.00	0.00
Active Pass Sea Surface Temperature	0.00	0.00	0.00	0.00	-1.20	0.00	1.97

Time Scale:	Sep '91	Oct '91	Nov '91	Dec '91	1992	Feb '92	Mar '92
San Juan Gulf Islands (Zone 1)	0.00	0.00	1.69	0.00	-1.14	0.00	0.00
Puget Sound (Zone 2)	0.00	0.00	1.06	0.00	-1.61	**-2.01**	0.00
Other Areas	0.00	0.00	-1.20	-1.02	1.43	0.00	0.00
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	1.56	0.00	0.00	0.00	0.00	0.00	0.00
Southern Oscilation Index	-1.80	-1.50	0.00	**-2.30**	**-3.40**	-1.40	**-3.00**
Active Pass Sea Surface Temperature	1.38	0.00	0.00	0.00	1.54	0.00	0.00

Time Scale:	Apr '92	May '92	Jun '92	Jul '92	Aug '92	Sep '92	Oct '92
San Juan Gulf Islands (Zone 1)	0.00	1.75	0.00	1.18	0.00	0.00	0.00
Puget Sound (Zone 2)	-1.56	0.00	0.00	0.00	0.00	0.00	0.00
Other Areas	0.00	-1.19	0.00	0.00	0.00	0.00	0.00
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Southern Oscilation Index	-1.40	0.00	-1.20	0.00	0.00	0.00	-1.90
Active Pass Sea Surface Temperature	**2.63**	**2.51**	**2.37**	**2.30**	1.33	0.00	**2.55**

Time Scale:	Nov '92	Dec '92	1993	Feb '93	Mar '93	Apr '93	May '93
San Juan Gulf Islands (Zone 1)	-1.35	0.00	-1.14	0.00	-1.09	0.00	0.00
Puget Sound (Zone 2)	0.00	0.00	0.00	-1.34	0.00	-1.04	0.00
Other Areas	0.00	0.00	0.00	0.00	1.28	0.00	0.00
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Southern Oscilation Index	0.00	0.00	-1.20	-1.30	-1.10	-1.60	0.00
Active Pass Sea Surface Temperature	0.00	**2.23**	0.00	1.02	0.00	0.00	0.00

Time Scale:	Jun '93	Jul '93	Aug '93	Sep '93	Oct '93	Nov '93	Dec '93
San Juan Gulf Islands (Zone 1)	0.00	1.42	-1.09	0.00	0.00	0.00	0.00
Puget Sound (Zone 2)	0.00	0.00	-1.37	0.00	0.00	-1.06	0.00
Other Areas	0.00	0.00	1.27	0.00	0.00	0.00	1.02
Fraser River Run Estimates	0.00	1.00	1.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	**5.24**	**3.94**	**3.12**	0.00	0.00	0.00
Southern Oscilation Index	-1.40	-1.10	-1.50	0.00	-1.50	0.00	0.00
Active Pass Sea Surface Temperature	1.32	0.00	0.00	1.72	0.00	0.00	0.00

Time Scale:	1994	Feb '94	Mar '94	Apr '94	May '94	Jun '94	Jul '94
San Juan Gulf Islands (Zone 1)	0.00	0.00	0.00	0.00	1.11	0.00	0.00
Puget Sound (Zone 2)	0.00	0.00	0.00	-1.56	0.00	0.00	0.00
Other Areas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Southern Oscilation Index	0.00	0.00	-1.40	-1.80	-1.00	0.00	-1.80
Active Pass Sea Surface Temperature	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Time Scale:	Aug '94	Sep '94	Oct '94	Nov '94	Dec '94	1995	Feb '95
San Juan Gulf Islands (Zone 1)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Puget Sound (Zone 2)	**-2.05**	0.00	0.00	0.00	0.00	1.61	0.00
Other Areas	0.00	0.00	0.00	0.00	0.00	-1.67	0.00
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7	0.00	0.00	0.00	0.00	0.00		
Southern Oscilation Index	-1.80	-1.80	-1.60	0.00	-1.60	0.00	0.00
Active Pass Sea Surface Temperature	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Time Scale:	Mar '95	Apr '95	May '95	Jun '95	Jul '95	Aug '95	Sep '95
San Juan Gulf Islands (Zone 1)	1.09	1.22	1.11	0.00	0.00	0.00	0.00
Puget Sound (Zone 2)	0.00	-1.04	0.00	0.00	0.00	-1.37	0.00
Other Areas	-1.02	0.00	0.00	0.00	0.00	0.00	0.00
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7							
Southern Oscilation Index	0.00	-1.10	0.00	0.00	0.00	0.00	0.00
Active Pass Sea Surface Temperature	0.00	0.00	1.86	1.42	0.00	0.00	0.00

Time Scale:	Oct '95	Nov '95	Dec '95	1996	Feb '96	Mar '96	Apr '96
San Juan Gulf Islands (Zone 1)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Puget Sound (Zone 2)	0.00	-1.06	**2.50**	-1.21	0.00	0.00	0.00
Other Areas	0.00	0.00	**-2.04**	0.00	0.00	0.00	0.00
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7							
Southern Oscilation Index	0.00	0.00	0.00	1.00	0.00	0.00	0.00
Active Pass Sea Surface Temperature	0.00	1.19	0.00	0.00	0.00	0.00	0.00

Time Scale:	May '96	Jun '96	Jul '96	Aug '96	Sep '96	Oct '96	Nov '96
San Juan Gulf Islands (Zone 1)	0.00	0.00	0.00	0.00	-1.17	0.00	-1.01
Puget Sound (Zone 2)	0.00	0.00	0.00	-1.37	0.00	0.00	1.77
Other Areas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fraser River Run Estimates	0.00	0.00	0.00	1.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7							
Southern Oscilation Index	0.00	1.00	0.00	0.00	0.00	0.00	0.00
Active Pass Sea Surface Temperature	0.00	0.00	0.00	0.00	-1.02	0.00	0.00

Time Scale:	Dec '96	1997	Feb '97	Mar '97	Apr '97	May '97	Jun '97
San Juan Gulf Islands (Zone 1)	0.00	1.14	**2.94**	0.00	1.95	0.00	0.00
Puget Sound (Zone 2)	0.00	0.00	-1.34	0.00	0.00	0.00	0.00
Other Areas	1.02	0.00	0.00	0.00	**-2.18**	0.00	0.00
Fraser River Run Estimates	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7							
Southern Oscilation Index	1.00	0.00	1.60	-1.10	0.00	-1.80	**-2.00**
Active Pass Sea Surface Temperature	0.00	0.00	0.00	-1.28	0.00	0.00	-1.52

Time Scale:	Jul '97	Aug '97	Sep '97	Oct '97	Nov '97	Dec '97
San Juan Gulf Islands (Zone 1)	1.89	1.45	**2.58**	0.00	0.00	0.00
Puget Sound (Zone 2)	0.00	**-2.05**	0.00	**7.35**	**7.45**	0.00
Other Areas	-1.19	0.00	-1.70	**-2.87**	**-3.15**	1.02
Fraser River Run Estimates	0.00	1.00	0.00	0.00	0.00	0.00
Sport Salmon Catch in Area 7						
Southern Oscilation Index	-1.00	**-2.10**	-1.60	-1.90	-1.40	-1.30
Active Pass Sea Surface Temperature	0.00	0.00	0.00	0.00	1.04	0.00

Table 25. Table of Data Parameters for Annual Plots.

Historical Variable	Time Scale:	Mean	SD	Units	N
Orca Population Ecology:	Number of Individual Orcas (Ctr. Whale Res.)	86.00	7.32	Individuals	20
Orca Habitat Use	No. of Days Detected in Zone 1	10.56	2.43	Days	20
Salmon Requirements:	Orca Community Salmon Requirements	779,947.37	71,292.44	sal./whale/day	20
Human Predation:	Mean Number of Whale Watching Vessels Present	14.55	7.93	boats/30 min.	8
Toxic Exposure:	Human Population	5,530,487.00	656,684.16	Individuals	20
Food Resource Depletion:	Fraser River Run Estimates (Intl. Pacific Salmn. Comm.)	17,598,290.79	10,967,615.84	Individuals	20
	Fraser River Commercial Catch	12,005,212.79	7,445,582.08	Individuals	19
	Wash. State Salmon Sport Catch (WDFW)	237,495.26	103,716.55	Individuals	17
Surface Disturbance:	Number of dedicated Whale Watching Boats	23.00	21.47	Individuals	20
Underwater Noise:	Commercial Fishing Openings (WDFW)	61.40	40.64	Days	10
	Shipping Traffic (U.S. Coast Guard / Wash. DOE)	191,273.00	63,682.79	Transits	11
	Number of Commercial Fishing Boats (WDFW, NMFS)	94.10	20.66	Individuals	20

Figure 59. Annual Scale Cumulative Matrix Values > 1 SD

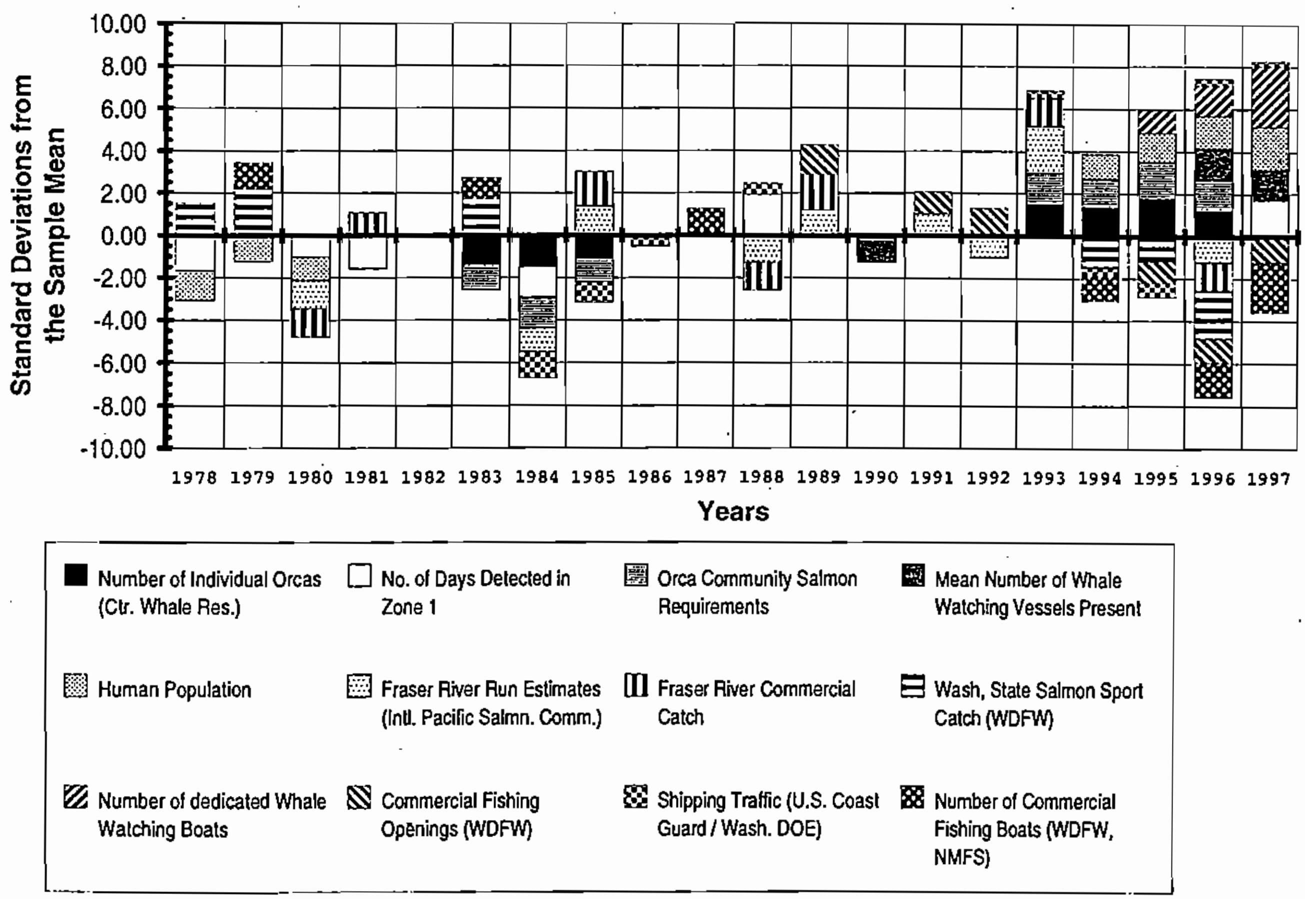


Table 26. Annual Scale Historical Interaction Matrix.

Historical Variable	Time Scale:	1978	1979	1980	1981	1982	1983	1984	1985
Orca Population Ecology:	Number of Individual Orcas (Ctr. Whale Res.)	0.00	0.00	0.00	0.00	0.00	-1.37	-1.50	-1.09
Orca Habitat Use	No. of Days Detected in Zone 1	-1.66	0.00	-1.01	-1.57	0.00	0.00	-1.41	0.00
Salmon Requirements:	Orca Community Salmon Requirements	0.00	0.00	0.00	0.00	0.00	-1.21	-1.47	-1.08
Human Predation:	Mean Number of Whale Watching Vessels Present	#	#	#	#	#	#	#	#
Toxic Exposure:	Human Population	-1.41	-1.23	-1.10	0.00	0.00	0.00	0.00	0.00
Food Resource Depletion:	Fraser River Run Estimates (Intl. Pacific Salmn. Comm.)	0.00	0.00	-1.34	0.00	0.00	0.00	-1.06	1.38
	Fraser River Commercial Catch	0.00	0.00	-1.33	1.08	0.00	0.00	0.00	1.64
	Wash. State Salmon Sport Catch (WDFW)	1.52	**2.18**	0.00	0.00	0.00	1.72	0.00	0.00
Surface Disturbance:	Number of dedicated Whale Watching Boats	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Underwater Noise:	Commercial Fishing Openings (WDFW)								
	Shipping Traffic (U.S. Coast Guard / Wash. DOE)								
	Number of Commercial Fishing Boats (WDFW, NMFS)	0.00	1.26	0.00	0.00	0.00	1.02	0.00	0.00

	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Number of Individual Orcas (Ctr. Whale Res.)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50	1.37	1.78	1.23	0.00
No. of Days Detected in Zone 1	0.00	0.00	1.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.71
Orca Community Salmon Requirements	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.48	1.35	1.73	1.48	0.00
Mean Number of Whale Watching Vessels Present	#	#	#	#	-1.28	0.00	0.00	0.00	0.00	0.00	1.47	1.44
Human Population	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.16	1.37	1.51	**2.00**
Fraser River Run Estimates (Intl. Pacific Salmn. Comm.)	0.00	0.00	-1.26	1.19	0.00	1.03	-1.02	**2.20**	0.00	0.00	-1.21	
Fraser River Commercial Catch	0.00	0.00	-1.30	1.70	0.00	0.00	0.00	1.31	0.00	0.00	-1.33	
Wash. State Salmon Sport Catch (WDFW)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.48	-1.19	**-2.29**	
Number of dedicated Whale Watching Boats	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.12	1.44	**2.89**
Commercial Fishing Openings (WDFW)			0.00	1.39	0.00	1.05	1.32	0.00	0.00	-1.02	-1.12	-1.22
Shipping Traffic (U.S. Coast Guard / Wash. DOE)												
Number of Commercial Fishing Boats (WDFW, NMFS)	0.00	1.26	0.00	0.00	0.00	0.00	0.00	0.00	-1.16	0.00	-1.65	**-2.37**

Table 27. Table of Data Parameters for Decal Plots.

Historical Variable	Time Scale:	Mean	SD	Units	N
Orca Population Ecology:	Pop. Growth	229.9	92.35	Individuals	20
Salmon Requirements:	Orca Food Requirements	1454981.25	488815.6023	Individuals	20
Human Predation:	Shootings	14.52	23.87858763	Events	20
	Captures	0.45	1.394538218	Events	20
Toxic Exposure:	DDT	1.7	1.720465053	ug/mg	15
	PCBs	8.4	10.17560107	ug/mg	15
	Mercury (Hg)	194.3333333	109.8516315	ug/mg	15
	Human Population	1710963.077	1865486.068	Individuals	15
Food Resource Depletion:	Fraser River Run Estimates	24988648.34	16628049.21	Individuals	20
	Fraser River Catch	3232409.95	4172179.636	Individuals	16
	Subsustance Catch	1076250	943087.5158	Individuals	20
Surface Disturbance:	Number of dedicated Whale Watching Boats	3.726666667	11.43206435	Individuals	15
	Mean Number of Whale Watching Boats	1.1025	3.446144871	Individuals	20
Underwater Noise:	Shipping Traffic	78329.11609	78641.49945	Transits	15
	Number of Commercial Fishing Boats	1296.8	1216.762402	Individuals	15

Figure 60. Decal Scale Cumulative Matrix Values > 1 SD

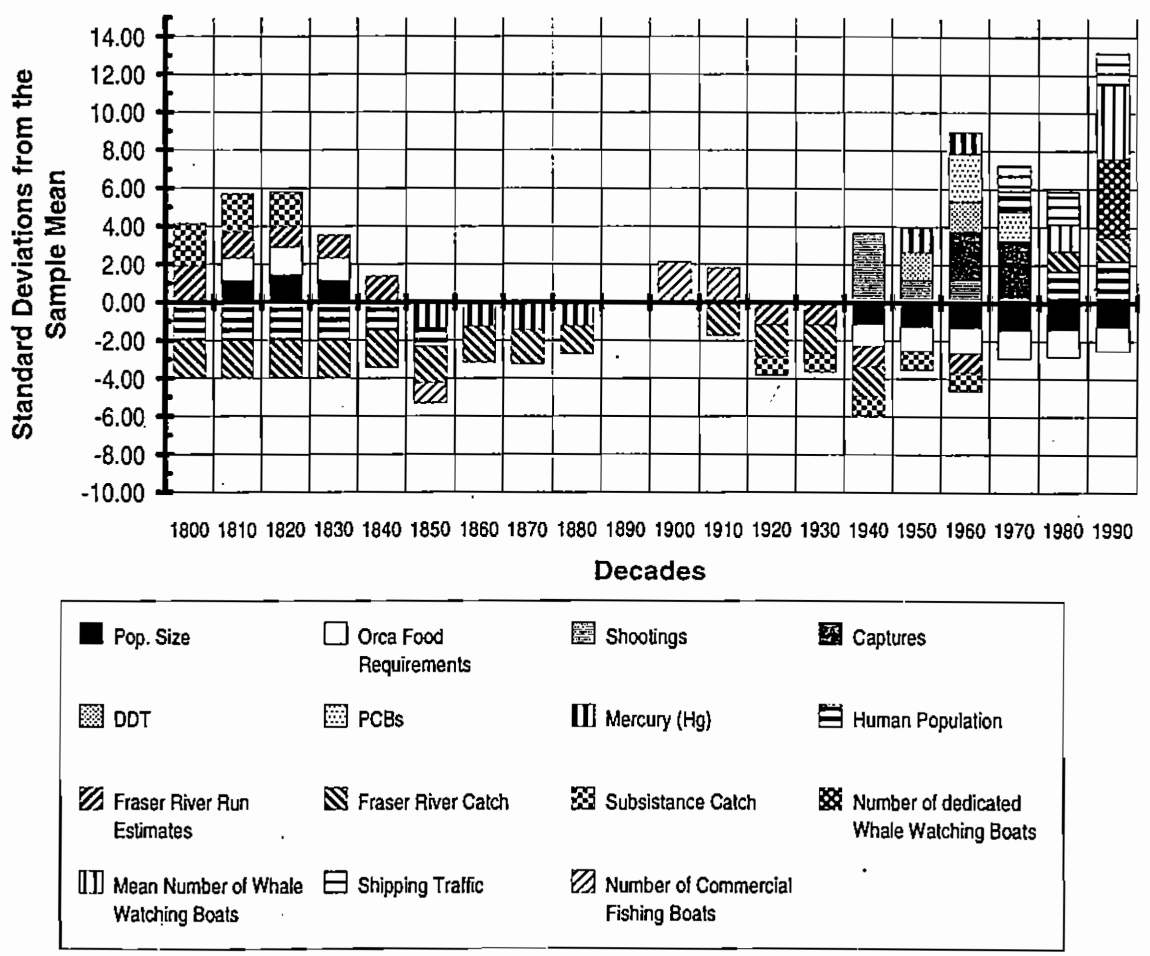


Table 28. Decal Scale Historical Interaction Matrix.

Historical Variable	Time Scale:	1800	1810	1820	1830	1840	1850	1860	1870	1880	1890
Orca Population Ecology:	Pop. Size	0.00	1.16	1.45	1.16	0.00	0.00	0.00	0.00	0.00	0.00
Salmon Requirements:	Orca Food Requirements	0.00	1.16	1.45	1.16	0.00	0.00	0.00	0.00	0.00	0.00
Human Predation:	Shootings	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Captures	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Toxic Exposure:	DDT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	PCBs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mercury (Hg)	0.00	0.00	0.00	0.00	0.00	-1.31	-1.27	-1.40	-1.22	0.00
	Human Population	**-2.00**	**-2.00**	**-2.00**	**-2.00**	-1.50	-1.00	0.00	0.00	0.00	0.00
Food Resource Depletion:	Fraser River Run Estimates	1.93	1.38	1.10	1.21	1.38	0.00	0.00	0.00	0.00	0.00
	Fraser River Catch	-1.96	-1.96	-1.96	-1.96	-1.91	-1.91	-1.88	-1.83	-1.47	0.00
	Subsistance Catch	**2.23**	**2.02**	1.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Surface Disturbance:	Number of dedicated Whale Watching Boats	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mean Number of Whale Watching Boats	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Underwater Noise:	Shipping Traffic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number of Commercial Fishing Boats	0.00	0.00	0.00	0.00	0.00	-1.06	0.00	0.00	0.00	0.00

Time Scale:	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990
Pop. Size	0.00	0.00	0.00	0.00	-1.15	-1.27	-1.31	-1.45	-1.41	-1.27
Orca Food Requirements	0.00	0.00	0.00	0.00	-1.15	-1.27	-1.31	-1.45	-1.41	-1.27
Shootings	0.00	0.00	0.00	0.00	3.66	1.20	1.20	0.00	0.00	0.00
Captures	0.00	0.00	0.00	0.00	0.00	0.00	2.55	**3.27**	0.00	0.00
DDT	0.00	0.00	0.00	0.00	0.00	1.45	1.57	0.00	0.00	0.00
PCBs	0.00	0.00	0.00	0.00	0.00	0.00	**2.52**	1.53	0.00	0.00
Mercury (Hg)	0.00	0.00	0.00	0.00	0.00	1.33	1.14	0.00	0.00	0.00
Human Population	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.09	1.67	**2.22**
Fraser River Run Estimates	0.00	0.00	-1.16	-1.16	-1.05	0.00	-1.00	0.00	0.00	0.00
Fraser River Catch	0.00	-1.71	-1.67	-1.47	-1.55	0.00	0.00	0.00	1.06	1.24
Subsistance Catch	0.00	0.00	-1.01	-1.01	-1.01	-1.01	-1.01	0.00	0.00	0.00
Number of dedicated Whale Watching Boats	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**4.14**
Mean Number of Whale Watching Boats	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.42	**3.90**
Shipping Traffic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.39	1.71	1.70
Number of Commercial Fishing Boats	2.14	1.81	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00