7. Oregon's Fish and Wildlife in a Changing Climate

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Summary and Knowledge Gaps

Oregon's fish and wildlife include animals on land, fish and other species in rivers and lakes, and various kinds of sea life in estuaries and coastal ocean. Of great cultural and economic value, this immense biodiversity—some of which is already threatened or endangered—inhabits complex and dynamic ecosystems we have only begun to understand, let alone examine in terms of climate change. However, it is clear that the abundance and distribution of species are shifting already and will shift more rapidly as habitats on land, in freshwater, and in sea are altered due to increasing temperatures and related environmental changes. Some patterns are already evident.

- Insects from south of Oregon, including pests, are moving into the state, and the timing of development of native species is advancing as spring conditions arrive sooner.
- Frogs are reproducing earlier in the year compared to past decades and emergent infectious diseases affecting frogs and their relatives are increasing in severity.
- Land birds are shifting their distributions northward and migrating earlier.
- Small mammals in eastern Oregon are contracting their ranges on mountaintops.
- In our fresh waters, climate-related habitat loss has increased in severity for salmon and other cool-water fishes.
- In the ocean, harmful algal blooms have increased substantially in the past 15 years, and recurring "dead zones" have appeared in recent years.
- The species composition of copepods (food for many marine fishes) has shifted substantially in recent years.
- Highly predatory Humboldt squid have recently shifted their distribution into Oregon waters from tropical and subtropical regions.

Of increasing concern are predicted changes in fish and wildlife populations during the coming decades as climate change accelerates. In general, these changes include continued northward shifts in species distributions, including species invading from the

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south, upward shifts of mountain species, and declines in the abundance of affected species. Species may be negatively affected directly by physiological stress caused by changes in temperature, water availability, and other environmental shifts, and/or indirectly by habitat degradation and negative interactions with species that benefit from climate change (diseases, parasites, predators, and competitors). Because there is a broad range of possibilities regarding the degree of forthcoming climate change, especially regarding the response of complex biological systems, the severity of predicted responses is unknown, even though the direction of such changes is more certain. Predictions of economic and cultural relevance in Oregon include:

- Increasing frequency and severity of insect pest outbreaks, including new invasive species (see Case Study 7A).
- Extinction of native frog species.
- High vulnerability of nine coastal bird species.
- Continuing range contraction of mammals on mountain tops and in deserts, with possible extinction of rare species.
- Declines in aquatic insects that feed freshwater fishes.
- Continuing decline of salmon and other cool-water fishes as warm-water species, especially invasives, thrive.
- Increasing severity of harmful algal blooms and "dead zones" in the ocean.
- Worsening ocean acidification that threatens shellfish and other sea life.
- Decline of some ocean fisheries, with perhaps emergence of new fisheries.
- Population declines of diving seabirds (e.g., murres and puffins).
- Shifts in migratory patterns of marine mammals and possible increases in diseases.

Knowledge gaps in understanding the responses of Oregon's fish and wildlife to climate change are due to lack of basic ecological understanding of smaller organisms, such as insects and many ocean species. Needed are broad-scale surveys of the biodiversity, geographical ranges, and population sizes of indicator species in all major land, freshwater, and ocean habitats. For these key species (including present and potential invasives) knowledge of ecological interactions (predation, competition, and mutualism) is essential for predicting indirect effects of a changing climate. To increase the accuracy of predictions, such ecological data must be integrated with climate models to produce region-by-region scenarios for future shifts in fish and wildlife communities.

Climate change and its effects on Oregon's fish and wildlife can be moderated by natural resource policies that foster ecological resilience (see Case Study 7B). Given that relatively intact ecosystems are known to be resistant to major changes, an effective resilience tool is to protect refuge habitats on land, in freshwater, and in the sea in networks of reserves where native species can occur and migrate in natural abundances, ages, and sizes. Resilience is also fostered by allowing natural cycles and disturbances to run their course, rather than attempting to rigidly control a changing biosphere.

7.1 Introduction

Oregon is blessed with a rich diversity of fish and wildlife that inhabits a broad variety of habitats on land, in freshwater, and in the sea. This biodiversity -- the genetic variation within species, the number of species, and the range of ecosystems -- provides innumerable benefits to Oregonians, including fisheries, hunting, outdoor sports and recreation, and scientific research. There are also numerous, less tangible, yet extremely valuable ecosystem goods and services provided by these species, such as pollination of crops by insects and transport of ocean nutrients to stream habitats by migrating salmon.

The habitats occupied by Oregon's fish and wildlife, and the effects of climate change on those habitats, are covered in chapters 1 (ocean), 3 (freshwater), and 5 (forests and rangelands). This chapter reviews what is known, predicted, and unknown about the effects of climate change on Oregon's living natural heritage, focusing in turn on the land, freshwater, and the sea. Focused perspectives (Case Study boxes) on invasive species and ecological resilience also are provided.

7.2 Land Animals

Oregon is rich in species of land animals. Many of these species occur only in very specialized habitats and are expected to respond to changes in the distributions of those habitats as climate changes. Species that occur in alpine areas or depend on aquatic habitats in eastern Oregon may be especially sensitive to climate change. Currently, we know relatively little about the precise habitat requirements for most species. We lack sufficient details on the current distributions and population sizes of nearly all species, even of birds, which are comparatively well-studied because of great interest by amateur birdwatchers. The lack of detailed data reduces our ability to predict responses to climate change. In the following summaries, we provide an overview of the current diversity of each animal group in Oregon, what is currently known about responses of each group to climate change in our state, what information from neighboring regions or states may be applicable to Oregon, and important gaps in knowledge that must be filled in the coming years.

7.2.1 Insects and Relatives

Insects and their relatives (collectively known as arthropods) are joint-legged invertebrates that function in numerous critical ecological roles (Miller, 1993). Most abundant across the coastal, valley, mountain, and range habitats of Oregon are insects, spiders, and mites. Lists of species are very incomplete but reasonable estimates indicate that more than 14,000 species of arthropod live in Oregon (Danks, 1995; Miller, unpublished). Insects, spiders, mites, centipedes, and millipedes serve integral roles in soil chemistry, plant growth, food and timber production, human health, and the structure and function of habitats and ecosystems. Importantly, arthropods are virtually everywhere. Many species are uniquely beneficial as pollinators and decomposers, or notorious as pests of crops and carriers of diseases that infect plants and animals. However, the majority of arthropods are relatively innocuous in the context of human concerns and public awareness. Nonetheless, these species are vital to the well-being of our environment and they are highly sensitive to climate dynamics (Forister et al., 2010).

The recognition of endangered and threatened species of arthropods, nationally and within Oregon, is relatively limited. In the context of all plant and animal species, the arthropods are extremely under-represented on federal and state lists of species of concern. Among the arthropods, butterflies dominate federal threatened and endangered species lists. In Oregon, two species of butterfly have been designated as federally threatened and endangered: the Oregon Silverspot, *Speyeria zerene hippolyta* (Figure 7.1) and the Fender's Blue, *Icaricia icarioides fenderi* (Miller and Hammond, 2007). These species, and others (Forister et al., 2010), are on the verge of extinction primarily due to habitat loss. However, the dynamics of rapid climate change creates an additional dimension to the environmental challenges that affect those species already recognized as teetering on the brink of extinction.

Figure 7.1 The Oregon Silverspot, *Speyeria zerene hippolyta*, a federally listed endangered species. View of the underside of the wings showing why the butterfly was given the common name of 'silverspot.'

Regardless of any official assessment, the status of a population or species may be strongly altered by climate change. Most critical are changes in temperature because all arthropods exhibit a very strong relationship between temperature and developmental rate—the time it takes to grow from a fertilized egg to an adult (Miller, 2004a,b). Also, climate in general influences the geographical range of each species—where that species is found on the globe. Thus, the critical issue with arthropods and climate change is a potential shift in seasonal timing (phenology) of critical life-history events, such as egg deposition, growth rates of immature stages, and timing of maturation of adults. The timing of these events is related to the seasonal cycles of plants and animals that provide food and shelter for arthropods. Most arthropods exhibit one generation per year. Thus, the sequence of development through life-history stages (egg, larva, pupa, adult) is intimately timed to occur in synchrony with other biological events. For example, a bee pollinator must develop from egg to adult so that the adult bee emerges from the pupal stage precisely when the flower it pollinates has nectar and pollen. In certain cases, the timing of multiple biological events must occur within days of one another for survival of one or more species.

The problem lies in the fact that each species has its own genetically-based, temperature-dependent, biological clock that dictates its phenology expressed under the temperature regime of its habitat. A change in the temperature regime will result in a change in the synchrony/asynchrony of the life cycles of interacting species. Therefore, a trend in changing climate (e.g., rising temperatures) will have the following possible consequences for arthropods and other species: (1) dying-out locally or regionally, (2) moving to a place where suitable conditions do exist (assuming such a place is available), or (3) adapting and remaining in the same area. The faster the rate of climate change, the more likely that scenarios (1) and (2) will occur and the less likely that scenario (3) will occur.

All three consequences listed above have been documented by scientific studies. Although examples within Oregon are few, the impacts are dramatic. In Oregon, during 2004–2008, Miller (in preparation) documented the phenology of moth flight at the H. J. Andrews Experimental Forest located at an elevation of 1,000 to 4,500 feet on the western slope of the Cascade Mountains about 35 miles east of Eugene. This study revealed that a rise of 2°C (3.6°F) will hasten the annual, and typically well defined, flight period in moths by more than 18 days. A shift of 18 days in the overall flight period is not a trivial issue in the survival of moth species. The seasonal timing of flight (a period of only 10–25 days for most species) is a critical time because this is the only chance females have to deposit eggs, an event followed by caterpillars feeding on suitable foliage. If moth flight times shift due to climate change, then likewise a certain degree of change is also occurring in plant growth. A shift in the seasonal timing of foliage maturation (bud break to leaf toughening) and moth flight creates a situation of asynchrony. Asynchrony between two or more species that depend on one another will result in negative consequences in the population dynamics and community composition for the moths and the plants. The implication is that all 5,000+ species of arthropods known to occur in the H.J. Andrews Forest (Parsons et al., 1991), let alone the 14,000+ species in Oregon, are temperature-dependent in their developmental sequence. The timing of the life history of each of these species will be affected one way or another by a warming climate, with the potential of compounding negative effects on those non-temperature-dependent species, such as insect-eating birds, bats, and mammals, that otherwise require arthropods for some type of ecological service, such as food.

This latter concern is illustrated by the interaction that exists between insects and migratory birds. These birds come to Oregon and rear their young, depending on insects to feed their nestlings. The birds migrate to the Cascade Mountains from South America based on day-length cues that are very consistent. However, the availability of the insect diet they require is not consistent through time because it is highly influenced by climate. As mentioned above, a 2°C (3.6°F) shift in warmer average temperatures has the potential of altering the availability of a required food resource by more than 18 days. If this food (e.g., a caterpillar) has developed into a later life stage (i.e., a butterfly) that is not a prey by the time the migratory birds arrive, then the bird populations are likely to be negatively affected due to a lack of food for their young.

Additional examples of how arthropods have been affected by climate change may be found in neighboring regions. For instance, subtropical mosquito species (often carriers of devastating diseases) are shifting their geographic distributions toward temperate regions like Oregon

(Epstein et al., 2008; Shope, 1992). In California, Forister et al. (2010) documented a geographical shift in butterfly assemblages across a valley-mountain transect in California. In British Columbia, Kurz et al. (2008) modeled the effect of shifting an entire forest from a minor carbon sink to a major carbon emitter due to an on-going massive outbreak of the mountain pine bark beetle (*Dendroctonus ponderosae*) that was initiated by climate warming. The mountain pine bark beetle (Fig. 7.2) is currently causing severe damage to forests in eastern Oregon (see Chapter 5).

Figure 7.2 The mountain pine bark beetle (*Dendroctonus ponderosae*) has caused severe damage to forests in eastern Oregon.

Another present-day concern in the Pacific Northwest (Oregon, Washington, and northern California) involves a new exotic insect pest of small fruits, *Drosophila suzukii*. This fly has entered the region explosively with potentially dire economic impacts on small fruit production (Bolda et al., 2010). Climate models (Damus, 2009) that predict the potential geographical range and population dynamics of *D. suzukii* are proving to be critical for designing and applying a regional management plan. One of the most valuable aspects of the climate models is that they can predict the geographic distribution and phenology of the fly based on real and projected temperature data. Two implications derived from the climate models are that, as average temperatures increase, there will be a subsequent increase in the geographic range of the fly and the number of generations per year. The ramifications of these predictions suggest the possibility that costs for fruit production will increase and greater losses in agricultural production will occur.

7.2.1.1 Research needs

The relevance of addressing arthropods as species vital to the study of climate change is clearly justified by examples from agriculture and human health. However, the approaches necessary to conduct a rigorously documented study that addresses arthropods and climate change must be established in a very precise manner to obtain high-resolution data suitable for statistical analysis. In addition to a network of field-based climate stations, research activities must include models based on an assessment of temperature-dependent requirements for arthropod development through the entire life cycle (egg to adult) for groups of species of special interest.

Two components that are essential to a well-planned comprehensive study of arthropods and climate change are (1) landscape-scale monitoring of species assemblages involving permanent sites subjected to repeated intra-annual sampling efforts at a frequency of 7–10 day intervals, and (2) expertise in identification of various species groups. The scope of the project at a landscape scale is a critical issue because the expected shift in species ranges may occur across 100s to 1,000s of miles. Therefore, a monitoring plan should encompass transects, founded on elevation or latitude, that represent gradients of climate conditions across a broad geographical region. Also, reliance on a single species as a model organism is not advisable. A species complex, involving dozens to hundreds of species, should be monitored. However, the identity of arthropods typically is not a simple matter, as accurate identification requires expertise that is acquired through specialization in systematics, and such taxonomists are few in number. To alleviate taxonomic problems with arthropods, new initiatives are presently underway. Recently, Miller and Luh (unpublished) developed an interactive website that can assist non-taxonomists with the rigors of identifying certain butterflies and moths (Lepidoptera) via the simple act of uploading an image, subjecting the image to an automated pixel-by-pixel analysis, and acquiring an accurate identification. Another team of scientists at Oregon State University is developing an automated identification system for aquatic insects (Larios et al., 2008). Both projects are in the pilot stage. These efforts have the potential to provide much needed taxonomic expertise to non-experts and thereby mitigate the demands of taxonomic specialization that thwart the inclusion of arthropods in large-scale ecological projects.

A final point reiterates the need to study multiple species rather than a single "iconic" species. A novel approach, yet to be conducted by any group of scientists, would be to integrate arthropods into climate studies in concert with other species, all of which are associated via ecological connections, such as food webs. Specifically, it would be valuable to design a project that includes a climate study involving numerous groups of plants, arthropods, and other animals that are ecologically linked, exhibiting a strong relationship of being inter-dependent, so the consequences of dying out, moving away, and adapting to a changed environment can be better understood and the new information used to address the goal of conserving biodiversity.

7.2.2 Amphibians and Reptiles

7.2.2.1 Amphibians

Oregon is considered a biodiversity hotspot for amphibians (frogs and salamanders) because of the relatively large number of species present within the state. There are an estimated 29 native amphibian species in Oregon: 17 salamanders and 12 frogs (Jones et al., 2005). The conservation status of these species varies considerably, with several currently experiencing range contractions while other species have healthy and robust populations. The Oregon Spotted Frog (*Rana pretiosa*) and the Oregon Slender Salamander (*Batrachoseps wrighti*) are the only two species in Oregon that are listed as vulnerable on the IUCN Red List, while the Siskiyou Mountains Salamander (*Plethodon stormi*) of southwest Oregon is listed as endangered (IUCN, 2003; Figure 7.3). Nine of Oregon's amphibian species have been assessed as being nearly threatened (IUCN, 2003). The Oregon Department of Fisheries and Wildlife designated the conservation status of 4 amphibian species as critical in all or part of their Oregon range—the Oregon Spotted Frog (*Rana pretiosa*), the Foothill Yellow-legged Frog (*R. boylii*), the Columbia

Spotted Frog (*R. luteiventris*), and the Northern Leopard Frog (*R. pipiens*) —and 17 other species as vulnerable. These classifications indicate that critically sensitive species are in immediate danger of extinction within specific geographic regions, and vulnerable species could become critically imperiled due to current threats to specific geographic regions or populations (OAR 635-100-040).

(a) (b) (c)

Figure 7.3 Three species of endangered and vulnerable Oregon amphibians: (a) Oregon Spotted Frog (photo by William Leonard), (b) Oregon Slender Salamander (photo by Gary Nafis), and (c) Foothill Yellow-Legged Frog (photo by David Paoletti).

Worldwide, amphibians are a group of serious conservation concern. Population extinctions and declines are already occurring on a global scale (IUCN, 2004), often due to additive and synergistic impacts from multiple environmental stressors, such as habitat loss and climate change (Alford et al., 2007; Root et al., 2003; Stuart et al., 2004; Wake and Vredenburg, 2008). Amphibians are strongly tied to specific habitats and can be indicators of environmental status (Feder and Berggen, 1992; Gibbons and Bennett, 1974; Blaustein et al., 1994; Olson et al., 2007). They are also cold-blooded (ectothermy), making them highly sensitive to shifts in temperature and moisture conditions (Blaustein et al., 2003; Pounds and Crump, 1994, Rome et al., 1992). Physiological constraints associated with an ectothermic life history and dependence on specific local conditions (microclimate) make amphibians particularly susceptible to changes in climate predicted to occur during this century (Blaustein et al., 1994; Carey and Alexander, 2003; Parmesan, 2006).

The majority of amphibian species in the Pacific Northwest have freshwater associations and require dispersal between aquatic and upland terrestrial habitats (Olson and Burnett, 2009). Many Oregon species breed in temporary (ephemeral) water bodies (i.e., wetlands, vernal pools, and intermittent headwater streams) and require adequate wet periods and water quality, as well as suitable temperatures. Changes in precipitation patterns and temperature regimes will affect wet periods, winter snow pack, and flooding events (Chapter 3). These changes will likely affect breeding success, survival, and dispersal, and alter breeding phenology (timing of seasonal reproduction) for many species native to Oregon (Blaustein et al., 2010; Corn, 2003). Environmental cues, such as temperature shifts and rain events, can trigger breeding in many amphibian species, and miscues can result in complete reproductive failure (Hartell, 2008). In addition, amphibians have species-specific temperature tolerances, and exceeding these thermal thresholds will reduce survival. For example, Pacific Giant Salamanders (*Dicamptodon tenebrosus*) and Tailed Frogs (*Ascaphus truei*) are normally found in rivers less than 13°C (55°F) in Oregon (Huff et al., 2005). However, embryonic and larval development rates are highly correlated with temperature, and warmer temperatures may advantageously affect species in ephemeral habitats (Duellman and Trueb, 1986).

Earlier spring thaws and warmer ambient temperatures may affect breeding phenology for many Oregon species. Several studies have shown that various amphibian species are breeding earlier in response to a warming climate (Beebee, 1995; Chadwick et al., 2006; Reading, 1998). Blaustein et al. (2001) examined the breeding patterns of two Oregon frog species, the Western Toad (*Bufo boreas*) and the Cascades Frog (*Rana cascadae*), and found that three of five populations analyzed had strong associations between breeding time and temperature. Only one population, however, had a statistical trend towards earlier breeding times over the two decades examined (Blaustein et al., 2001). While this study concluded that climate change was not influencing breeding phenology for these two Oregon species, subsequent analysis of these data by Corn (2003) revealed that significant relationships existed between dates of breeding and snow accumulation. Corn concluded that breeding phenology of mountain species are driven more by snow pack than by air temperature, and that 20-year data sets are too short to reveal significant changes in life history (Corn, 2003).

Lawler et al. (2009, 2010) employed climate models to project species turnover and range shifts for amphibians and other faunal groups across the Western Hemisphere. This analysis found that amphibian species loss was greatest in range-restricted species inhabiting areas with significant precipitation decreases. These models found greater species gain and loss rates for amphibians relative to birds and mammals due to predicted range expansions and contractions (Lawler et al., 2009). Similarly, Olson and Suzuki (in review) predicted that amphibian species with small geographic ranges in the Cascade Mountains and the western Cascade foothill regions will be negatively affected by reduced precipitation and variable wet periods. Six amphibian species have ranges restricted to the Cascade Mountains and are therefore at risk from shifting climate conditions (Jones et al., 2005). Predicted increases in temperature, a reduction in total snow pack, and increased variability in precipitation patterns in the Cascade Mountains and in the foothills of the Cascades (Chapter 3) will likely reduce available breeding habitats and upland hibernation habitats (hibernacula) for these species.

Climate change will also affect ecological interactions among species of amphibian. Shifts in breeding phenologies may result in species sharing similar breeding habitats when they did not previously overlap (Blaustein et al., 2010). These shifts will result in new competitive interactions and predator/prey dynamics in these shared environments. Invasive American Bullfrogs (*Lithobates catesbeianus*) have invaded permanent and ephemeral breeding habitats in much of Oregon, and earlier breeding phenologies would increase their overlap with native amphibians substantially (Bury and Whelan, 1984). Vegetation structure and heterogeneity will also be affected by changes in temperature, precipitation, and wet periods (Stroh et al., 2008). These changes will affect larval and adult habitat use, reproductive success, and may influence egg-laying behavior for aquatic and terrestrial species (Williams et al., 2008). And because a changing climate influences the geographic distribution of potential competitors, predators, and prey, amphibians will encounter different biotic communities and experience subsequent changes in their population dynamics (Alford, 1989; Lawler and Morin, 1993).

Disease dynamics in amphibian assemblages are also predicted to change with climate. Amphibian species differ in susceptibility to many of the pathogens and parasites present in Oregon, thus the effects will be both species-specific and region-specific (Alford et al., 2007; Garcia et al., 2006; Kiesecker and Blaustein, 1995). The emergent amphibian disease chytridiomycosis has been implicated in the decline of amphibian populations worldwide, and the impacts of this disease may be compounded by climate change (Pounds et al., 2006; Alford et al., 2007; Bosch et al., 2007). The fungus causing chytridiomycosis (*Batrachochytrium dendrobatadis*) is present in Oregon and is transmitted via aquatic spores, so changes in freshwater wet periods may affect transmission rates and prevalence throughout the pathogen's range (Daszak et al., 1999; Lawler et al., 2010). Yellow-Legged Frogs (*Rana boylii*) in Northern California were found to have significantly higher infection rates from a parasitic copepod during two years when daily mean summer temperatures exceeded 20°C (68°F) (Kupferburg et al., 2009). Similarly, Kiesecker and Blaustein (1995) found that decreased wet periods and warmer water temperatures facilitated infection of frogs in the Oregon Cascades by the fungus *Saprolegnia*. Such studies suggest that climate change in Oregon will negatively affect amphibian species via disease both directly and indirectly.

7.2.2.2 Reptiles

Reptiles are divided into several distinctive groups, the three occurring in Oregon being turtles, lizards, and snakes. Oregon is home to two native and two introduced species of turtle, as well as four native species of sea turtle. Oregon has twelve native species of lizard and fifteen species of snake (Storm and Leonard, 1995). The highest diversity of reptiles on Earth tends to occur in warm, tropical locations. The number of species declines with distance from the equator owing, at least in part, to declines in temperature and reduced length of summer as one moves away from the equator. Thus, given Oregon's northern location, the state has comparatively few species of reptiles. As of 2004, Oregon had seven reptile species (excluding sea turtles) that were of conservation concern, but none were federally endangered or threatened (Oregon Natural Heritage Information Center, 2004). The Painted Turtle (*Chrysemys picta*) and Northwestern Pond Turtle (*Emys marmorata marmorata*) are considered to be of conservation concern. The only lizard of concern is the Northern Sagebrush Lizard (*Sceloporus graciosus graciosus*). Four snakes are of concern: Western Rattlesnake (*Crotalus viridus*), Common Kingsnake (*Lampropeltis getula*), California Mountain Kingsnake (*Lampropeltis zonata*), and Ground Snake (*Sonora semiannulata*). All sea turtles are federally listed as endangered or threatened.

The possible influence of climate change on reptiles in Oregon has yet to be studied. Based on the biology of reptiles, one can make some predictions of possible outcomes, but these predictions must be evaluated with appropriate studies. Reptiles are cold-blooded (ectothermic), which means their activity varies with the temperature of their environment; they do not generate their own body heat as birds and mammals do. Reptiles become active when temperatures warm, so most of their activity occurs during warm periods and seasons. Typically this means that activities are limited to times and places where temperatures are, at a minimum, above freezing, but typically temperatures for reptile activity must be much warmer. This dependence on temperature indicates that climate change will affect the activities of reptiles, and perhaps their distribution and abundance (Tewksbury et al., 2008). One might expect that as climate warms, the numbers of places that reptiles can live could increase. Longer periods within a year that are warm enough to allow certain species to establish populations might occur. Habitats that are presently too cold to support certain reptiles could warm enough to allow expansion of ranges into those habitats or sites (for example, moving up elevation in mountainous landscapes).

However, simply expecting all reptiles to expand their distributions or increase in numbers as the climate warms is not realistic (Tewksbury et al., 2008). Another key factor limiting the distribution and abundance of some reptiles is the ability to stay cool (Huey et al., 2009). Many reptiles regulate their body temperatures to keep the temperature within specific ranges (warm, but not too warm). A common strategy is to engage in behavioral thermoregulation: when temperatures are too hot, reptiles move to shady sites or underground and find cooler locations that allow them to maintain their body temperatures appropriately. In some cases, if the climate warms too much, the distribution of particular species may be more affected by availability of appropriate cover, such as shade from vegetation, than by temperature alone (Kearney et al., 2009). Therefore, it is possible that distributions and abundances of some reptiles may change as vegetation within habitats they select also changes (see Chapter 5). Given that few studies have directly evaluated how reptiles will respond to climate change, and little is known particularly about the Pacific Northwest and Oregon, additional studies are required to evaluate expectations of how climate change will affect reptiles.

7.2.3 Land Birds

Oregon is one of the most ecologically diverse states in the U.S. with all four of the world's major biomes represented: alpine/tundra, desert, grassland, and forest. Given the ubiquitous distribution of land birds throughout the state and these regions, there is immense avian diversity representing over half of all land birds known to occur in North America north of Mexico (810 species, Sibley, 2000): 360 bird species regularly occur in Oregon and an additional 135 are more occasional visitors (Marshall et al., 2003). Among land birds breeding in Oregon, three are federally listed under the U.S. Endangered Species Act: Northern Spotted Owl (*Strix occidentalis caurina*), Western Snowy Plover *(Charadrius alexandrinus nivosus*), and the Marbled Murrelet (*Brachyramphus marmoratus*). The U.S. Fish and Wildlife Service recently (March 2010) determined that ESA-listing of the Greater Sage-Grouse (*Centrocercus urophasianus*) was "warranted, but precluded by higher priority listing actions." They will develop a proposed rule to list the Greater Sage-Grouse as their priorities allow (Federal Register 2010). Federal species considered candidates for Endangered Species Act-listing include Yellow-Billed Cuckoos (*Coccyzus americanus*) and Streaked Horned Larks (*Eremophila alpestris strigata*). There are an addition 22 avian species of federal concern (www.fws.gov/oregonfwo/species/Data/Default.asp#Birds).

Birds provide recreational benefits to hunters, bird-watchers, and overall appreciators of nature. They contribute substantially to Oregon tourism, outdoor recreation, outdoor sporting good manufacturers, as well as private and federal habitat conservation efforts in the State. The ubiquitous distribution of birds throughout all habitats in Oregon lends them to be susceptible to the varying effects climate change may have on each biome. Further, most birds are migratory, hence they are also subjected to changing climates along their migratory pathways going north and south, as well as their wintering grounds (Both et al., 2009). As reported in the most recent *State of the Birds* (NABCI, 2010): "Birds in every terrestrial and aquatic habitat will be affected by climate change, although individual species in each habitat are likely to respond differently."

Avian response to climate change around the world has been manifested in several ways: the geographical distribution of species has shifted poleward and to higher altitudes; and the beginning of the breeding season and/or migration is shifting to earlier dates (Moller et al., 2004; Gienapp, 2008; Sheldon, 2010). Some birds that once were migratory (e.g., Canada Geese, *Branta canadensis*) have become permanent residents in one location throughout the year. Such change can have a domino effect on other species accustomed to occupying previously open habitats during certain times of year.

The 2010 *State of the Birds* evaluated vulnerability to climate change for every avian species in North America (NABCI, 2010). Among all Oregon birds, nine species were given the highest rating for vulnerability and all were coastal species. Two of these species were breeding Black Oystercatchers (*Haematopus bachmani*; Fig. 7.4) and Pigeon Guillemots (*Cepphus columba*), and seven were species that migrated through or wintered on the Oregon coast: Surfbird (*Aphriza virgata*), Wandering Tattler (*Tringa incana*), Yellow-Billed Loon (*Gavia adamsii*), Black Turnstone (*Arenaria melanocephala*), Western Sandpiper (*Calidris mauri*), Rock Sandpiper (*Calidris ptilocnemis*), and Short-Billed Dowitcher (*Limnodromus griseus*; also found in the Willamette Valley and Great Basin).

Figure 7.4 Rising sea levels and ocean acidification threaten breeding and feeding habitats, respectively, for these Black Oystercatchers, one of nine bird species in Oregon given the highest rating for vulnerability to climate change by the North American Bird Conservation Initiative (NACBI, 2010). Photo by Brian Guzzetti.

Climate change has not been definitively studied for birds in Oregon, although observed general patterns in climate allow one to suggest changes that might occur among the varied habitats. Overall, predictions for Oregon and the Pacific Northwest are for warmer wetter winters and hotter drier summers (Karl et al. 2009; Chapter 1). On the Pacific Coast, rising sea levels are expected to inundate or fragment low-lying habitats such as the estuaries, rocky intertidal areas and sandy beaches (Chapter 6). Increasing frequency and severity of storms and increases in water temperature and acidity will affect the quality and quantity of coastal habitats and alter marine food webs (Chapter 6 and this chapter). Changes in nearshore sea surface temperatures, though smaller than on land, are likely to substantially exceed interannual variability (Chapter 1). Coastal bird species are expected to shift their distributions northward, as warmer temperatures cause shifts in food resources and nesting opportunities (Browne and Dell, 2007). Lower seasonal flows of freshwater into Pacific coastal marshes will change water and soil salinity and affect the plants and invertebrates needed by foraging waterbirds. This will affect beach nesting and foraging for resident species such as Snowy Plovers and Black Oystercatchers. The *State of the Birds* (NABCI, 2010) found that most coastal birds show medium or high vulnerability to climate change. In addition to the most vulnerable species listed above, coastal species expected to be particularly impacted are diving ducks, such as Canvasbacks (*Aythya valisineria*) and Ruddy Ducks (*Oxyura jamaicensis*) because their existing habitats in the region have already been severely affected by human development (Glick, 2005; Brown and Dell, 2007). Other migratory birds such as the Western Sandpiper, Wandering Tattler, Whimbrel (*Numenius phaeopus*), Harlequin Duck (*Histrionicus histrionicus*), Red-Throated Loon (*Gavia stellata*) and many others will be vulnerable to these changes in their stopover and wintering habitats.

The Willamette Valley provides refuge for hundreds of thousands of Canada Geese, Dunlin (*Calidris alpina*), and other water birds in the winter (Taft and Haig 2003). The predicted warmer, wetter winters could enhance this wetland/savannah habitat. However, the more ephemeral wetlands are created by rain, the more they are drained for agricultural reasons (Taft et al., 2008). Thus, summer residents such as Oregon's state bird, the Western Meadowlark (*Sturnella neglecta*), may not fare as well as warmer temperatures dry up water resources and invertebrates. The largest urban areas in Oregon are located in the Willamette Valley, and common urban birds such as Vaux's Swift (*Chaetura vaux*) and Common Nighthawks (*Chordeiles minor*) are declining (NABCI, 2009). Ironically, resident urban birds appear to be holding their own, yet migrants such as the swifts and nighthawks are not.

Further inland, snowpack has decreased substantially and will continue to do so (Chapter 3). Impacts will probably be high for mountainous wetlands where temperature-sensitive birds will be unable to move upslope (NABCI, 2010). Wetlands that depend on snowmelt will diminish or disappear. This lack of water or declining water levels in permanent and ephemeral Cascade Mountain lakes may most affect nearby cavity-nesting ducks such as the mergansers, Common Goldeneye (*Bucephala clangula*), and Bufflehead (*B. albeola*). Other Pacific forest birds of similar concern include Marbled Murrelet, Spotted Owl, Olive-Sided Flycatcher *(Contopus cooperi*), Varied Thrush (*Ixoreus naevius*), Band-Tailed Pigeon (*Patagioenas fasciata*), Rufous Hummingbird (*Selasphorus rufus*), White-Headed Woodpecker (*Picoides albolarvatus*) and Chestnut-Backed Chickadee (*Poecile rufescens*) (NABCI, 2009).

Warmer, wetter winters and hotter drier summers may prove to be an additional challenge for the threatened Northern Spotted Owl in the Coast Range and Cascade Mountains (Johnson, 1994; Glenn, 2009; Carroll, 2010). Glenn (2009) and Carroll (2010) both found changing climate, particularly wetter winters, accounted for moderate to high amounts of variation in owl survival and population growth rates. McRae et al. (2008) similarly found that small changes in vital rates resulting from climate change or other stressors can have large consequences for population trajectories in Winter Wrens (*Troglodytes troglodytes*) in mature conifer forests in the

Cascades as well as Song Sparrows (*Melospiza melodia*), which prefer more open, shrubby Cascade habitats.

In the Great Basin, decreased summer precipitation will result in an increase in fuels from the growth of annual weeds leading to conditions for extensive and intensive fires. Many arid land birds (over 40%; NABCI, 2009) are at increased risk because of fire, drought and the potential for summertime temperatures greater than they can tolerate. Important wintering areas for many arid land birds may also become unsuitable due to increased drought (NABCI, 2010). Greater Sage-Grouse, other ground-nesting and sage-nesting birds are particularly vulnerable because of their high site fidelity. The climate-enhanced succession to juniper forest in the Great Basin will further exacerbate these habitat limitations.

Understanding the impact of climate change for the many water bird species using the chain of wetlands in Oregon's western Great Basin is complex. Most simply put, the higher salinity (salty) wetlands such as Lake Abert and Summer Lake in south-central Oregon provide superabundant invertebrate food resources for adults (Haig et al., 1998; Plissner et al., 2000). However, chicks need to live near freshwater because they do not possess a developed salt gland (Mahoney and Jehl, 1985; Barnes and Nudds, 1991; Hannam et al., 2003). Thus, the juxtaposition of the need for fresh and saline wetlands is exacerbated by changing climate patterns for the region. If summers are hotter, then freshwater sites will become more saline and less useful for raising young water birds. However if there is increased precipitation, then the decreased salinity at sites like Summer Lake and Abert Lake will decrease food availability for adult breeding birds and millions of water birds that pass through on migration. These changes will be felt most by the species most dependent on them. Most of North America's Snowy Plovers breed in the region. Most of North America's Eared Grebes (*Aechmophorus occidentalis*), Long-Billed Dowitchers (*Limnodromus scolopaceus*), and the all of the world's Wilson's Phalaropes (*Phalaropus tricolor*) use the region during migration. Most of the world's American Avocets (*Recurvirostra americana*) use the region for an extended post-breeding period—over 50% of this species breed in the Great Basin, and most of the world's White-Faced Ibis (*Plegadis chihi*) breed in the Great Basin (reviewed in Warnock et al. 1998). Western Grebe (*Aechmophorus occidentalis*), Clark's Grebe (*A. clarkii*) and Northern Pintail (*Anas acuta*) will also be vulnerable to changes in water level and distribution that affect breeding habitats (NABCI, 2010).

7.2.3.1. Research needs

As the climate changes and Oregon birds respond to these perturbations, it is important to recall that most of Oregon's birds are migrants. Thus, we need to understand how their world is changing in each phase of their annual cycle and how carryover of changes in one phase of the annual cycle is affecting the next (Webster et al., 2002). In many cases, we do not know migrant pathways to winter sites or locations of these winter sites. Understanding this annual connectivity is key to conservation planning. Closer to home, we need to better document basic information on distribution, abundance, elevation, and habitats used by birds now and as they change in the future. Even the most common of Oregon's birds must be understood, as the scale of change we are undergoing is far greater than we could have imagined. Patterns in Oregon will likely follow those predicted for California (Stralberg et al., 2009), hence managers will need to consider the potential for changes in community composition and unanticipated consequences of novel species assemblages. One way to track these changes would be to institute a system such as the California Avian Data Center (data.prbo.org/cadc2) in which a species, habitat, region, etc. can be queried as to its projected distribution as a result of climate change over particular time frames. At the least, bird distribution information could be entered into eBird (ebird.org) or the USGS North American Bird Phenology Program (www.pwrc.usgs.gov/bpp/index.cfm), web-based datasets for amateurs and professionals interested in changing locations of bird species in real time.

In any case, the unprecedented events we are experiencing will require an unprecedented effort to understand the changes on Oregon's birds and provide for their future existence.

7.2.4 Land mammals

Mammals in Oregon are a major source of economic activity through hunting, wildlife watching, and trapping. Mammals also influence habitat for fish, birds, and other species, help control agricultural pests, and are highly valued by the public as wilderness symbols and part of the state's biodiversity. Oregon has a diverse assemblage of land mammals representing most mammalian orders and families found in North America, including about 128 native species and at least 9 established non-native species (Verts and Carraway, 1998). Species found only in (i.e., endemic to) Oregon include two species of shrew (*Sorex bairdi* and *S. pacificus*) and the Camas pocket gopher (*Thomomys bulbivorus*). The red tree vole (*Arborimus longicaudus*) is endemic to Oregon and extreme northeastern California, and the gray vole (*Microtus canicaudus*) is endemic to Oregon and Clark County of Washington (Verts and Carraway, 1998). Oregon was recently recolonized by gray wolf (*Canis lupus*) and also colonized by moose (*Alces alces*) (Pat Matthews, Oregon Department of Fish and Wildlife, personal communication). Species listed under the Endangered Species Act (ESA) include the endangered Columbian subspecies of white-tailed deer (*Odocoileus virginianus leucurus*), gray wolves, and the threatened Canada lynx (*Lynx canadensis*) (Oregon Natural Heritage Information Center, 2004; Fig. 7.2.4.A), although lynx are not known to breed in Oregon (Verts and Carroway 1998). Recent candidate species for ESA listing include fisher (*Martes pennanti*), Washington ground squirrel (*Spermophilus washingtoni*), and American pika (*Ochotona princeps*). The state is also home to at least 18 U.S. Fish and Wildlife Service "species of concern," including pygmy rabbit (*Brachylagus idahoensis*), wolverine (*Gulo gulo*), 10 species of bat, 3 species of pocket gopher (*Thomomys* spp.), Preble's shrew (*Sorex preblei*), and two species of vole (*Arborimus* spp.) (United States Fish and Wildlife Service, 2010).

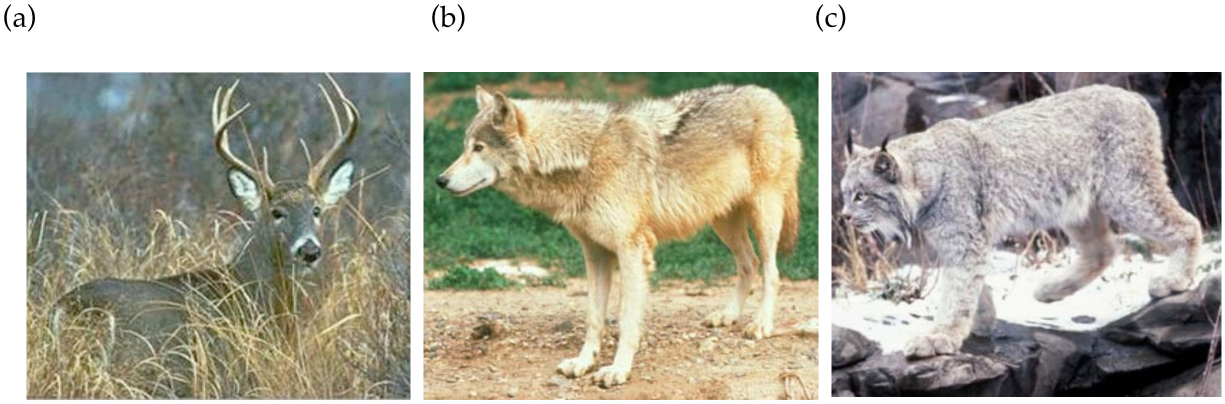


Figure 7.5 Three large endangered mammals in Oregon. (a) The Columbian white-tailed deer is restricted to Douglas County and several islands in the Columbia River. (b) The gray wolf has recently recolonized Oregon, yet the impact of climate change on large predators in Oregon is unclear. (c) The Canada lynx is associated with persistent snow cover during winter months (photos courtesy of the American Society of Mammalogists).

The effects of expected climate change on Oregon's mammals have not been evaluated specifically, but several studies have examined past and future climate effects on small mammals in larger regions that include Oregon. For instance, Beever et al. (2003) recorded more apparent population extinctions of pika (*O. princeps*) in low elevation mountain ranges in the Great Basin deserts of western North America, including areas of eastern Oregon. This range contraction to higher elevations has occurred over the past 7,500 years as the climate has warmed and become more arid (Grayson, 2005), but warming is expected to accelerate much more rapidly during this century (Galbreath et al., 2009; Chapter 1). However, some low elevation populations of pika have persisted (Beever et al., 2008; Simpson, 2009), perhaps due to favorable small-scale habitats that provide shelter from higher temperatures. Studies of historical change in species distribution or abundance from the fossil record (Grayson, 2000; Blois and Hadly, 2009) demonstrate that periods of warming and drying occurred in the Great Basin within the last 10,000 years. These past climate shifts were associated with rapid loss or range contraction of species of small mammals adapted to wetter conditions, such as pocket gophers (*Thomomys* spp.), pygmy rabbit (*B. idahoensis*), and yellow-bellied marmot (*Marmota flaviventris*), as well as expansion of species adapted for arid habitats, such as kangaroo rats (*Dipodomys* spp.). Grayson (2000, 2006) predicted that increases in summer temperature would cause declines in species such as bushy-tailed woodrat (*Neotoma cinerea*), Great Basin pocket mouse (*Perognathus parvus*), and western harvest mouse (*Reithrodontomys megalotis*), but only if precipitation decreases (see Chapter 3). Any major shift in precipitation (drier or wetter) would be expected to influence communities of small mammals by favoring either dry or wet-adapted species (Grayson, 2000). Predicted extinction of many Great Basin mammal species, such as the western jumping mouse (*Zapus princeps*), Belding's ground squirrel (*Spermophilus beldingi*), and the whitetailed jackrabbit (*Lepus townsendii*) resulting from an anticipated 3°C (5.4°F) temperature increase (McDonald and Brown, 1992; see Chapter 1) may be overstated because dispersal potential was underestimated for many Great Basin species (Grayson, 2006; Waltari and Guralnick, 2009).

Few if any studies have evaluated effects of climate change on mammals elsewhere in Oregon, other than a range-wide assessment of pika that included habitat in the Cascade Mountain

Range (Galbreath et al., 2009). Because most Oregon mammal species are not endemic to the state (Verts and Carraway, 1998), some climate change research on mammals outside Oregon is relevant. Most such research has occurred in California, which has a similar range of habitats and high faunal overlap with Oregon. Moritz et al. (2008) evaluated changes from historic (early 20th century) to current distributions of 28 small mammal species in the Sierra Nevada mountains of California. They found that half of those species shifted their ranges to higher elevations over that period of warming, including Belding's ground squirrel (*S. beldingi*), water shrew (*Sorex palustris*), American pika (*O. princeps*), bushy-tailed woodrat (*N. cinerea*), golden-mantled ground squirrel (*Spermophilus lateralis*), and long-tailed vole (*Microtus longicaudus*). However, some lower-elevation species, such as the western harvest mouse (*R. megalotis*) and the montane shrew (*Sorex monticolus*), expanded their ranges. Also, migration appeared to moderate some of the apparent impacts of climate change over the last century (Moritz et al., 2008). Desert bighorn sheep (*Ovis canadensis nelsoni*) in the Mojave, Great Basin, and Sonoran Deserts of California likewise showed a range contraction to higher elevation and wetter mountain ranges during the period 1940–2000; populations in higher elevation habitats also retained greater genetic diversity (Epps et al., 2006). After observing recolonization of some lower elevation habitats by desert bighorn sheep, Epps et al. (2010) argued that maintaining connectivity among fragmented populations of climate-sensitive species may offer the best opportunity to manage impacts of climate change at local and regional scales. Wolverine (*G. gulo*), possibly extirpated from Oregon but still occasionally reported, require persistent winter snows for successful reproduction and, thus, have been negatively affected by declining snowpack across North America (Brodie and Post, 2010). Canada lynx are also associated with winter snow cover (Verts and Carraway 1998) and could be affected by changes in snowpack. There is little research on the effects of climate change on bats in the western United States, although Adams and Hayes (2008) determined that the fringed bat (*Myotis thysanodes*) had high water requirements during lactation and would have less successful reproduction if the climate becomes more arid. Reproductive success in many temperate bat species is linked to precipitation (e.g., Frick et al., 2010).

Climate envelope modeling of the responses of land mammals to climate change in California suggested that the greatest potential for changes in species distributions was in the arid eastern regions, while mammal distributions in the Sierra Nevada and Central Valley remained relatively stable (Parra and Monahan, 2008), suggesting that similar patterns might be observed in the arid regions of eastern Oregon. Precipitation, rather than temperature, often has the strongest influence on mammalian body condition or population dynamics, particularly in arid regions. For instance, precipitation was the stronger determinant of body size of California ground squirrel (*Spermophilus beecheyi*; Blois et al., 2008) as well as diet quality and reproductive success of desert bighorn sheep (Epps, 2004; Wehausen, 2005). However, predicted changes in precipitation are much more variable than predicted changes in temperature among the current spectrum of global climate change models (e.g., Loarie et al., 2008; Parra and Monahan, 2008; see Chapter 3), rendering impacts on species in arid lands and other habitats even less predictable.

7.2.4.1 Research needs

Anticipating the impacts of future climate change on mammals requires (1) understanding how to accurately downscale global climate change models to regional scales; (2) understanding the effects of climate on habitat (in particular, vegetation and surface water); (3) understanding the effects of changes in habitat, precipitation, and temperature on physiology, behavior, and population dynamics; and (4) understanding complex interactions among species and with other factors, such as disease. The first two areas are being addressed in other arenas of climate change research, whereas the third often must be approached on a species-by-species basis. Species inhabiting deserts (Loarie et al., 2009), high elevations (Parmesan, 2006), and other ecosystems already identified as "high risk" are the most obvious candidates for future research. Some interactions between species are already anticipated. For instance, American beaver (*Castor canadensis*) dams may retain water for longer periods in freshwater streams, which could help mitigate impacts of early snowmelt or changes in precipitation (Hood and Bayley, 2008) on freshwater ecosystems (see Section 7.3). Other important considerations include how predicted climate changes that affect human activities on agricultural lands (Chapter 4) and managed forests (Chapter 5) may affect mammal species restricted to such habitats, such as the Camas pocket gopher (*T. bulbivorus*), which are found only in the intensively-farmed Willamette Valley. Refining predictions for future precipitation and identifying basic relationships among mammalian population dynamics and climate variables may be the highest priorities for future research.

7.3 Freshwater Fishes and Invertebrates

Land use change and industrial/municipal development have directly and indirectly warmed streams and rivers throughout Oregon, contributing to the decline of anadromous salmon and trout, resident salmonid fishes, and other cold water species (USACE, 2008; NWPCC, 2004). More than 11,000 miles of streams and rivers in Oregon have been listed as impaired based on temperatures that exceed the water quality standard. In a recent analysis of water quality in the Willamette River basin, more than 35% of the streams were classified as poor quality (Annear et al., 2004). The human population in the Willamette Basin is projected to double over the next 50 years (Hulse et al., 2002), creating more pressure to convert riparian areas and floodplains, develop more roads and drainage ditches, and generate greater volumes of thermal effluents that heat streams and rivers. In addition to accelerated human impacts on river systems, the regional and global climate is projected to warm substantially in coming decades (Chapter 1). The distribution of cold-water species will potentially shrink and become disconnected as thermal regimes in river networks warm more rapidly due to human influences and climate warming.

7.3.1 Freshwater Invertebrates

Aquatic invertebrates are present in all Oregon freshwater habitats, from seasonal alpine ponds and temporary (ephemeral) desert streams, to permanent (perennial) lakes and rivers. Broadly speaking, "aquatic invertebrates" include all of the aquatic insects (mayflies, dragonflies, stoneflies, etc.) as well as crayfish, snails, fairy shrimp, clams, and related groups. Aquatic invertebrates are key consumers of aquatic plants and forest leaf litter, and in turn they constitute a critical food source for fish (including young salmon and steelhead), birds, bats, and other animals. Recreationally, many groups of aquatic insects are important for trout fisheries and the fly fishing industry. Many aquatic invertebrate species require clean, cold water year-round, and for this reason they are used to monitor the ecosystem status of rivers and streams (Carter et al., 2007).

Oregon possesses a great diversity of aquatic invertebrate species, due largely to the sheer volume and diversity of aquatic habitats distributed across the state. For example, Oregon is home to at least 88 species of dragonflies and damselflies (Kondratieff, 2000), 116 species of stoneflies (Kondratieff and Baumann, 2000), and 142 species of mayflies (Meyer and McCafferty, 2007). Distinct invertebrate communities are found in springtime ponds, snowmelt-driven headwater streams, isolated desert springs, and large rivers. Of particular interest with respect to climate change are "headwater specialist" species, which are often restricted to high-elevation, cold-temperature mountain streams that are heavily influenced by melting snowpack (Meyer et al., 2007). While no studies have directly examined how climate change might affect any of these habitats in Oregon, we can obtain guidance from studies done in similar habitats in North America, Europe, and Australia.

Aquatic invertebrates are strongly affected by changes in both hydrology (a river's characteristic pattern of baseflow, flood, and drought) and temperature, and both of these factors are expected to change substantially under most climate change scenarios. For many freshwater aquatic organisms, hydrology is the "master variable" that dictates fundamental aspects of their life cycle, ecology, and distribution (Poff et al., 1997). Similarly, stream temperature affects the growth rate, biomass, and distribution of many aquatic invertebrate species (Vannote and Sweeney, 1980).

In Oregon's mountain regions, a shift from winter snowpack to winter rainfall could reduce the abundance and diversity of aquatic invertebrates. Although milder winter conditions could create new stream habitat at higher elevations, studies from other regions suggest these habitats might not be suitable for many aquatic invertebrate species. In a long-term study in the Swiss Alps, Finn and coauthors (2010) found that stream habitats became significantly less stable (higher flow variability) as permanent snowpack retreated over a five decade period. This instability was also linked to fluctuations in aquatic invertebrate community structure over shorter timescales. This change may have been due to decreasing or more erratic groundwater recharge as glaciers receded, as documented by Haldorsen and Heim (1999) for Arctic streams.

Climate predictions for mountain regions also include more winter precipitation falling as rain instead of snow, as well as earlier melting of accumulated snowpack (Chapter 3). This change will create a substantially different environment for aquatic invertebrates because in snowpack-dominated streams, winter flows are relatively constant, and there is a pronounced but predictable spring flood associated with melting of the snowpack. By contrast, rainfall-dominated streams can experience major floods during the winter season. Studies of streams in the Oregon Cascades have shown that flow variability influences communities of aquatic invertebrates, with more stable stream types generally exhibiting higher density and greater biodiversity (Yamamuro, 2009). In some parts of Oregon, deep volcanic aquifers might be expected to buffer stream hydrology and maintain stable flows, even as more precipitation falls as rain instead of snow (Chapter 3). For most streams, however, a shift towards more variable winter flows may result in lower biodiversity and abundance of aquatic invertebrates.

In Oregon's arid regions, less frequent or more variable precipitation may cause some streams and ponds to shift from perennial (surface water year-round) to intermittent (surface water for only part of the year). The transition from perennial to intermittent water bodies can bring major shifts in invertebrate community structure as well, due to differences in nutrient dynamics and predator communities (e.g., intermittent habitats often are fishless). The differences in water permanence alone may be sufficient to produce differences in invertebrate communities, because many invertebrate species are unable to survive prolonged periods of drought and desiccation (drying). In other arid regions, decreased precipitation is expected to be especially problematic because groundwater and stream flows already are compromised by increasing human demand and extraction in the American Southwest (Grimm et al., 1997; Deacon et al., 2007). The situation likely will be similar in Oregon's arid regions, where high demand for limited water supplies will only exacerbate the ecological changes produced by a changing climate.

Increasing temperatures may reduce the biodiversity of aquatic invertebrate communities, especially when the temperature tolerances of some species are exceeded. Most aquatic invertebrates have a defined range of stream temperature tolerance within which they can survive, with some species adapted to warm, oxygen-poor waters and others specializing on colder, oxygen-rich habitats. Studies in European alpine zones have noted a local increase in the number of species as cold snowmelt-driven streams became warmer due to climate change (e.g., Brown et al., 2007, and Jurasinski and Kreyling, 2007, for plant communities), possibly because of the enhanced ecosystem productivity that can be associated with warmer temperatures. At face value, this increase in species diversity at a single site may seem like a positive effect of a warming climate. However, these same studies found that overall diversity across sites actually decreased, primarily because alpine headwater specialists were being replaced by widespread generalist species from lower elevations. Several species that require cold temperatures had declined greatly and were predicted to become locally extinct if the warming trend continued. To some degree, the combined effects of changing hydrology and increasing stream temperatures might eventually push many headwater species "off the top of the mountain," as has been extensively documented for many terrestrial plant and animal species (e.g., Section 7.2.4). Overall, warming temperatures in Oregon mountain streams can be predicted to provide some positive benefits at the local scale (increased local diversity), but these benefits are predicted to be outweighed by negative impacts at the regional scale (decreased overall diversity and loss of some specialist species).

Aside from altering patterns of aquatic invertebrate biodiversity and distribution, changes in water temperature alter the population dynamics of individual species. The "phenology" of aquatic invertebrates refers to their cycle of growth, maturation, and reproduction. For many species, if not most, phenology is strongly determined by temperature. Thus, a shift towards warmer spring temperatures might produce a much earlier phenology, such that aquatic invertebrates reach reproductive maturity at an earlier date (e.g., Section 7.2.1). This phenomenon is well-documented in plants, insects, and birds, with similar patterns occurring in aquatic invertebrates (Finn and Poff, 2008; Strayer and Dudgeon, 2010). Mayflies in the Rocky Mountains have been observed to emerge earlier during periods of lower snow pack and earlier snowmelt (Harper and Peckarsky, 2006). The ramifications for entire aquatic communities of such shifts in the phenology of single species remain unknown. It is possible that some aquatic invertebrate prey species could become unsynchronized with their predators (fish, birds, or other animals), but this outcome remains to be demonstrated directly.

In summary, Oregon has a great diversity of aquatic habitats that likely will be affected by climate change. The most immediate effects are likely to arise from changes in aquatic hydrology and temperature. The expectation from studies in other regions similar to Oregon is that biodiversity will decrease in general, although local increases are possible. Headwater specialists that depend on cold water and snowmelt are especially vulnerable, as are arid land species that depend on year-round water.

7.3.2 Salmon and other freshwater fishes

Projection of the effects of climate change on 57 species of North American freshwater fish indicated that 37% of the current locations inhabited by cold-water fishes would not support these species over the next century (Mohseni et al., 2003). Another study of climate effects on coldwater fishes concluded that trout habitats throughout the U.S. would be reduced by 15–40% by 2090 (O'Neal et al., 2002). This study provided regional estimates as well, and projected that trout habitat in the Pacific Northwest would decline by 8–33% by 2090. Salmon habitat is even more vulnerable to the effects of climate change because more of the habitat of salmon is at lower, warmer elevations. O'Neal et al. (2002) projected that suitable salmon habitat in Oregon and Idaho would shrink by 40% by 2090, but Washington would experience only a 22% loss, reflecting the cooler temperatures found in more northerly coastal drainages. Bull trout (*Salvelinus confluentus*) require colder temperature than other salmonid fishes and may be more sensitive to regional climate warming. Estimates of climate-related habitat loss for bull trout in the Columbia River basin range from 22% to 92% (B. Reiman, personal communication, as cited by ISAB, 2007).

Similar results have been projected for other regions with native salmonid fishes. Estimates of habitat loss for brook trout (*Salvelinus fontinalis*) in the Appalachian Mountains range from 53% to 97% (Fleebe et al., 2006). Habitat for trout in the North Platte River in the Rocky Mountains of Colorado is projected to shrink by 7–72% as a result of climate change (Rahel, 1996). Species of cold-water fish in the Muskegon River basin in Michigan are projected to decline by 2100, but the geographic ranges of cool-water and warm-water species are predicted to expand (Steen et al., 2010).

The context for analyses of habitat losses related to climate change assumes that air surface temperatures will change, leading to increased rates of warming from headwater streams to large rivers (Chapter 3). Temperatures at stream sources will change slightly but warm more rapidly, and higher temperatures in large rivers will reflect the increases in surface air temperatures. Summer droughts and reduced snow pack will cause contraction of the stream network and current year-round headwater streams will become intermittent seasonal streams.

Rain-on-snow zones will extended higher in elevation and winter flood magnitudes may increase. Human population growth will increase demands for water, and withdrawals from surface water and groundwater will exacerbate effects of climate change on water temperatures and low-flow stream networks.

Various native freshwater fishes in the Pacific Northwest require cold water and are potentially vulnerable to warming associated with climate change. Coho salmon (*Oncorhynchus kisutch*), rainbow trout (*O. mykiss*), cutthroat trout (*O. clarki*), and five species of sculpin (*Cottus* spp.) normally are found in waters less than 17°C (63°F) (Huff et al., 2006; Fig. 7.6). Columbia River white sturgeon (*Acipenser transmontanus*) spawn at temperatures in the range of 10–18°C (50–64°F) (Parsley et al., 1993). Sturgeon eggs die at 20°C (68°F) (Wang et al., 1985). The upper lethal temperature limit of eggs and larvae of Pacific lamprey (*Lampetra tridentata*) is 22°C (72°F) (Meeuwig et al., 2005). The state of Oregon has reviewed thermal tolerances and upper incipient lethal levels in establishing temperature standards under the Clean Water Act (see tables in Oregon Department of Environmental Quality, 1995; McCullough et al., 2001). In the face of climate change, the length of streams and rivers that exceeds the upper incipient lethal levels for species of native fish would likely expand.

Figure 7.6. Cutthroat trout, one of many native Pacific Northwest freshwater fishes potentially vulnerable to a warming climate.

Climate change scenarios in the Pacific Northwest project increased frequency and duration of summer drought (Chapter 3). Small headwater streams will become intermittent, increasing the death rate of eggs and juvenile fish. Extension of drought into early autumn can have substantial negative impacts on salmonid fishes. Populations of spring Chinook salmon (*Oncorhynchus tschawytscha*) in the Salmon River in Idaho increase with the size of autumn water discharges (Crozier and Zabel, 2006). Chinook salmon juveniles in wide and shallow streams are affected by summer low flows and maximum temperatures more than fish in deeper channels (Torgerson et al., 1999; Crozier and Zabel, 2006).

Water temperature influences the time required for fish eggs to develop and the rate at which fry and juvenile fish grow. Life histories of freshwater fishes are closely tied to habitat conditions, food supplies, migration, and transitions between freshwater and saltwater for anadromous species. Shifts in timing and the consequences for critical life-history requirements (such as migration, egg development, juvenile rearing, ocean entry and migration, adult return) make projections related to timing highly variable, but such changes have substantial potential to negatively affect hatching, growth, migration, and survival. Warmer water temperatures are likely to lead to shorter incubation periods and faster growth and maturation of young fish (Beckman et al., 1998). Faster growth and maturation can have positive effects because young fish attain larger sizes before winter, which increases their survival potential (Quinn and Peterson, 1996). High summer temperatures can also increase metabolic costs and decrease growth during summer (Healy, 2006). However, accelerated growth can also cause earlier entry of juvenile salmon into the ocean. Because salmon and steelhead stocks have evolved to migrate and enter the ocean at specific times of the year, changes in that timing could have either negative or positive outcomes. Timing of ocean entry is known to be a primary factor in survival and production of pink salmon (*Oncorhynchus gorbuscha*) in the ocean (Henderson et al., 1992; Pearcy, 1992). In Carnation Creek, British Columbia, increased stream temperatures due to logging caused more rapid growth in coho salmon, and juveniles entered the ocean two weeks earlier than normal. Returns of adult coho salmon decreased, and the authors hypothesized that change in timing of ocean entry resulted in higher consumption of young salmon by marine predators (Holtby et al., 1990).

Migration of salmon in the Columbia River is strongly influenced by river temperatures (Goniea et al., 2006; ISAB, 2007). Movement of adult steelhead trout and Chinook salmon decrease sharply at temperatures greater than 18°C (64°F) (Richter and Kolmes, 2005). Others have suggested that 16°C (61°F) is the upper limit for migration of salmon in the upper Columbia and Snake Rivers (Salinger and Anderson, 2006). At higher temperatures, migrating salmon move into cold water refuges in tributaries or deep pools, and hold position until temperatures in the mainstem river decrease (Perry et al., 2002). Adult Chinook salmon did not survive when exposed to a constant temperature of 22°C (72°F) (McCullough et al., 2001).

7.3.2.1 Cold-water refuges

Cold-water refuges for aquatic organisms are created by the exchange of stream waters and ground waters throughout river networks and deep aquifer sources in specific geologic landscapes. Cutthroat trout use cold-water refuges in the mainstem Willamette River disproportionately during summer periods of high temperature (Hulse and Gregory, 2007). Similar results have been observed for coho salmon in the Smith River, and Chinook salmon east of the Cascades (Raskauskas, 2005). Aquifers with sources in the High Cascades create cold-water springs that provide a substantial portion of the water in some tributaries during summer low flow (Tague and Grant, 2004). Distributions of different types of cold-water refuges could determine the future distributions and abundances of native cold-water fishes under warmer climate regimes.

Cold-water habitats occur in alcoves (side channels) on floodplains and in-channel gravel bars (Hulse and Gregory, 2007; Burkeholder et al., 2008). In the upper Willamette River, more than 68% of the sites sampled in floodplain alcoves were colder than the mainstem river, and 37% were 2–9°C (4–16°F) colder than the mainstem sites. Cold-water habitats created by the exchange of stream waters and ground waters provide critical refuges for native salmonid fishes, but few studies have directly linked the use of cold-water habitats with the processes that create and maintain these essential refuges. Chinook salmon in the Yakima River exhibited core body temperatures 2.5°C (4.5°F) lower than the surrounding river temperature (Bermann and Quinn, 1991), demonstrating a need for cold water habitats throughout the river network for adult salmon. The availability of suitable thermal refuges and appropriate holding habitat within mainstem rivers may affect long-term population survival. Torgerson et al. (1999) found Chinook salmon in the John Day River system primarily in deeper pools or tributary junctions with cooler temperatures. Subsequent studies revealed little exchange of stream waters and ground waters in these reaches, so the cooler temperatures were source-related and not exchange-related (Wright et al., 2005). Juvenile coho salmon in the Smith River avoided warmer mainstem river habitats (up to 25°C or 77°F) and aggregated in cold-water habitats (Raskauskas, 2005). Fifteen cold-water refuges identified in 15 km (9 mi) of stream contained the majority of coho salmon in the reach. In floodplain alcoves of the Willamette River colder than the mainstem, more than 80% of the fish species observed were native species; but in floodplain alcoves warmer than the mainstem, 60% of the species observed were non-native species (S. Gregory and D. Hulse, unpublished data). Studies of fish distributions and water temperatures in Oregon demonstrated that most native fish in the Willamette River occured in waters less than 20°C (68°F), with only redside shiner (*Richardsonius balteatus*) and speckled dace (*Rhinichthys osculus*) normally occupying waters as warm as 23-25°C (73-77°F) (Huff et al., 2005).

7.3.2.2 Effects of increased flooding

In the Pacific Northwest, climate change assessments indicate that winter floods may increase as a result of expanded rain-on-snow zones (Chapter 3). Expanded area of floodplain could have both positive and negative effects on aquatic ecosystems. Floods remove silt from streambeds, create spawning gravel deposits, create pools, deposit riffles, accumulate wood in complex habitats, deliver food resources from adjacent terrestrial ecosystems, and shape diverse and productive floodplains (Swanson et al., 1998, Hulse and Gregory 2004). Increased flooding would provide more of these benefits and possibly restore flood processes in tributaries where flood control has greatly decreased the frequency and magnitude of flooding. But floods also can have detrimental effects on aquatic communities, especially in reaches where channel simplification and bank hardening increase the power of floods but eliminate access to lateral floodplain and riparian refuges. Winter floods can scour gravel nests (redds) while the eggs of Pacific salmon and other salmonid fishes are in the gravel (Jager, 1997). Earlier snowmelt can result in exposure of redds if water levels drop sooner and more rapidly. Siltation during flood events also has the potential to blanket gravels with silt and smother eggs or trap fry.

7.3.2.3 Effects of increased diseases and parasites

Warmer waters also increase exposure of fish to diseases and potentially alter the resistance of aquatic organisms to pathogens and parasites (Marcogliese, 2001). Recent studies have documented pre-spawning death rates of 65-90% in spring Chinook salmon in the Willamette River system (C. Schreck, unpublished data). These mortalities occur after migration to their spawning grounds but before spawning, losses not included in regional estimates of returning adult salmon. Disease, exposure to environmental contaminants, and the stress of high temperatures are potential causal factors. Native salmonid fishes in the Willamette River system also are noted for their high susceptibility to bacterial disease. Several of these diseases also have intermediate hosts (e.g., *Ceratomyxa shasta* with a ploychaete worm host *Manayunkia* *speciosa*) likely to increase at higher temperatures and in areas of increased sediment deposits, both of which could be worsened by changes in water temperature and flow rates as a result of climate change and human population growth. Elevated temperatures and diseases (primarily the bacterial disease columnaris) were the major causes of the deaths of 33,000 Chinook salmon in the lower Klamath River in 2002 (California Department of Fish and Game, 2003).

7.3.2.4 Effects of community interactions and invasive species

Biotic interactions (competition, predation, etc.) have major influence on the performance of freshwater fishes. Many native species are territorial and compete for feeding positions, hiding cover, and spawning locations. In the Umpqua River, Oregon, juvenile steelhead trout were dominant over redside shiners and occupied the most effective feeding locations at temperatures less than 15°C (59°F) (Reeves et al., 1987). However, at temperature above 19°C (66°F), redside shiners were dominant and steelhead growth rates declined. In the Rocky Mountains, native cutthroat trout and non-native brook trout were equally competitive in feeding at 10°C (50°F), but brook trout were more efficient in feeding at 20°C (68°F) (DeStaso and Rahel, 1994).

Predation is a major biotic interaction that strongly influences the survival of freshwater fishes. As described earlier, shifts in the timing of migration may expose fish to higher predation in freshwater or marine environments than they would experience under current run timing (Holtby et al., 1990). Consumption of juvenile salmonid fishes by northern pikeminnow (*Ptychocheilus oregonensis*), smallmouth bass (*Micropterus dolomieu*), and walleye (*Sander vitreus*) was greatest as temperatures increased in midsummer (Vigg et al., 1991). In addition, fish may be less able to avoid predators under thermal stress. Chinook salmon were less able to avoid predatory northern pikeminnow at temperatures higher than 20°C (68°F) (Marine and Cech, 2004). Migrating juvenile salmon in the Willamette and Columbia Rivers use shallow margin habitats (Friesen et al., 2004; Tiffan et al., 2006). Increasing temperatures in these lateral habitats would cause these migrating juveniles to move to deeper waters and experience greater risk of predation (Poe et al., 1991).

Many non-native fish species that have been introduced into the Pacific Northwest are warm-water species. There are increased proportions of non-native species and decreased richness of native species in warmer reaches of the Willamette River (Hughes et al., 2005). Non-native species can cause extensive habitat degradation (e.g., carp, catfish), prey on native fish species (largemouth bass, smallmouth bass, walleye, yellow perch, bluegill, warmouth, etc.), hybridize with native species (e.g., brook trout and bull trout), and compete with native species for habitat and food resources. Many invasive species benefit simply from increased maximum temperatures, but increased minimum temperatures in winter may allow non-native species to successfully invade streams and rivers where they currently are excluded by low winter temperatures. Distributions of non-native species have been documented in the Pacific Northwest (LaVigne et al., 2008), but there has been little research on factors that determine their success or their impacts on native communities (see Case Study 7A).

7.3.2.5 Adaptation to temperature increases through contemporary evolution

Surface water temperatures are projected to increase by roughly 2–4°C (4–7°F) over the next 100 years (Chapter 3). In many streams and rivers, these temperature increases will either exceed the lethal level for some species or lead to declines caused by physiological and reproductive stress, disease, competition, predation, or presence of invasive species at temperatures lower than lethal levels. This scenario assumes that these species have no ability to adapt to changing temperature. Recent research in New Zealand observed that fall Chinook salmon transplanted from the Sacramento River in 1901 and subsequently outplanted or migrating to warmer rivers in New Zealand have evolved in response to the warmer rivers (Quinn et al., 2001; Kinnison et al., 2008). In less than 30 generations, there was divergence of traits (such as age at maturity, date of return to freshwater, reproductive morphology, reproductive allocation) and shifts in physiological performance (survival and growth) (Quinn et al., 2001; Kinnison et al., 2008). Physiological responses have shifted their maximum physiological performances by as much as 2°C (4°F), indicating that some species like salmonid fishes might be able to adapt to and survive projected temperature increases. Others have observed heritable shifts in traits of sockeye salmon populations in fewer than 13 generations (Hendry et al., 2000). Ecological adaptation and contemporary evolution could allow some species to "keep up" with changing temperature regimes in the Pacific Northwest. Note that salmonid fishes exhibit faster trait divergence and evolutionary rates than many other fish species. Contemporary evolution may not be effective in helping other species of native fish adapt to climate change.

7.3.2.6 Restoration actions to moderate the effects of climate change

The major actions that could be taken to minimize habitat losses and ecological consequences of climate change for freshwater fishes in the Pacific Northwest include (1) maintaining water volumes in streams and rivers, (2) improving water quality and habitat complexity in degraded reaches, (3) maintaining natural flow regimes to the extent possible, (4) protecting and restoring riparian and floodplain vegetation, (5) maintaining dynamics floodplains and channels, (6) protecting existing cold-water refuges, and (7) restoring watershed conditions in uplands. These actions are not novel or unique to climate change. These are conservation actions repeatedly called for by all resource management agencies in the Pacific Northwest for the last 50 years. The challenge of climate change in freshwater ecosystems is not a need to respond to a new change but rather the need to implement existing conservation strategies more widely and successfully.

Life histories of aquatic organisms in freshwaters of the Oregon are complex. Some fish species, such as rainbow trout (*O. mykiss*) and cutthroat trout (*O. clarki*), have both resident and anadromous life histories (anadromous rainbows are called "steelheads"). Responses to changes in water temperature and discharge related to climate change may include complex shifts in proportions of life history types, distributions, and timing of life history stages. Changes in freshwater streams, lakes, estuaries, or ocean can be modified by differences in changes in these other major regional habitats within the geographic range of the species. Management decisions will be complex, possibly amplifiying, counteracting or altering the biological responses to environmental shifts related to regional climate change. Monitoring of resource trends and anticipating alternative trajectories of change will be essential for effective adaptive management (see Case Study 7B).

Many ecosystem services, such as flood storage in river floodplains, habitat for aquatic communities, cold-water refuges, and riparian (riverbank) wildlife habitats have been dramatically reduced over the last 150 years in the Pacific Northwest as a result of channel alteration, dikes, riprap, flood control, water withdrawal, and waste discharge. River and stream channels have been straightened and hardened and channel-forming high water flows have been reduced. Floodplain forest and riparian habitats have been reduced by more than 80% in the lowlands. River temperatures have increased and many cold-water refuges along river margins have been destroyed. Restoration measures include efforts to repair channel dynamics (e.g., removal of bank-control structures, reconnection of historical alcoves and other lateral habitats), revegetation (e.g., reforestation, restoration of non-forest wetlands), decreased consumption and removal of surface water, water reuse, and matching various uses to different water-quality sources (Battin et al., 2007). The scientific and logistic challenges of these restoration efforts are substantial, but the rate of restoration mostly is limited by social constraints (e.g., land owner participation and attitude, effective incentives, policies and governance structure).

7.4 Ocean Life

Oregon's territorial sea extends from the beach to 3 nautical miles offshore, yet is part of a much larger ocean region known as the California Current Large Marine Ecosystem (Sherman, 1991). The chemical and physical properties of Oregon's ocean environment, including past and predicted changes due to warming and acidification, are reviewed in Chapter 1. Regarding sea life, our region is part of the Columbian Pacific Marine Ecoregion, extending coastally from Vancouver Island south to Cape Mendocino in northern California (Wilkinson et al., 2009). A region of seasonal upwelling that fertilizes nearshore waters and supports a productive ecosystem, Oregon's territorial sea and numerous estuaries at the mouths of major watersheds support a broad variety of plant and animal life of immense ecological, cultural and economic value, especially in terms of tourism and fishing.

This rich cornucopia of ocean species lives as a web of consumers and prey (Fig. 7.7), the basis of which are the tiny, single-celled, drifting phytoplankton that are the grasses of the sea. These plant-like organisms are eaten by zooplankton, tiny drifting animals that include both permanent forms and the early life stages (larvae) of fishes and larger invertebrates. Many larger animals eat zooplankton, and so the web builds upwards to the top predators, including large fishes, seabirds, marine mammals, and, of course, humans. Because this complex food web interconnects so many species, and because each part of the web faces specific issues with respect to ocean warming and acidification, this section covers in turn phytoplankton, zooplankton, seafloor life, fishes and fisheries, seabirds, and marine mammals.

It is important to keep in mind that predicted future changes in each of these groups of sea life will propagate through the entire food web in ways that may not be predictable. Such indirect effects include both bottom-up processes, involving changes in the productivity of phytoplankton and seaweeds that feed higher levels in the food web, as well as top-down processes, involving changes in the distribution and abundance of top predators that affect lower levels. Overall, it is highly likely that substantial surprises will be forthcoming in ocean ecosystems during this century as the ocean warms and acidifies.

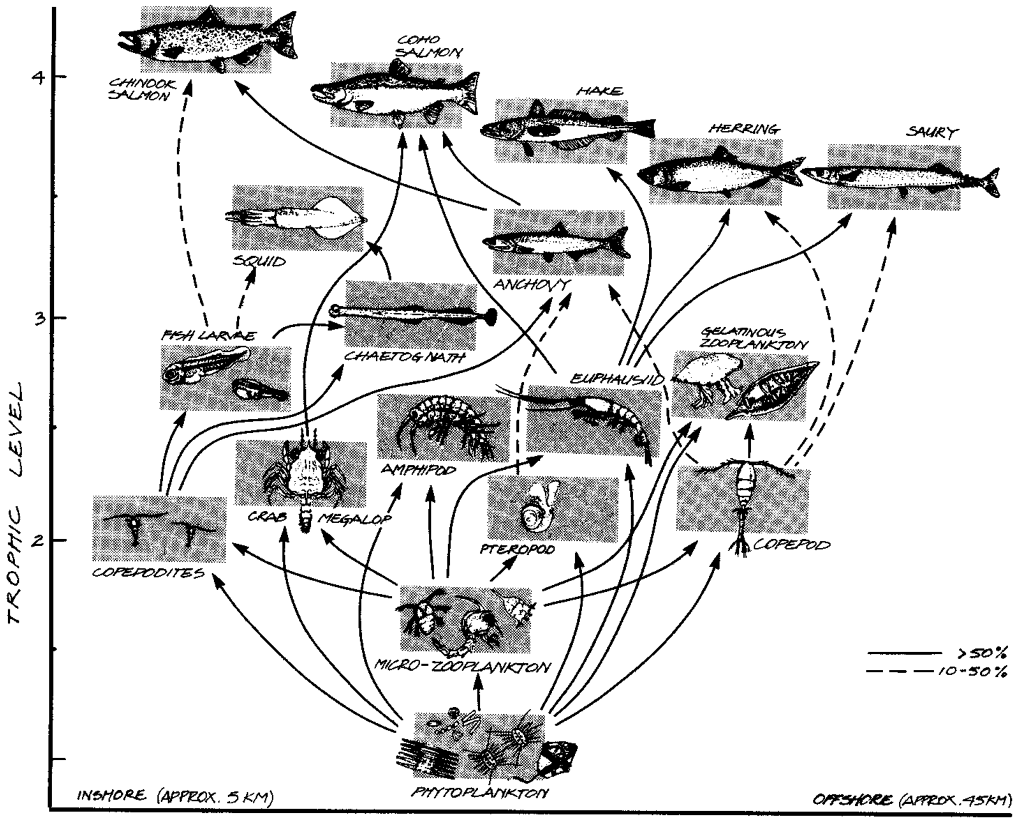


Figure 7.7 Partial food web in Oregon's ocean. Arrows flow from prey to predators, with dashed arrows representing minor links (10–50% consumption). Lower trophic levels feed higher trophic levels. Many species are missing, including larger fishes, seabirds, marine mammals, and human fisheries, as well as all seafloor species. (From Oregon Ocean Resources Management Task Force, 1991.)

7.4.1 Phytoplankton: base of the ocean food web

The term phytoplankton, from the Greek "phyton" (plant) and "planktos" (wanderer), encompasses all microalgae and bacteria that, in the same manner as terrestrial plants, are able to use inorganic nutrients and sunlight to fuel photosynthesis, growth and reproduction. Although they are generally small in size, ranging from 1 to 50 μm (micrometer), phytoplankton are responsible for the production of food and energy that supports most forms of life in the coastal marine environment (Fig. 7.7). Although most phytoplankton are harmless to higher trophic levels—including humans—a few species can develop into harmful algal blooms. Living at the base of the food web, phytoplankton will be the first responders to climate change. Thus, efforts to monitor alterations in the patterns of abundance, diversity and activity of this vital component of the ocean ecosystem are necessary to inform our understanding of potential impacts on higher trophic levels.

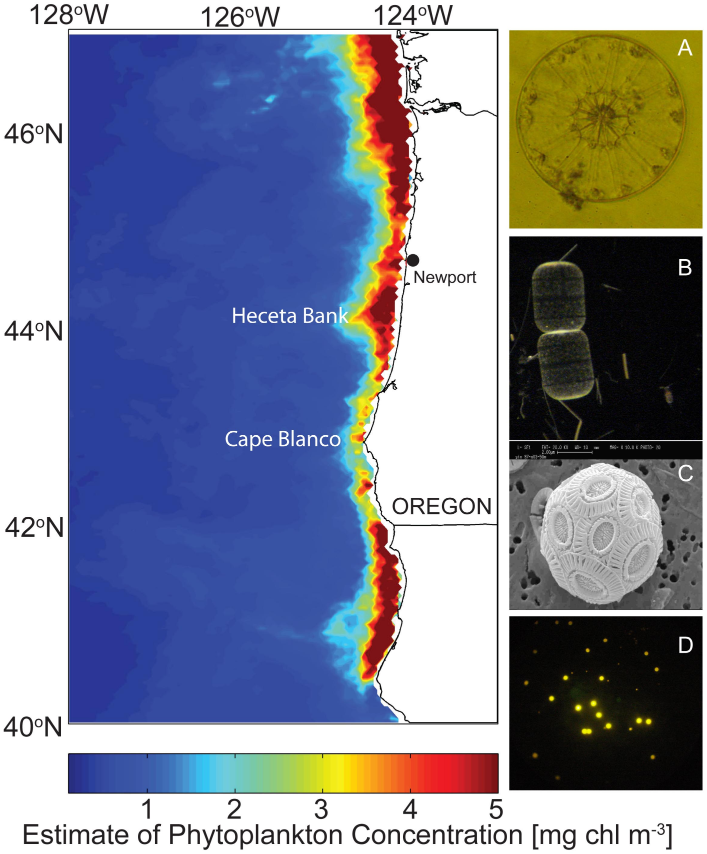


Figure 7.8. Annual mean phytoplankton concentrations for the Oregon region in 2009, where blue represents low levels and red, high levels. The location of Newport, the coastal outcropping at Cape Blanco, and the offshore rocky region, Heceta Bank, are noted. Images to the right illustrate phytoplankton groups common to local waters, including (A–B) diatoms, (C) coccolithophores, and (D) small single-celled cyanobacteria.

7.4.1.2 Variation in time and space

The marine environment over the continental shelf off the Oregon coast supports a large diversity of phytoplankton (Fig. 7.8), including all major classes of microalgae and photosynthetic bacteria (Rappe et al., 1998). However, the abundance of these classes varies in space and time, with primitive microalgae dominating in coastal regions and during periods of high nutrient concentrations, while small marine unicellular photosynthetic bacteria increase in relative abundance as nutrient and productivity levels decrease offshore. Furthermore, phytoplankton concentrations and productivity display a strong seasonal cycle, with maximum values observed during summer upwelling (Thomas et al., 2001; Chapter 1). As these upwelled, nutrient-rich waters move from the coast into the open ocean, phytoplankton grow, remove excess nutrients and form large accumulations (termed "blooms") that ultimately support higher trophic levels and enhance fishery yields.

The accumulation of phytoplankton along the Oregon coast is not uniform as the distributions of these photosynthetic organisms are affected by ocean currents, seafloor contours, and river inputs (Barth and Wheeler, 2005). For example, during summer months, the southward movement of the Columbia River plume acts as a boundary for the offshore extent of elevated concentrations of phytoplankton along the northern Oregon coast. South of Newport, phytoplankton blooms move offshore, as currents flow around the west side of the prominent Stonewall and Heceta Banks and then return to the coast (Barth 2003). The return flow often tends northward, making these banks retentive features that contribute to the accumulation of organic matter resulting from phytoplankton productivity. Finally, the outcropping of Cape Blanco is another topographic feature that forces coastal currents offshore, transporting plankton into the open ocean as well as creating a region of high retention for phytoplankton and larvae south of the Cape. Thus, during the summer months, Heceta Bank and Cape Blanco are zones of persistent and elevated productivity, supporting major fishing grounds. In contrast to the summer upwelling dynamics, the delivery of nutrients into the coastal ocean by rivers becomes an important factor during winter months, affecting the growth and distribution of nearshore phytoplankton. Recent studies suggest that inputs from rivers contribute significantly to the availability of iron and other essential micro-nutrients in these coastal ecosystems (Chase et al., 2007).

In addition to seasonal and latitudinal variability in phytoplankton production, there is also strong between-year variability caused by two main factors: (1) the onset and strength of the upwelling season, and (2) the occurrence of El Niño events. The timing and strength of the upwelling season, possibly caused by the latitudinal position of the jet stream in the upper atmosphere (Bane et al., 2007, Barth et al., 2007) or other atmospheric forcing anomalies (Schwing et al., 2006), not only affects the delivery of nutrients to the well-lit upper layers of the water column, where phytoplankton have sufficient light to grow, but also can delay the transfer of energy to higher trophic levels (Barth et al., 2007). This timing of food availability may be critical to species with strong seasonal reproductive or migratory cycles.

El Niño events, as well as longer-term inter-decadal changes in ocean conditions over the North Pacific, termed the Pacific Decadal Oscillation (PDO, see Chapter 1), can bring warmer waters along the Oregon coast that appear to displace zooplankton populations northward, and probably phytoplankton species as well (Peterson and Keister 2002). In addition, these warm waters deepen the position of cold and nutrient rich waters along the coast, causing a reduction in the availability of nutrients in the well-lit surface layers that support phytoplankton growth and accumulation during the upwelling season. As a result, fisheries production typically drops during El Niño events and warm phases of the PDO (Pearcy and Schoener, 1987; Mantua et al., 1997).

7.4.1.3 Effects of climate change

Although we do not have extensive data characterizing long-term changes in phytoplankton abundance, diversity, and productivity in response to climate trends, we can still assess the potential effects of predicted changes in environmental factors (previously described in Chapter 1). At a regional scale, long-term changes in the position of the upper atmospheric jet stream affect the timing and duration of upwelling, and hence the delivery of nutrients to the surface ocean and the magnitude of annual primary production in coastal waters. In addition, these changes have substantial effects on annual precipitation and evaporation over the continent, causing changes in the magnitude of terrestrial nutrient inputs to coastal ecosystems through river discharges. However, land and water use changes in the Columbia and Klamath Basins may need to be considered when assessing long-term changes in river inputs along the Oregon Coast and their impact on coastal phytoplankton dynamics (see Chapter 3).

At a broader scale, potential changes in the dynamics of the offshore North Pacific Ocean, including changes in large-scale currents and increasingly warm surface waters that form a barrier to vertical mixing, may affect the chemical composition of seawater being delivered to and upwelled near the coast of Oregon. Several recent studies have suggested that significant changes in water chemistry can already be observed at large scales, including a decrease in oxygen content (Chan et al., 2008) and an increase in acidity (Feely et al., 2009). Alterations of the rate and magnitude of the delivery of nutrients to the surface ocean could not only alter primary productivity but also lead to changes in the decomposition of this organic matter and a biological drawdown of oxygen (via respiration) which could worsen regions of hypoxia, better known as "dead zones."

7.4.1.4 Dead zones

Off the coast of Oregon, hypoxic (low oxygen) and anoxic (effectively no oxygen) events have affected both the water column and the benthic environment during the past decade (see also Sections 7.4.2 and 7.4.3). However, the strength and duration of these events displays strong inter-annual variability (Grantham et al., 2004; Chan et al., 2008) resulting from chemical properties of upwelled water, the strength and frequency of upwelling favorable winds along the coast (see Chapter 1), and the ensuing rates of primary production and subsequent microbial respiration over the continental shelf. Although the production and sedimentation of organic matter by phytoplankton plays an important role in the enhancement of hypoxic and anoxic environments over the shelf, it is less clear how the reduction of oxygen in subsurface waters affects phytoplankton diversity and abundance in surface waters. A loss of upwelled nutrients through denitrification (nitrogen gas releasing) processes in hypoxic waters can also occur. However, this loss is relatively small compared to the availability of nutrients during upwelling periods. In coastal regions experiencing severe hypoxia during summer months, such as the central coast of Chile and off Peru, phytoplankton abundance and diversity in surface waters remains high (Escribano et al., 2003), suggesting that an expansion in space and time of hypoxia over the Oregon continental shelf will primarily affect higher trophic levels, subsurface and seafloor microbial processes, and the nutrient cycles they control.

7.4.1.5 Ocean acidification and phytoplankton

The human-induced rise in atmospheric carbon dioxide (CO_2) and subsequent transfer of a portion of this anthropogenic CO_2 to the oceans may also impact the chemical and biological function of our ecosystems (Doney et al., 2009). By removing CO_2, oceanic uptake has slowed the pace of human-induced climate change while creating another problem: a change in ocean carbonate chemistry and a decrease in ocean pH levels. This phenomenon, termed "ocean acidification," has already led to a decrease in the mean pH of the California Current system to levels that previously were not expected to occur for decades (Hauri et al., 2009). It is not clear to what extent these changes have affected the diversity and activity of phytoplankton. However, output from models and our understanding of the physiology of organisms cultured in a laboratory setting suggest that there will be clear winners and losers emerging as the ocean acidifies (Doney et al., 2009; Hauri et al., 2009).

7.4.1.6 Harmful algal blooms (HABs)

Major groups of phytoplankton observed along the Oregon coast include a variety of types and cell sizes (Anderson, 1965; Sherr et al., 2005). As outlined above, phytoplankton form the primary source of food sustaining coastal fisheries. However, phytoplankton blooms can also be detrimental to local ecosystems and the economy. Although we have adequate knowledge of the major factors controlling the distribution of total phytoplankton abundance and productivity along the Oregon coast in time and space, we still have only a rudimentary understanding of the factors controlling variability in the distributions of particular species of phytoplankton. The issue of which species dominate the composition of phytoplankton is of particular importance when trying to characterize and predict the abundance of species that have a strong negative impact on human health and the local economy. Some of these species include those that generate harmful algal blooms (HABs).

Of the major phytoplankton groups, diatoms and dinoflagellates are known to include species that can have adverse ecological and socioeconomic effects through the generation of HABs off the Oregon coast. Of particular interest are the diatoms *Pseudo-nitzschia* spp., and the dinoflagellates *Alexandrium* spp. and *Akashiwo sanguinea*. Certain, but not all, strains of *Pseudo-nitzschia* produce a neurotoxin called domoic acid which accumulates in coastal shellfish such as razor clams and mussels and can lead to amnesic shellfish poisoning (ASP) in humans. Similarly, armored dinoflagellates of the genus *Alexandrium* produce saxitoxin, a potent neurotoxin responsible for paralytic shellfish poisoning (PSP) in humans (Horner et al., 1997).

Long-term monitoring efforts off the Oregon coast indicate that *Alexandrium* blooms appear to predominate south of Cape Blanco, whereas along the central and northern Oregon coast, *Pseudo-nitzschia* seems to be the major group responsible for HABs and the closure of commercial shellfisheries (Fig. 7.9). In addition, the dinoflagellate *Akashiwo sanguinea* was responsible for an extensive bloom off Washington and northern Oregon in 2009 that caused significant seabird mortality as a result of algal production of chemicals that dissolved the natural oils found in feathers. Without these oils, seabirds can lose body heat and die of hypothermia (see Section 7.4.5).

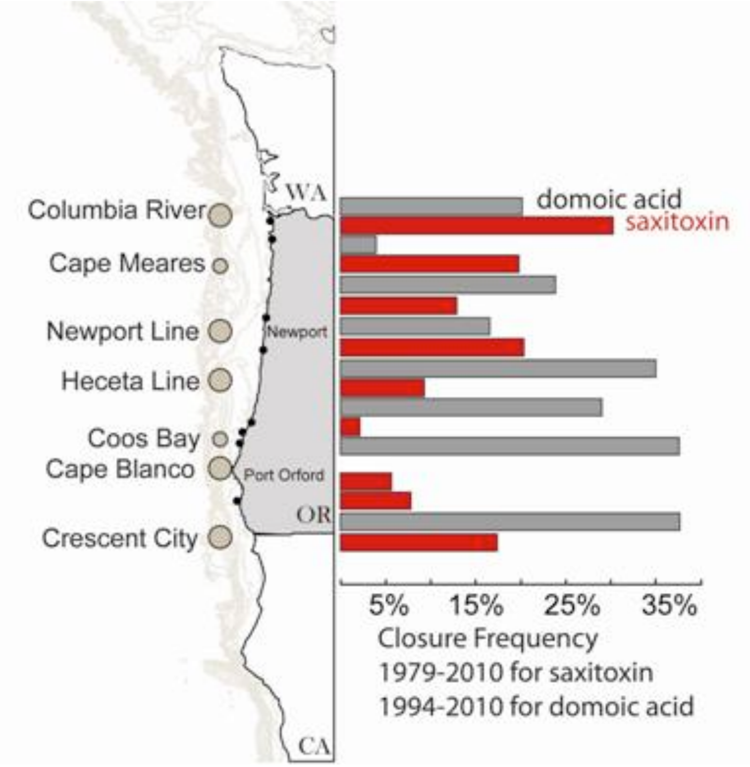


Figure 7.9 Left: Current sites in the Oregon surf zone (dots) and offshore sampling lines (circles) sampled for harmful algal blooms relative to ocean depth contours (gray lines). Regions near the Columbia River outflow, Heceta Bank and Cape Blanco are sites of strong summer phytoplankton blooms. Right: The percentage of positive samples exceeding shellfish fishery closure limits are shown as bars for domoic acid (grey) and saxitoxin (red) at different latitudes along the coast.

HABs have afflicted the west coast of the United States for decades. However, over the past 15 years their frequency has increased significantly (Hallegraeff, 1993; Anderson et al., 2008). In Oregon, HAB events have led to more frequent closures of commercially important razor clam and mussel fisheries and exerted a considerable economic impact on coastal communities in Oregon.

At present, although we understand the environmental conditions leading to the development of phytoplankton blooms along the Oregon coast, we still do not know what combination of physical, chemical, and biological factors select for the development of a specific harmful algal bloom. Recently, Tweddle et al. (2010) reported that saxitoxin contamination of mussels south of Cape Blanco is strongly associated with late-summer upwelling. Thus, latitudinal variations in upwelling expected under various climate change scenarios (Bakun, 1990; Schwing and Mendelssohn, 1997) may significantly affect the frequency and distribution of this HAB along the west coast. For this reason, the effect of both the timing of upwelling and the spatial patterns of bloom formation along the Oregon coast must be better understood to improve our capacity to assess how and to what extent climate change may affect the diversity of phytoplankton species that cause harmful algal blooms.

7.4.2 Zooplankton: Food for Sea Life

Zooplankton are small animals—often 0.2 to 40 mm (0.008 to 1.6 in) in body length—that inhabit open marine waters, including the estuaries, nearshore ocean, and offshore areas off Oregon. Zooplankton are diverse, with representatives from most major animal groups (phyla). Peterson and Miller (1976) found close to 100 species of zooplankton (excluding protists) on the inner-middle continental shelf of Oregon, with the greatest diversity within the copepods (estimated 58 species). Some of the most important zooplankton in our region are tiny and relatively poorly studied protists (Neuer and Cowles, 1994), euphausiids (Gomez-Gutierrez et al., 2005), copepods (Peterson and Miller, 1975, 1976), and a group collectively known as gelatinous zooplankton: pelagic tunicates (salps and doliolids) (Lavaniegos and Ohman, 2007) and jellyfish of various kinds (Suchman and Brodeur, 2005). Some gelatinous zooplankton are relatively large, and in some summers can become very abundant, with blooms developing rapidly. However, these events are intermittent, often short-lived, and difficult to predict or relate to specific ocean conditions.

This review considers only euphausiids (commonly called "krill") and copepods for two reasons. First, euphausiids and copepods, especially the latter, dominate the abundance and species diversity of mid-sized zooplankton off Oregon, and second, the other types of zooplankton have not been sufficiently studied to examine seasonal and interannual variability and long-term trends. The life spans of many copepods are several weeks to 4–5 months, while the dominant euphausiids off Oregon have 1–2 year life spans. These mid-sized zooplankton are important ecologically because they are a key conduit for the transfer of photosynthetic production by phytoplankton (Section 7.4.1) to higher trophic levels, such as forage fish, harvested fish species, and marine birds and mammals (Sections 7.4.4–7.4.6). The type of copepods, their individual size, and their lipid (fat) content, may be important in determining whether the food web of the Oregon shelf is good or bad for growth and survival of organisms at higher trophic levels, such as anchovies and salmon (Fig. 7.4.A). Because of their small size and relatively weak swimming ability, zooplankton drift with the ocean currents. Thus, unlike stronger swimming fish, their distributions are strongly controlled by physical processes rather than biological movements.

7.4.2.1 Variation in time and space

Climate variability may affect zooplankton populations in several ways, perhaps altering species composition, relative abundances, reproductive output, and the magnitude and timing of changes in these factors. Also, because zooplankton, by definition, drift with ocean currents, species distributions may change due to altered currents. Many of these factors are unknown for most species, and what is known focuses on zooplankton variability derived from sustained sampling programs off the coast of Oregon. In some cases, zooplankton patterns off northern California or southern British Columbia are similar to those off Oregon (e.g., Mackas et al., 2004, 2006), and so provide information relevant to Oregon. Temporal variability in zooplankton biovolume is spatially coherent along the coast of California (Chelton et al., 1982; Roesler and Chelton, 1987). Given significant alongshore covariability of zooplankton biomass within the California Current Large Marine Ecosystem, it should be noted that Roemmich and McGowan (1995ab) reported that the total biomass of zooplankton off southern California declined by 80%

between the late 1960s and the mid-1990s. However, this result has been rebutted by several subsequent papers (Lavaniegos and Ohman, 2003, 2007) that showed that zooplankton biovolume (used by Roemmich and McGowan) was biased by the decline of pelagic tunicates, which have large biovolumes but small carbon biomass. There was in fact no long-term trend in total zooplankton carbon biomass nor of the dominant planktonic copepods or euphausiids off southern or central California, in contrast to the earlier reported multidecadal decline in zooplankton biovolume (Lavaniegos and Ohman, 2007).

The section of Chapter 1 on physical changes in the marine environment concludes that, during the past 30–50 years, Oregon's coastal ocean has experienced (1) increased intensity of upwelling, (2) increased variability of upwelling, (3) increased summer water temperatures, (4) reduced spring-summer Columbia River discharge of freshwater, (5) decreased summer salinity of subsurface waters, and (6) declines in near-bottom oxygen concentrations, especially close to shore. Zooplankton off Oregon are strongly influenced by both regional coastal and global marine environmental factors. Important regionally is the seasonal influence of alongshore winds that affect upwelling of deeper nutrient-rich waters, and the role of freshwater from the Columbia River (Huyer et al., 2007). In the winter, winds blow from the south along the Oregon coast. This causes surface waters to move onshore, and pile-up at the coast, pushing inshore waters downward in the water column and offshore, a process called "downwelling." However, sometime in spring, often in April but varying in time from year to year (Pierce et al., 2006), the large-scale atmospheric pressure systems over the Pacific and North American continent shift, and the wind off Oregon shifts to blowing from the north, a seasonal change known as the "spring transition" (Checkley and Barth, 2009). With southward winds, surface water is pushed offshore and is replaced near the coast with water that ascends from deeper depths, a process called "upwelling." Upwelled water is cold, salty and rich in the inorganic nutrients required to fuel photosynthesis by phytoplankton (see Chapter 1 and Section 7.4.1). The copepods, euphausiids and gelatinous zooplankton consume phytoplankton to support their growth and reproduction. A second effect of the change in wind direction is that, prior to the spring transition (e.g., in winter), alongshore flow is primarily from the south, transporting zooplankton species that are more common in California northward into Oregon waters. After the spring transition (e.g., in summer), alongshore flow is to the south, transporting northern species of copepods to Oregon.

Oregon’s ocean is also affected by changes occurring elsewhere in the Pacific Basin. For instance, changes in atmospheric pressure systems, winds and ocean surface temperatures in the equatorial Pacific associated with El Niño can have effects that influence seawater characteristics and temperatures as well as species composition and abundance of zooplankton off Oregon (Peterson et al., 2002; Keister et al., 2005). Longer-term, interdecadal changes in North Pacific atmospheric pressure systems and ocean conditions—the Pacific Decadal Oscillation—can change ocean current strengths and water temperatures off Oregon that affect the species composition, distribution and abundance of zooplankton and fish off Oregon over periods of years (Batchelder et al., 2002; Peterson and Schwing, 2003).

To evaluate whether climate change affects zooplankton biomass or community structure, one must first examine and account for the influence of seasonal factors and between-year variability on zooplankton. Off the U.S. west coast generally, two specific North Pacific climate indices, the Pacific Decadal Oscillation (PDO) and the North Pacific Gyre Oscillation (NPGO) (Di Lorenzo et al., 2008), explain significant annual-to-decadal variability in temperature, salinity, nutrient concentrations, phytoplankton and zooplankton. Hooff and Peterson (2006) documented the mean seasonal cycle of copepod biomass and number of species at a permanent station off Newport. Both measures exhibited strong seasonality reflecting the influence of upwelling on productivity (abundance is highest during the May to September summer upwelling) and coastal currents (number of species is lowest during May to September). The number of species reflects the influence and mixing of different sources of seawater that have different copepod species, with northern sources having generally fewer species than southern sources. To remove the strong seasonal influence, we focus here on the summertime (May to September) period, where abundance is high and species richness relatively low. Using data collected from the summers of 1969–2007, we find that the number of copepod species and the biomass of warm water copepods is greatest when the PDO index value is positive and the ocean off Oregon is anomalously warm, and that there is not a long-term "ocean warming" trend in total copepod biomass (including both cold and warm water types). Using data from Hooff and Peterson (2006), Peterson (2009) argued that copepod species richness on the inner-shelf of central Oregon has increased by 2–3 species over this 40-year interval. However, an analysis that accounts for the effect of the PDO on the number of species during the summer months, suggests that there has been no detectable long-term increase in the number of copepod species in our region (Batchelder and Peterson, unpublished data).

Mackas et al. (2007) recently summarized changes in zooplankton in the region immediately to the north of Oregon during 1979–2005. Their results have some relevance to the Oregon region because many of the seasonally dominant species off Oregon are shared with British Columbia (BC). Overall, zooplankton populations between Oregon and BC have exhibited northward latitudinal shifts in their geographic centers of abundance in response to episodically warm conditions (Mackas et al., 2001; Batchelder et al., 2002; Peterson and Keister, 2003; Keister et al., 2005). Throughout this period, biomass of northern copepods and southern copepods have varied inversely. Northern copepods increase off Oregon and BC when temperatures are cool and southward currents are stronger, while southern copepods are associated with warm temperatures and northward transport. This effect is most evident during strong El Niños and La Niñas (the opposite conditions of El Niño), but is also observed in relation to longer-term temperature fluctuations associated with the PDO (Mackas et al., 2004; Keister and Peterson, 2003; Keister et al., 2005). These PDO-associated variations in species composition between "northern" and "southern" species influences the overall bioenergetic content of the food web —northern species are lipid-rich whereas southern species are lipid-poor (Lee et al. 2006). Thus, fish such as salmon which need lipid-rich prey (euphausiids and small pelagic fishes such as smelts and anchovies) have higher survival when cold water zooplankton dominate. Similar shifts in species composition and community structure have been observed in four copepod species assemblages in the Northeast Atlantic (Beaugrand et al., 2002). Such changes may become more common as ocean warming progresses, with effects on other zooplankton species (which may also move northward), as well as on higher trophic levels that are accustomed and adapted to feed on the "normal" zooplankton that were typical until recently.

The large copepod *Neocalanus plumchrus* is abundant in the Gulf of Alaska and off Canada, but is usually less important off Oregon (but see Liu and Peterson, 2010). Mackas et al. (2007) have documented phenological (life history timing) changes in *N. plumchrus* that appear to be due to warming of the surface waters providing faster growth and development. The same observation has been made off Oregon (Liu and Peterson, 2010). Interestingly, in 2007 and 2008, copepods of the genus *Neocalanus* have been more important and constituted a greater fraction of the spring zooplankton biomass on the Oregon continental shelf than during earlier years. Since these species are typical of northern waters, this pattern suggests that there was greater southward inflow to the Oregon system during those years. The cause of this sudden brief increase in biomass is not known.

7.4.2.2 Ocean acidification and zooplankton

Observed and projected human-caused increases in atmospheric concentrations of the greenhouse gas carbon dioxide suggest that concentration of this greenhouse gas in seawater has increased and will increase, increasing the acidity of the ocean as carbon dioxide reacts with water and forms carbonic acid, a phenomenon called "ocean acidification" (OA). Regions of the west coast, including Oregon, have recently been found to be particularly susceptible to OA, due to the upwelling of deep waters having high carbon dioxide content and low pH (Feely et al., 2008; Hauri et al., 2009). More acidic conditions reduce the availability of carbonate ions to marine organisms that form calcium carbonate (essentially, limestone) skeletons or shells. One group of zooplankton, the pelagic pteropod snails, use calcium carbonate to form their thin and fragile shell, and are particularly susceptible to more acid ocean conditions (Orr et al., 2005; Fabry et al., 2008). The ability of these pelagic snails to form or maintain the integrity of their shells is reduced in more acidic waters. The pteropod *Limacina helicina* was present in more than half of the Oregon nearshore samples of Peterson and Miller (1976), and was most abundant in May and June. Seasonal upwelling enhances the development of high acidity, corrosive waters in spring and summer, which might affect these marine snails. To date, there have been no specific studies to evaluate shell dissolution rates or growth rates of these snails off Oregon, but studies on *L. helicina* elsewhere suggest they experience significant shell dissolution in high carbon dioxide waters (Orr et al., 2005). One ecological significance of pteropods is that they are prey for the larvae of some marine fishes.

In summary, because of a concerted and ongoing effort to sample zooplankton at a variety of scales of time and space during the past decade off Oregon, we have learned much about the temporal and spatial patterns of fluctuations in abundance and species composition. However, this decade of sampling has also shown the tremendous amount of variability in “climate forcing” and how that has influenced the ocean ecosystem, including the zooplankton. Several “anomalous” events, including (1) one of the strongest recorded El Niños in 1997–1998, (2) a strong La Niña in 1999, (3) a prolonged three-year cold period through 2003, including anomalously strong southward flow of subarctic waters in 2002, and (4) a very late spring transition to upwelling in 2005, have clearly shown that the zooplankton assemblage, production, and abundance respond strongly and rapidly to environmental variation at multiple spatial scales. This variability is superimposed on strong seasonal cycles. Although there are hints of how zooplankton populations on the Oregon shelf may respond to climate variability and global warming, there are no well documented trends as yet that indicate clearly the direction or magnitude of future changes. Clearly two physical factors seem to control species composition and rates of production, the Pacific Decadal Oscillation and strength of local upwelling. However, it is not clear how either will change in the future (Chapter 1). Only a handful of global climate models include the PDO, but those that do project that the PDO will continue into the future (Wang et al., 2010). Bakun (1990) suggested that local upwelling will intensify due to stronger gradients between the North Pacific high and the low pressure system centered over the western United States, yet there is as yet no evidence that this is happening.

7.4.3 Seafloor Species: Invertebrates and Seaweeds

The responses of seafloor-dwelling invertebrates and seaweeds to ocean warming and acidification are likely to be complex, with a host of factors changing and a variety of consequences arising (Harley et al. 2006). Evaluating how seafloor species along the Oregon coast have responded to climate change is severely compromised by the general lack of long-term data sets on these organisms. Although research on populations and communities of organisms that live along the Oregon shore has been ongoing for decades, funding patterns typically have limited the duration of studies to relatively short periods, usually a few years at a time. The primary exception has been research on rocky intertidal zones conducted by the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) program, a consortium of four universities along the U.S. west coast, with Oregon State University as the lead institution (http://piscoweb.org).

If one moves beyond Oregon to consider the entire coast of the California Current Large Marine Ecosystem (CCLME), which ranges from the Straits of Juan de Fuca in Washington to the tip of the Baja California peninsula, a few additional data sets become available. The following summarizes trends seen in these limited data sets, focusing first on Oregon and then adding insights obtained from the broader CCLME. Examined are the extents to which these changes may reflect responses to climate change, and conclusions focus on the kinds of threats faced by marine organisms from well-documented changes that are currently underway in the climate of the northern CCLME (Chapter 1).

7.4.3.1 Rocky intertidal invertebrates

Data gathered for up to 20 years along the Oregon coast have revealed that the abundance of phytoplankton and the recruitment of mussels (clam-like species that attach to rocks) increased dramatically during the 2000s (Menge et al., 2009). Mussel growth rates have also increased in response to the increases in phytoplankton, an important food source for mussels, which filter such food particles out of seawater (Menge et al., 2008). These changes are linked to climate fluctuations, as reflected in El Niño Southern Oscillation (ENSO), the North Pacific Gyre Oscillation (NPGO), and the Pacific Decadal Oscillation (PDO) (see Chapter 1). Such climatic cycles vary in duration from the relatively short ENSO (3–7 years) to moderate NPGO (10–15 years) to long PDO (20–30 years). Each has been found to underlie major natural shifts in marine ecosystems (e.g., Glynn, 1988; Chavez et al., 1999; Peterson and Schwing, 2003; Di Lorenzo et al., 2008).

Off Oregon, strong links have been detected between the NPGO and large increases in phytoplankton and mussel recruitment (Menge et al., 2009). ENSO and PDO did not appear to have an influence, suggesting that the 10–15 year shifts in winds that are reflected in the NPGO are the primary drivers of these changes. The suggested mechanism causing this link is that, with stronger winds over the North Pacific, coastal phytoplankton blooms are denser, leading to higher survival of larvae of mussels, and perhaps more favorable conditions for movement of larvae to the rocky shore. Whether or not these changes are a result of climate change is not clear as data sets are not yet long enough to resolve long-term trends.

The rate of mussel growth is a potentially valuable indicator of mussel well-being. Faster growth resulting from higher food likely decreases the time to maturity and enhances reproductive output. Faster growth also influences competitive ability; in the mussel world, large size means an ability to overgrow and smother other organisms competing for attachment space on rock surfaces (Paine 1966). The increase in phytoplankton in the 2000s led to a surge in growth of mussels along the Cape Foulweather region of Oregon, which brought their growth on par with mussels along the Cape Perpetua region to the south, but did not change growth rate in the latter region (Menge et al., 2008). This finding likely indicates that mussel feeding capacity is limited (e.g., Hawkins and Bayne, 1992), such that, above some threshold level, mussels are unable to consume additional food. In this case, mussel growth was linked to both ENSO and PDO climate patterns, with faster growth occurring during warm-phase events of both of these cycles. This pattern indicates that temperature also affects mussel growth. The stimulating effect of warmer water likely is limited because, like most invertebrates, mussels have an upper temperature tolerance limit, beyond which they die (Somero 2002, Jones et al. 2009). This link to water temperature, which has shown long-term increases over the Oregon continental shelf (Chapter 1), predicts that mussels will initially benefit from warming of coastal waters, but unless they can adapt rapidly, will eventually decline.

How have intertidal ecosystems responded to these changes in the coastal ocean? Have mussels become more abundant? Scientists have thus far found no persistent change in the abundance of mussels, barnacles, and other rocky intertidal organisms (Menge et al., 2010). Thus, despite recent large inputs of new mussels, the abundance of large mussels has not yet changed. The reasons for this lack of response are unknown. In contrast to mussel recruitment, barnacle recruitment did not change in the 2000s (Menge et al., 2010). This result is important because the tiny mussel recruits depend on the textured surfaces provided by barnacle populations already attached to the rock. So, if barnacle populations have not changed, there is no way for mussel colonization to increase despite the large numbers of larvae seeking an attachment location. This result suggests that responses to climatic variation differ among the different species of the rocky intertidal ecosystem.

At present, our ecological information for rocky intertidal invertebrates in Oregon is limited to the above summary, which is clearly inadequate for detection of responses related to climate change. The linkage of some of these patterns or processes to climatic variation, which is expressed in physical conditions such as air or water temperature, wind and current strength, upwelling intensity, wave height, sea level height, and other factors (Chapter 1), potentially could inform forecasts of expected biological changes. When considered in the context of entire ecosystems, however, such efforts are likely confounded by multiple sources of complexity, as suggested by the differential responses of mussel and barnacle recruitment. Thus, one can presently say little that is definitive about how rocky intertidal systems in Oregon are responding to climate change, or about how they will respond in the future, although modeling approaches may help.

7.4.3.2 Rocky intertidal seaweeds

The ecological survey data referenced above also have not revealed any longer-term changes in abundances of seaweeds and other marine plants. Although losses in abundance of giant kelp have been attributed to El Niño events in California (e.g., Paine, 1986; Dayton et al., 1999), no response of intertidal seaweeds (or invertebrates) to El Niño conditions was detected in moderately long-term studies on Tatoosh Island, Washington (Paine, 1986). On the Oregon coast, however, the 1997–98 El Niño led to massive losses of intertidal kelps, such as *Saccharina sessile* and *Lessoniopsis littoralis* (Freidenburg, 2005), likely due to a combination of warm water and low nutrients. Complete recovery occurred within two years, however, and no comparable changes have occurred since, despite the occurrences of weak El Niños in 2003, 2005 and 2007. These perturbations suggest that at least kelps (the large brown algae that dominate kelp forests and exposed rocky shores) would be negatively affected by large increases in temperature and sharp declines in nutrients associated with a warming ocean. As noted in Chapter 1, data are insufficient to determine long-term trends in nutrients, but seawater temperatures off the Oregon coast have definitely been rising, thus suggesting potential negative effects through time. But as also noted in Chapter 1, and as predicted by Bakun (1990), upwelling intensity has been increasing as well, implying colder summer temperatures and higher nutrients inshore, up to about 10 km (6 mi) from shore. These changes may positively affect nearshore marine ecosystems.

7.4.3.3 Ocean acidification and rocky intertidal species

A potentially more serious effect of climate change is acidification of seawater as excess atmospheric carbon dioxide absorbed by the oceans is converted to carbonic acid, which lowers the pH (Orr et al., 2005). Ocean acidification has been forecast as an issue of great concern by chemical oceanographers (e.g., Orr et al., 2005; Doney et al., 2009; Feely et al., 2009), and changes in the acidity of seawater have already been detected (Feely et al., 2004; Fabry, 2008). Importantly, a recent survey of waters along the coast of Oregon and northern California revealed that seawater acidity and levels of aragonite saturation (a measure of the ability of calcifying organisms to precipitate carbonate-based hard parts such as shells) are already at levels not forecast for another 150 yr for the ocean in general (Feely et al., 2008). Thus, it is possible that calcifying species, including animals (mussels, oysters, scallops, clams, limpets, snails, echinoderms, crustaceans) and seaweeds (coralline algae), may be under severe stress in nearshore habitats of the Oregon coast (Pörtner et al., 2004; Vézina and Hoegh-Guldberg, 2008, and included papers; Kroeker et al., 2010). Field evidence suggests that these calcifiers are generally inhibited by high levels of carbon dioxide and resulting acidification of the oceans (Hall-Spencer et al., 2008), although lab studies have yielded more mixed results (Ries et al., 2009). Larvae of calcified marine invertebrates may be especially at risk (O'Donnell et al., 2009). Failure of oyster recruitment has occurred in Oregon in recent years, and studies are underway to determine whether this failure is a consequence of ocean acidification (C. Langdon, OSU, personal communication). Investigation of the impacts of acidification on calcified species in coastal environments will be a research area of high activity in the coming years. At present it is unknown whether invertebrates and seaweeds in Oregon have already been affected by this new challenge.

7.4.3.4 *Changes in California rocky intertidal systems*

In a recent review of how intertidal ecosystems have responded to climate change, Helmuth et al. (2006) documented 21 instances of change, yet only two of these were from the CCLME and both were in California. In central California, re-sampling in the 1990s of plots originally sampled in the 1930s revealed substantial northward shifts in distribution had occurred for 15 of 18 species (Barry et al., 1995; Sagarin et al., 1999; Fig. 7.10). Average water temperature had increased by 0.79°C (1.42°F) and average summer temperature by 1.94°C (3.49°F) over this 60-year period. In southern California, evidence suggests that the northern range limit of the whelk *Kelletia kelletii* had moved northward from about 1980 to 2000 (Zacherl et al., 2003). Finally, Smith et al. (2006) documented a sharp decline in the number of species (average 58.9% loss, maximum 80% loss) associated with intertidal mussel beds. The authors attributed these declines to climate change, but could only speculate on the specific mechanism(s) underlying the loss of species. In any case, Oregon has gained 10 species of invertebrate from California over the past three decades (Carlton, 2000).

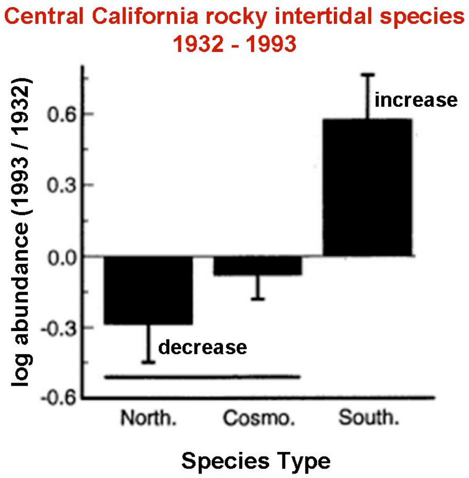


Figure 7.10 Relative changes in the abundance of (left to right) northern cold-water species, cosmopolitan species, and southern warm-water species of rocky intertidal organisms in Monterey, CA, between 1932 and 1993 (modified from Barry et al., 1995).

7.4.3.5 *Changes in estuaries*

The Oregon shoreline is interrupted by over thirty major and minor estuaries that encompass a broad range of land-margin habitats located at the nexus of land and sea. Estuaries are important nursery habitats for some salmon and marine fishes, feeding habitats for shorebirds, and natural flood buffers, among other ecosystem services. The structure of Oregon's estuaries is diverse and includes: (a) river-dominated drowned river mouths (i.e., Columbia, Umpqua, Coquille, Rogue, Chetco); (b) tidal dominated drowned river-mouths (i.e., Tillamook, Siletz, Yaquina, Alsea, Coos); (c) bar-built coastal lagoons (i.e., Netarts, Sand Lake, New River); and (d) numerous tidal creeks (Rumrill, 2006).

The combination of these meteorological and nearshore ocean changes reviewed in Chapter 1 will exert stress on the communities of estuarine organisms. The range of estuarine community responses to the climate change stressors is anticipated to include elevational shifts in the distribution of submerged aquatic vegetation, disruption of shell formation for calcifying organisms, alteration of the phenology of phytoplankton blooms, shoreward migration of tidal marshes, and increased colonization by non-indigenous aquatic species. It is important to note, however, that these anticipated shifts are largely speculative and that long-term time-series data are lacking to definitively identify perturbations of the estuarine communities that can be attributed to human caused climate change.

As one example, shifts in the acidity of nearshore ocean waters has adverse impacts on the larvae of native Olympia oysters (*Ostrea lurida*) and non-native Pacific oysters (*Crassostrea gigas*) that inhabit the intertidal zone of Netarts Bay (Langdon and Hales, personal communication). Water conditions in Netarts Bay during the summer upwelling season are influenced directly by ocean waters, and the estuary receives very little influence from the adjacent coastal watershed. Like the larvae of several other groups of marine invertebrates that require calcium carbonate for their shells and other structures (Orr et al., 2005; Kurihara, 2008), oyster larvae are sensitive to acidified marine waters, which dissolve their thin calcified shells (Miller et al., 2009). In addition, the upwelled waters that are brought to the surface along the Oregon coast (cold, hypoxic, nutrient-rich), intensified by climate change, are highly conducive to outbreaks of the pathogenic bacterium (*Vibrio tubiashii*), which is lethal to oyster larvae and early juveniles.

7.4.3.6 Subtidal and deepsea species

This section focuses almost exclusively on rocky intertidal and estuarine species because subtidal and deepsea invertebrates and seaweeds are poorly studied in our region. It is nonetheless likely that seafloor species throughout Oregon's territorial sea will be affected by a warming ocean. Invertebrate species at risk include commercially valuable flat abalone (*Haliotis walallensis*), which is taken off southern Oregon (Rogers-Bennett, 2007).

It is especially important to note that, regardless of the specific habitat, shellfish and other species with calcium carbonate structures will be adversely affected by ocean acidification (Orr et al., 2005). Species at risk from acidification include Dungeness crab (*Cancer magister*), which the target of the most valuable marine fishery in Oregon. However, a recent review suggested that crustaceans (crabs and relatives) are less susceptible to ocean acidification than other calcified invertebrates (Kroeker et al., 2010). Especially at risk are deep-sea corals with calcium carbonate skeletons (Guinotte et al., 2006).

7.4.3.7 Future changes

Based on species-level responses to factors expected to change in ocean waters, including acidity, temperature, upwelling intensity, sea level, and oxygen concentration, one can predict that abundances of many seafloor organisms, particularly those with calcified structures, likely will decline during this century. However, Menge et al., (2010) suggest that simple predictions based on how individual species are expected to respond may be misleading. A study on the outer coast of Washington suggests that, while some species (such as mussels) appear to have declined in abundance as ocean acidity increased over the past 10 years, others (such as barnacles and calcifying algae) did not change (Wootton et al., 2008). In this study, species interactions combined with different tolerances of acidity stress appeared to influence the changes that actually occurred. Paradoxical benefits under ocean acidification are also possible. Lab studies suggest that growth rates the ochre sea star (*Pisaster ochraceus*) increase under high carbon dioxide regimes (Gooding et al., 2009). Fleshy seaweeds may also benefit from the future ocean, because, rates of photosynthesis may increase with higher levels of carbon dioxide (Hall-Spencer et al., 2008; Ries et al., 2009). Nonetheless, it seems likely that the future ocean will not treat most seafloor invertebrates and seaweeds well, and that the ecosystems inhabited by these organisms will undergo major disruptions.

7.4.4 Marine fishes and fisheries

Marine fishes are of substantial economic and cultural value to the people of Oregon, mostly in terms of commercial and recreational fisheries, as well as sports diving. Fish distributions (where fish are found) and abundances (the number of fish) are strongly affected by changes in ocean climate, which is highly seasonal and variable off Oregon (Mantua et al., 1997; McFarlane et al., 2000; Hallowed et al., 2001; Lehodey et al., 2006). As the ocean generally warms and seawater acidifies over the course of this century, the ecology of marine fishes and fisheries in Oregon's ocean are expected to change in two basic ways.

(1) Distributions will shift poleward (northward off Oregon) and perhaps into deeper, cooler waters.

(2) Abundances will change, with warmer-water species increasing as cooler-water species decline.

Mechanisms causing these expected changes are both direct and indirect (reviews by Scavia et al., 2002; Roessig et al., 2004; Harley et al., 2006; Brander, 2007). Direct mechanisms involve mostly physiological effects of changes in water temperature on survival, growth, reproduction, and movements (Pörtner et al., 2004; Pörtner and Farrell, 2008). Also a direct mechanism, ocean acidification may inhibit the sense of smell in marine fishes (Munday et al., 2009; Dixson et al., 2010), although a recent review suggested that fishes may be tolerant of acidification relative to many invertebrates (Kroeker et al., 2010). Indirect mechanisms involve shifts in currents, food availability, and the structure of marine ecosystems, including diseases, predators and competitors. As reviewed below, these changes in turn are predicted to affect fisheries yields off the Pacific Northwest. In general, smaller, faster-growing, shorter-lived species are expected to respond more rapidly to climate change than larger, slower-growing, longer-lived species, as has been documented in the English Channel (Genner et al., 2010). However, the range of possibilities in such predictions is very high due to the immense complexity of marine climates and ecosystems in general. This is especially true given that climate change will interact with fishing intensity and other human effects in unknown and perhaps synergistic ways (Scavia et al., 2002; Roessig et al., 2004; Harley et al., 2006; Brander, 2007; Hsieh et al., 2008).

7.4.4.1 Shifts in fish distributions

As active swimmers, marine fishes typically have the ability to choose the water temperatures that best fit their physiology, such that the northern and southern range limits of species often are set by temperature tolerances (Horn and Allen, 1978). Therefore, as the ocean warms, the geographical centers of distribution and the range limits of coastal temperate (cool-water) marine fishes are shifting poleward (northward in the Northern Hemisphere), a pattern that has been documented in California (Holbrook et al., 1997; Hsieh et al., 2009), Alaska (Grebmeier et al., 2006; Mueter and Litzow, 2008), the U.S. east coast (Murawski, 1993; Nye et al., 2009), Australia (Figueira and Booth, 2010), and Europe (Perry et al., 2005). Observed and projected rates of poleward shifts are 30–130 km (20–80 mi) per year (e.g., Perry et al., 2005; Dulvy et al., 2008; Mueter and Litzow, 2008; Cheung et al., 2009). Additionally, there is evidence that cool-water species are moving to deeper, cooler waters as surface waters warm, as documented in the North Sea (Dulvy et al., 2008). Note, however, that if climate change causes more intensive upwelling of cooler water along the Oregon coast, then such poleward shifts may not be evident nearshore (see Chapter 1).

With Northern Hemisphere species often shifting their distributions northward as the ocean warms, will Oregon see an overall increase or a decrease in the number of marine fish species? Along the West Coast from Baja California northward, the diversity of coastal marine fishes peaks in southern California near the Mexican border (about 32°N), where southern warm-water species and northern cool-water species mix, then steadily decreases northward (Horn and Allen, 1978). Therefore, as the ocean warms, Oregon likely will gain more species immigrating into state waters from the south and lose fewer species emigrating out of the state to the north, resulting in a net gain in the number of fish species, as has been documented in the North Sea (Hiddink and Hofstede, 2008). Possible candidates for California fishes immigrating to Oregon are five nearshore species whose present northern range limits are between Cape Mendocino and Crescent City (Table 7.1).

Table 7.1 (a) Nearshore California marine fishes whose present northern range limits are off northern California (between Cape Mendocino and Crescent City). These species are possible candidates for range extensions into Oregon waters as the ocean warms. (b) Nearshore marine fishes whose present northern range limits are off Oregon. These species are possible candidates for increasing abundance in Oregon waters as the ocean warms. Range limits from Miller and Lea (1972).

Family	Species	Common name	Present northern range limit in California
a. Species with northern range limit off northern California:			
Cebidichthyidae	*Cebidichthys violaceus*	monkeyface-eel	Crescent City
Carcharhinidae	*Mustelus californicus*	gray smoothhound shark	Cape Mendocino
Cottidae	*Clinocottus analis*	wooly sculpin	Cape Mendocino
Embiotocidae	*Hypsurus caryi*	rainbow surfperch	Cape Mendocino
Pleuronectidae	*Hypsopsetta guttulata*	diamond turbot	Cape Mendocino
b. Species with northern range limit off Oregon:			
Carcharhinidae	*Triakis semifasciata*	leopard shark	
Myliobatidae	*Myliobatis californica*	bat ray	
Argentinidae	*Argentina sialis*	Pacific argentine	
Ophidiidae	*Chilara taylori*	spotted cusk-eel	
Exocoetidae	*Cypselurus californicus*	California flyingfish	
Atherinidae	*Atherinopsis californiensis*	jacksmelt	
Scorpaenidae	*Sebastes rastrelliger*	grass rockfish	
Zaniolepididae	*Zaniolepis frenata*	shortspine combfish	
Cottidae	*Clinocottus recalvus*	bald sculpin	
Sciaenidae	*Seriphus politus*	queenfish	
Embiotocidae	*Hyperprosopon anale*	spotfish surfperch	

The only documented recent first-time immigrant to Oregon waters is Humboldt or jumbo squid (*Dosidicus gigas*), which first appeared in 1997 during the strongest El Niño warm-water intrusion in the past century (Pearcy, 2002). Subsequently, this predator has been observed as far north as southeastern Alaska (Keyl et al., 2008, Fig. 7.4.4.A). Zeidberg and Robison (2007) argue that even though this species is associated with warm-water events, is not dependent on warmer waters. In any case, this large (>2 m [>7 ft]), fast-growing, short-lived (1–2 yr) species is a voracious predator of various fishes (Zeidberg and Robison, 2007; Field, 2008), including Pacific salmon (J. Field, NOAA, personal communication). Zeidberg and Robison (2007) documented that, since 1998—the year Humboldt squid first invaded the West Coast in force—the abundance of Pacific hake (also known as Pacific whiting, *Merluccius productus*) has been low when the abundance of Humboldt squid has been high. By volume, hake comprise the largest fishery off the Oregon coast (ODFW/OCZMA, 2009). In a recent sonar study off Canada, hake were found to be more widely dispersed in the presence of Humboldt squid, indicative of predator-prey interactions (Holmes et al., 2008). Originally a tropical and subtropical species, Humboldt squid also have expanded their range southward to Chile, where they threaten the Chilean hake (*M. gayi*) fishery (Alarcon-Munos et al., 2008; Arancibia and Neira, 2008). They also may affect marine mammals off Oregon (see Section 7.4.6). Paradoxically, Humboldt squid are predicted to suffer population declines as the ocean acidifies (Rosa and Seibel, 2008)

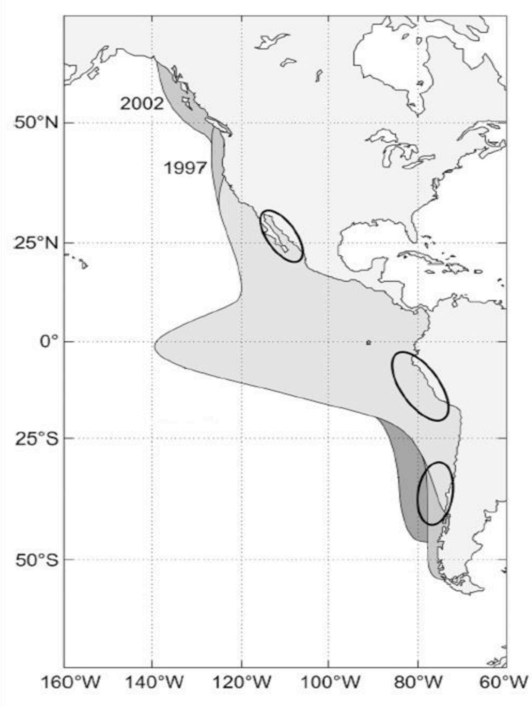


Figure 7.11 Geographic spread of Humboldt squid (Dosidicus gigas) from its historic range in the eastern tropical and subtropical Pacific (light gray) northward and southward along the west coasts of North and South America (darker grays). Ovals enclose major fishing regions that may be affected by this predator. (Modified from Keyl et al., 2008.)

Projecting into the future, ocean distributions of Pacific salmon (*Oncorhynchus* spp.) generally are predicted to shift northward (Welch et al., 1998; Ishida et al., 2001). More generally, Cheung et al. (2009) predicted the rates of local invasions (such as warm-water fish species shifting northward into Oregon waters) and local extinctions (such as cool-water fish species shifting northward out of Oregon waters) from 2003 to 2050 for 1,066 marine fishery species worldwide (including 228 invertebrate species, Cheung et al., 2010). Their "dynamic bioclimate envelope model" predicted future distributions based on changes in suitable habitat, dispersal, and environmental conditions for each species under a high carbon emissions scenario (IPCC scenario A1B, which is equivalent to 720 ppm CO_2; see Chapter 1). For the Oregon coast, the model predicted that the number of invasions of new fishery species will be less than 15% of the more than 100 fishery species currently present (i.e., on the order of 15 species), and that the number of extinctions will be less than 2% of the current fishery species (i.e., a couple species) (Cheung et al., 2009). Globally, they predicted that the geographic ranges of demersal (seafloor-associated) fishery species will shift about 200 km (125 mi) poleward by 2050.

As with all models, these predictions are hypotheses with high ranges of possibilities, especially given that the model did not include possible synergistic interactions among known causative factors, and did not include poorly known additional factors, such as ocean acidification. Nonetheless, sensitivity analyses indicated that the predictions are robust with respect to uncertainties in the factors examined, and the predicted rates of poleward shifts correspond to those observed, leading Cheung et al. (2009) to conclude that their predictions are conservative.

7.4.4.2 Shifts in fish abundances

With a warming ocean, the general expectation is that cool-water species will decline in abundance as warm-water species become more abundant (reviews by Scavia et al., 2002; Roessig et al., 2004; Harley et al., 2006; Brander, 2007). There has not been sufficient monitoring of fish populations off Oregon to assess these predictions rigorously, especially given that fish abundance varies with fishing intensity as well as ocean conditions and associated ecological fluctuations (Mantua et al., 1997; McFarlane et al., 2000; Hallowed et al., 2001; Lehodey et al. 2006). However, there are indirect means of addressing this issue.

Periods of warm-water intrusion off Oregon during El Niño (the strongest of the past century being 1997–98) and other variations in ocean conditions (the period of 2003–2006 being unusually warm) have been associated with shifts in the abundance of marine fishes (W. Peterson, NOAA, personal communication). Survival of Sacramento River fall Chinook salmon stocks that went to sea during the spring and summer of 2005 and 2006 became so low that the salmon fishery was closed coast-wide during the summers of 2008 and 2009. This coast-wide closure was necessary because the Sacramento River stocks are major contributors to the Oregon and northern California salmon fishery (W. Peterson, NOAA, personal communication; see also the Pacific Fisheries Management Council web page). Other recent changes include increased abundance of Pacific sardine (*Sardinops sagax*) (Emmett et al., 2005), and the first records of spawning by Pacific hake, a species normally spawns off Baja California (Phillips et al., 2007). Albacore tuna (*Thunnus alalunga*) now occurs far closer to shore than during the 1970s, and has now become a major regional fishery in the Pacific Northwest (W. Peterson, NOAA, personal communication).

Fisheries catch records from Oregon show trends consistent with (but not necessarily demonstrating) shifts expected due to climate change. The Pacific States Marine Fisheries Commission maintains commercial catch records in the Pacific Fisheries Information Network (PacFIN) database (pacfin.psmfc.org). Examining this database from its inception in 1981 through 2009 for Oregon landings, several patterns suggest that warm-water fishery species are increasing in abundance. First, the annual catch of albacore tuna did not exceed 10,000 pounds until 1998, the year of a particularly strong El Niño. In the 11 years since 1998, annual catch has exceeded 10,000 pounds 3 years (2004, 2007, and 2009). However, catch per unit effort off Oregon has not increased substantially since the early 1960s (A. Phillips, OSU, personal communication, data from NOAA Southwest Fisheries Science Center). Second, although yellowtail (*Seriola dorsalis*) are known to stray into Washington waters, no commercial catch was recorded in Oregon until 2009. Third, "unspecified" squid, a category separate from market squid (*Loligo opalescens*) and probably including immigrating Humboldt squid (see above), first appeared in commercial landing records in Oregon in 2007 and have been recorded annually since then. Additionally, there is an increasing number of unpublished reports of mahi-mahi (a.k.a. dolphinfish or dorado, *Coryphaena hippurus*) taken by recreational fishermen off Oregon, including during non-El Niño years (M. Hixon, OSU, personal communication).

Projecting into the future, warm ocean conditions often cause declines in cool-water species, such as Pacific salmon (Miller and Fluharty, 1992; Pearcy, 1992; Ishida et al., 2001). Ocean climate modeling by Beamish and Noakes (2002) indicates that ocean conditions will become increasingly unfavorable for salmon off Oregon. However, conditions should improve for warm-water species. Of the 554 species of coastal marine fish described in Miller and Lea's (1972) "Guide to the Coastal Marine Fishes of California," 11 nearshore species have present northern range limits along the Oregon coast (Table 7.1). Assuming that water temperature is the primary factor limiting northern distribution limits, it is reasonable to predict that these 11 species will become more abundant off Oregon as ocean waters warm.

7.4.4.3 Shifts in marine fisheries

Climate variability, especially associated with El Niño events (reviews by Diaz and Markgraf, 2000; Glantz, 2001), has long been known to affect marine fisheries, yet human-caused climate change presents new challenges in understanding fish population dynamics (reviews by Cushing, 1982; Glantz, 1992; McGinn, 2002). Catches vary with changes in both fishing intensity and ocean climate, so disentangling these causes is extremely difficult, especially in terms of predicting an uncertain future (Sharp, 1987; Mantua et al., 1997; McFarlane et al., 2000; Hallowed et al., 2001; Lehodey et al., 2006). Nonetheless, it is likely that those species becoming more abundant along the Oregon coast (see above) may benefit local fisheries, just as declining species will reduce catches. In a global analysis, Cheung et al. (2010) combined previously projected changes in species distributions (Cheung et al., 2009, see above) with published projections of changes in primary productivity (Sarmiento et al., 2004; see Section 7.4.1) to predict regional shifts in "maximum catch potential" (MCP) of 1,066 fishery species from 2005 to 2050. They defined MCP as the maximum exploitable catch assuming that the geographic range and selectivity of fisheries remain unchanged over this half-century period. Under a high carbon emissions scenario (IPCC scenario A1B, which is equivalent to 720 ppm CO_2; see Chapter 1), most of the Oregon coast is predicted to suffer a decline in annual commercial fishery catch of at least 0.50 metric tons (0.55 U.S. tons) per km^2 (1 km^2 = 0.39 mi^2 = 0.29 nmi^2) between 2005 and 2050, representing an estimated 30–50% loss (Fig. 7.12). Under the unlikely scenario of carbon emissions stabilized at 2000 levels (365 ppm CO_2), these predictions lower to catch decreases of only 0.05–0.50 metric tons (0.06–0.55 U.S. tons) per km^2 annually, representing only a 5–15% loss (Cheung et al., 2010). The same broad range of possibilities, sensitivity analyses, and conservative conclusions apply to this analysis as discussed above for Cheung et al. (2009).

In a separate modeling effort, Biswas et al. (2009) predicted with a probability of 64% that catches in the Northeast Pacific (from Oregon to Alaska) will decline during this century. A third recent (and as yet unpublished) model predicts that, in addition to sea surface temperatures increasing, nutrients will concentrate below 50–100 m (27–55 fathoms) depth and the northerly flowing California Undercurrent will strengthen (Rykaczewski and Dunne, 2010). The increase in sea surface temperatures, consistent with the other models, should decrease the production of surface-dwelling salmon species, coho salmon and steelhead in particular, largely because of changes in food web structure associated with changes from a cold-water and lipid-rich copepod and forage-fish community to a warm-water, lipid-poor community (Hooff and Peterson, 2006). If deeper nutrients increase, as suggested by Rykaczewski and Dunne (2010), then there is likely to be a corresponding increase in the production of phytoplankton and zooplankton. However, it is not clear how (or whether) increased production will alter food-web structure because community composition is determined by circulation patterns that may be more important than production rates. Strengthening of the California Undercurrent could benefit Pacific hake because this species takes advantage of the undercurrent during their annual northerly migration, yet a stronger current could also increase the invasion rate of Humboldt squid (see above, W. Peterson, NOAA, personal communication).

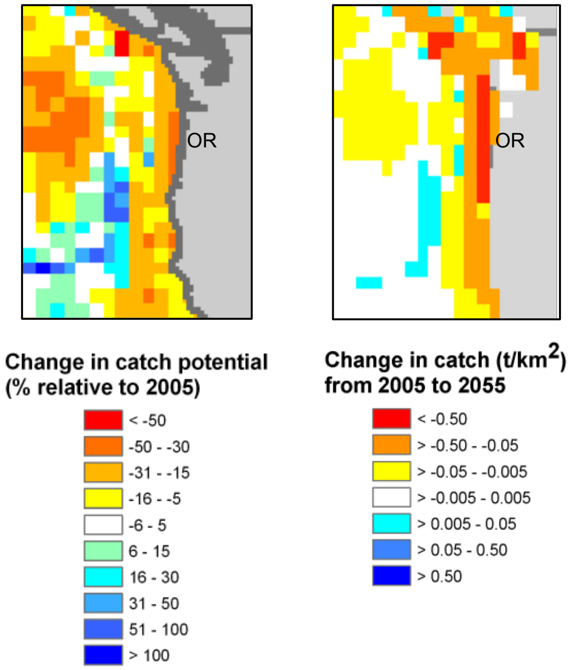


Figure 7.12. Predicted changes in marine fisheries catch off the Oregon coast from 2005 to 2055. Warm colors indicate predicted decreases and cool colors indicate predicted increases in terms of percent change (left) and absolute change (right) in catch within each 0.5-degree latitude-longitude plot. (Extracted from Cheung et al., 2010.)

Regarding recreational fishing, Bennett et al. (2004) investigated the interactive effects of ocean climate (El Niño events) and fishing intensity on catches of rockfishes (*Sebastes* spp.), comparing southern and northern California. They found that northern California, which is relatively similar to Oregon, experienced increased catch per unit effort during warm-water periods. Rather than this pattern being caused by changes in fish populations (because rockfishes reproduce too slowly to keep pace with El Niño events), the authors suggested that "lower food production and higher metabolic activity in warmer water may result in fish being hungrier and more active, rendering them more vulnerable to a set hook" (*ibid.*, pp. 2507–2508).

In conclusion, there are likely to be "winners" and "losers" among fishery species as Oregon's ocean warms and acidifies. Only time will reveal exactly what changes will occur. In any case, it is important to emphasize that this report focuses entirely on changes within Oregon's ocean. Oregon's fisheries and their income are not restricted to the Oregon coast. Landings in Oregon of marine fish captured in Alaskan waters were valued at about $1.4 million during 2002–2009 (J. Olsen, Pacific Fisheries Information Network, personal communication). Much more substantially, 271 Oregon fishing vessels fished off Alaska in 2008, and Oregon residents grossed over $104 million from commercial fisheries off Alaska that year, accounting for about 8% of gross earnings from Alaskan fisheries (ODFW/OCZMA, 2009). The fisheries link between Oregon and Alaska is relevant to this report because arctic and subarctic marine ecosystems are warming and changing much more rapidly than anywhere else in the world's oceans (Ciannelli et al., 2005; Grebmeier et al., 2006; Perovich and Richter-Menge, 2009), so these distant impacts will undoubtedly affect Oregon's economy.

7.4.5 Seabirds

Oregon is home to roughly 1.3 million breeding seabirds, representing more than 15 species (Naughton et al., 2007) and many more seasonal migratory species, and has some of the largest breeding colonies in the California Current Large Marine Ecosystem (CCLME). Oregon’s seabirds are both an economically important natural resource and an ecologically important mid- to upper-trophic level foraging guild. Economically, Oregon ranks 7th in per capita wildlife viewing (mostly birdwatching) in the U.S., with 49% (1.29 million) of the population participating (www.birdiq.com/learn/economics.html). The Oregon Coast birding trail (www.oregoncoastbirding.com) includes many seabird viewing opportunities within the Oregon Islands National Wildlife Refuge (www.fws.gov/oregoncoast/index.htm), which, along with Three Arch Rocks National Wildlife Refuge, protects most of the breeding colonies on the coast. Ecologically, Oregon’s seabirds forage upon both zooplankton and forage fishes, with the dominant piscivores consuming an estimated 49,000 metric tons (54,000 U.S. tons) of forage fish during the summer season (Wiens and Scott, 1975). A single species, the common murre (*Uria aalge*), is estimated to consume over 225,000 metric tons (248,000 U.S. tons) of prey annually off the California and southern Oregon coasts (Roth et al., 2008). Contemporary estimates of prey consumption by Oregon seabirds are lacking. However, it is clear that seabirds are ecologically important consumers within the marine food web.

No sufficiently long-term studies of Oregon seabirds have been conducted to adequately address the potential effects of climate change. Some effects of changing climate-driven ocean conditions, however, have been documented during long-term studies of seabirds in neighboring regions of the CCLME (see Chapter 1), and therefore, offer some basis for the predicted responses presented here.

Potential effects include the following:

1) Ocean warming potentially affecting prey distribution, abundance, or density, and causing reduced breeding success and survival of pursuit-diving seabirds (e.g., murres and puffins), ultimately resulting in population declines.

2) Species distributions shifting northward with a warming trend, enhancing (or initiating) breeding populations for species at the northern edge of their range, and negatively affecting species at the southern edge of their range.
3) Increased overwinter mortality with increased storm intensity or variability.
4) Inundation of breeding colonies from sea-level rise, especially for beach or estuary breeding species.
5) Potential increases in the occurrence of harmful algal blooms that can negatively affect seabirds through acute toxicity, lowered immunity, or other physiological stresses (see Section 7.4.1).
6) Increased hypoxia ("dead zones;" see Section 7.4.1) affecting seabird prey, potentially either enhancing foraging opportunities (aggregating prey nearer the surface and away from oxygen depleted bottom water) or reducing food availability (through increased prey mortality).
7) Potential indirect effects of ocean acidification through alteration of marine food webs and prey availability (see previous sections of Chapter 7).
8) Potential decrease in foraging opportunities due to increased between-species competition for prey as population increases and range expansions of other predators occur, such as the recent movement of Humboldt squid into the Pacific Northwest (see Section 7.4.4).

Seabirds along the Oregon coast most commonly are viewed on shore in large breeding colonies and the viewing public often does not appreciate that these animals forage exclusively at sea, some diving to depths of over 150 m (490 ft) and many strictly at sea during most of the year. The fact that seabirds do breed on shore, however, allows researchers to more readily quantify reproductive output, diet, and population change compared with many other marine animals. Consequently, seabirds have been shown to be sensitive indicators, or sentinels, of changing ocean conditions (Aebischer et al., 1990; Piatt et al., 2007). Indeed, one of the first publicly visible signs along the Oregon coast of reductions in prey abundance due to changes in ocean conditions (e.g., 2005) or acute toxicity due to harmful algal blooms (e.g., 2009; see Section 7.4.4) were mass mortalities of seabirds resulting in many carcasses found on local beaches (Shumway et al., 2003; Parrish et al., 2008). Similarly, large increases in numbers of seabirds frequently are evident when prey abundance rebounds in one region and/or declines in another, causing a population shift (e.g., dramatic increases in several species during winter 2009-2010 on the Oregon coast potentially were caused by changes in prey abundance).

One effect of ocean warming is change in the timing of upwelling (Bograd et al., 2009; see Chapter 1) which in turn affects the timing of seabird breeding in our region (Wolf et al., 2009). In general, birds that initiate reproduction earlier in the spring are more successful and delayed upwelling can cause catastrophic breeding failures (Sydeman et al., 2006). Long-term ocean warming has affected the community composition and abundance of seabirds in the southern CCLME (Veit et al., 1996, 1997), with an overall decline in numbers resulting from fewer cold-water associated pursuit-diving seabirds, such as sooty shearwater (*Puffinus griseus*) and rhinoceros auklet (*Cerorhinca monocerata*), and an increase in warm-water associated near-surface feeding species, such as pink-footed shearwater (*Puffinus creatopus*) and Leach's storm-petrel (*Oceanodroma leucorhoa;* Hyrenbach and Veit, 2003). In the northern CCLME, warming ocean temperatures were correlated with declines in reproductive success of tufted puffin (*Fratercula cirrhata*), whose populations have declined precipitously (<2% of 1979 levels; Fig. 7.13) in coastal Oregon (Kocourek et al. 2009), and marbled murrelet (*Brachyramphus marmoratus*). Both of these species are cold-water associated, pursuit-diving seabirds (Gjerdrum et al., 2003; Becker et al., 2007). Pursuit-diving seabirds are common in highly productive regions (e.g., high latitudes, upwelling regions), where prey densities are sufficient to meet energetic demands of searching for prey while diving (diving birds generally have high flight costs as a trade-off for enhanced diving efficiency). In contrast, surface-feeding birds with low flight costs can better search larger areas for more sparsely distributed prey aggregations. This represents the dominant foraging mode in less productive regions (e.g., low latitude, unproductive regions). Hence, evidence suggests that a shift in the CCLME toward seabird assemblages characteristic of warmer, lower productivity waters has begun, as has as a trend toward decreasing species diversity (Sydeman et al., 2009). Indeed, deteriorating ocean conditions have been linked to reduced overwinter survival of seabirds such as Atlantic puffin (*Fratercula arctica*) in the North Sea (Harris et al., 2010).

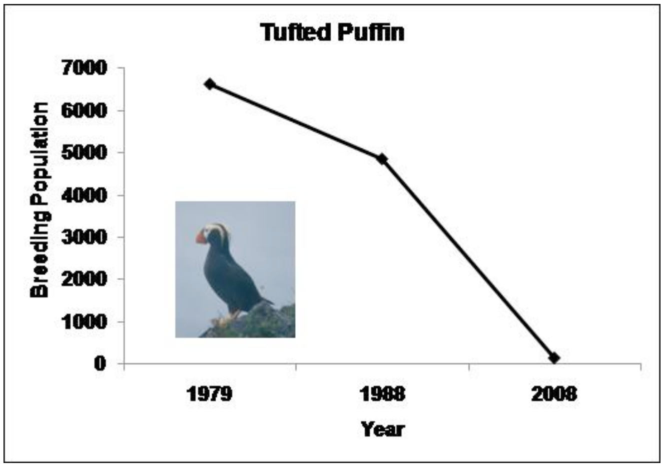


Figure 7.13 Decline in the estimated breeding population size of the tufted puffin, a pursuit diving seabird, on the Oregon coast. Data from Kocourek et al. (2009).

Species range shifts also have been documented for the Oregon coast, in particular the occurrence of California brown pelican (*Pelecanus occidentalis californicus*), a nonbreeding, summer migrant whose numbers in Oregon have increased a hundred-fold during the past several decades (Wright et al., 2007; U.S. Fish and Wildlife Service, unpublished data). While this dramatic increase reflects, in part, an increasing population, major northward expansions have been associated with warm weather anomalies, such as El Niño events. The winter of 2009–2010 saw the first significant over-wintering by brown pelicans along the coast of Oregon (records of pelicans present in all winter months also occurred in 1998 and 2002, but individual sightings were sparse, in contrast to 2010; R. Bayer, Lincoln County bird sighting compiler, personal communication). In contrast to these shifts in post-breeding, migratory range, forced shifts in breeding distribution may be more problematic for seabirds, as sufficient predator-free, breeding habitat (e.g., offshore islands and sea stacks) may become limited.

Increased winter storm intensity also can affect seabird populations, with some species (and age classes) being more susceptible to storm-associated mortality than others (Frederiksen et al., 2008). Sea level rise should have little direct effect on many seabird colonies in coastal Oregon because most tend to be well above the current high tide level (see Chapter 6). However, species nesting adjacent to rocky intertidal zones (e.g., black oystercatcher, *Haematopus bachmani*, see Section 7.2.3. for photo), on beaches (e.g., western snowy plover, *Charadrius alexandrinus*), or on low-lying sandy islands in estuaries (e.g., terns and gulls) will experience habitat loss due to sea level rise (Daniels et al., 1993) and increased storm-driven wave heights (Ruggiero et al., 2010). Potential loss of nesting habitat in estuaries is a particular concern for the Columbia River, which currently provides nesting sites for the Pacific population's largest colony of Caspian tern (*Hydroprogne caspia*, approximately 18,000 birds; Suryan et al., 2004), equally as many double-crested cormorants (*Phalacrocorax auritus*; Adkins and Roby, 2010), and post-breeding feeding and roosting habitat for thousands of brown pelicans (Wright et al., 2007; U.S. Fish and Wildlife Service, unpublished data).

Seabirds exhibit direct responses to inter-annual (El Niño) and decadal (Pacific Decadal Oscillation/North Pacific Gyre Oscillation) changes in ocean climate. The 1982–1983 El Niño, one of the strongest on record, resulted in the death of millions of seabirds in the equatorial Pacific Ocean due to starvation, and also affected reproductive success of some species globally (Schreiber and Schreiber, 1989). In Oregon, the 1982–1983 El Niño caused reduced seabird reproductive success and increased mortality (Hodder and Graybill, 1985; Bayer, 1986). During the 1997 El Niño, common murre colonies along the Oregon and Washington coasts suffered mass abandonment and breeding failure (Parrish et al. 2001; Roy Lowe, USFWS personal observation) and thousands of emaciated birds washed ashore during summer as they made their way north (T. Good and J. Parrish, unpublished data).

Harmful algal blooms (see Section 7.4.1) associated with changes in climate can also have negative impacts on seabirds. Impairment or mortality occurs more commonly through toxicity, such as domoic acid poisoning (Shumway et al., 2003). However, recent events of surfactant-producing red tides also have caused mass mortalities of seabirds (Jessup et al., 2009). In the latter cases, foam from the organic material of the red tide contained surfactant-like proteins coated the feathers of birds and removed the protective oils, causing hypothermia. This was first described during a 2007 mass mortality event in California (Jessup et al., 2009), and was recorded for the first time to cause seabird mortality off Oregon and Washington in 2009. It is not clear to what extent these events are occurring for the first time, or simply being detected for the first time, but such mortality is certainly worthy of close monitoring and documentation in the future (Shumway et al., 2003; Jessup et al., 2009).

The occurrence of low oxygen waters and hypoxia ("dead zones") in Oregon's nearshore environment has increased in recent decades (Grantham et al., 2004; Chan et al., 2008; see Chapter 1). The effect of hypoxic marine conditions on seabirds, however, is neither known for the Oregon coast nor under study. One could speculate that the effect would be either positive or negative, depending on the portion of the water column affected and the prey of seabirds affected. A positive response could result from mobile seabird prey being driven away from low oxygen bottom waters and into greater concentrations in the upper water column, thereby enhancing foraging opportunities. A negative response could result from increased mortality of prey or movement of prey away from nearshore feeding areas and consequent reductions in availability.

Likewise, the potential effect of ocean acidification on seabirds is largely unknown. However, given that Oregon shelf waters are already potentially corrosive to species that form calcium carbonate shells and as the ocean continues to absorb carbon dioxide from the atmosphere causing increasing corrosive effects (see Chapter 1), there are potential food-web level consequences that could affect seabird populations. For example, if marine ecosystems are shifted toward more toward communities with low calcium requirements, such as jellyfish, this shift could affect seabird food supplies. In summary, there are a variety of direct and indirect pathways by which Oregon's seabird populations may be effected by climate change that have population- and community-level consequences.

7.4.6 Marine mammals

Marine mammals typically are widely distributed, highly mobile and, before human exploitation, most were more abundant than today (Clapham and Baker, 2009). The cool waters off the Oregon coast have a rich diversity of marine mammal species, but few are strictly resident and none are restricted entirely to Oregon waters (Maser et al., 1981). Of the 86 living species of whales and dolphins (cetaceans) currently recognized (Perrin, 2009), 23 have been sighted live or found beached in Oregon. Of the 32 living species of seals and sea lions (pinnipeds) currently recognized (Committee on Taxonomy, 2009), 6 have been sighted live or found beached in Oregon and 2 more (the ribbon seal and the ringed seal) are considered likely to range into Oregon waters based on occasional sightings in California.

A recent review of potential impacts of climate change on marine mammals worldwide did not identify obvious risks to the cetaceans most commonly found in Oregon waters, but highlighted general uncertainty about direct and indirect effects of climate change (Simmonds and Eliott, 2009). Climate change will shift the overall state of the world's oceans toward a future of increased warming and acidity, reduced sea-ice cover, and higher sea levels (Chapters 1 and 6), with a resulting reduction in productivity and loss of marine biodiversity (Moore and Huntington, 2008). However, the impact of these predicted changes on a specific geographic region, such as Oregon, or on a specific taxonomic group, such as marine mammals, is highly uncertain, especially over a few decades. Only in the Arctic, where the effects of reduction in ice cover are already evident, is there likely to be predictable and measurable near-term impacts on ice-obligate and ice-associated species of marine mammals (Laidre et al., 2008). Even here, the impact of climate change will be compounded (or confounded) by two other human-caused threats: hunting and pollution (Laidre et al., 2008).

As with other marine species (e.g., marine fishes, Section 7.4.5), the expected influence of climate change on marine mammals will be both direct and indirect. Unlike other marine species, however, marine mammals are capable of rapid learning and physiological resilience across a relatively long lifespan. This behavioral plasticity and innate resilience should allow many species to respond to environmental changes within a single generation (Learmonth et al., 2006). Off Oregon, the near-term impact of direct mechanisms, such as water temperature, are unlikely to be as consequential as the indirect influences of shifts in prey and the structure of marine ecosystems, including diseases, predators and competitors.

7.4.6.1 Distribution and range extensions

The most obvious effect of warming oceans on marine mammals will be shifts in local distributions or range expansions of species, as individuals respond to temperature tolerances and preferences. Using a classification of cetaceans into climatic groups, MacLeod (2009) predicted that 88% of cetacean species will experience shifts in their geographical distributions in response to changes in water temperature resulting from climate change. For 47% of these species, predicted changes are anticipated to have unfavorable implications for their conservation, and for 21%, the changes could put at least one geographically isolated population of that species at risk of extinction (MacLeod, 2009).

Given Oregon's location in middle latitudes and its cool waters, most marine mammals currently found in our waters are unlikely to be excluded by the modest increase in sea-surface temperatures predicted for the next few decades. The one exception might be the Steller sea lion (*Eumetopias jubatus*), for which Oregon is at the southerly (but not southernmost) extent of its range. Instead, the overall response to warmer waters is likely to be an increase in frequency of more tropical species, resulting in a regional increase in species diversity (Whitehead et al., 2008). Some evidence of this change is already indicated by records of species beyond their normal geographic ranges, such as the subtropical Guadalupe fur seal (*Arctocephalus townsendi*) being sighted off Oregon during 2006–2009. Other species likely to expand their range northwards from California include many of the more subtropical dolphins, such as bottlenose dolphin (*Tursiops truncatus*), rough-toothed dolphin (*Steno bredanensis*), and pantropical spotted dolphin (*Stenella attenuata*; Learmonth et al., 2006). The range expansions of these and other species are likely to result in new interactions among species.

Inshore and offshore shifts in distributions of some marine mammals could result from changes in sea surface temperature and shifts in upwelling, as well as the associated changes in the distributions of their prey (Learmonth et al., 2006). For some seals, particularly harbor seal (*Phoca vitulina*), the predicted rise in sea level and the observed increase in the intensity of waves along the Oregon coast will likely lead to a loss of beach habitat for haul-out (Chapter 6).

7.4.6.2 Changes in abundance and population growth

The impact of climate change on abundance and rates of increase of marine mammal populations is difficult to predict, as many species are still recovering from past exploitation, and so, are assumed to be below normal limits set by the environment (Baker and Clapham, 2004). For those species nearing recovery to pre-exploitation numbers, the expected influence of crowding effects, such as increased juvenile mortality, are likely to further confound interpretations of climate change. This situation is likely to be true for the western North Pacific gray whale (*Eschrichtius robustus*) and the North Pacific humpback whale (*Megaptera novaeangliae*), both of which are thought to have recovered to pre-exploitation numbers (although the local population of humpbacks in Oregon remains at low numbers). Nonetheless, efforts to assess the role of climate change or environmental variation on population dynamics of marine mammals are ongoing in cases where there are long-term data sets of abundance and recruitment (Leaper et al., 2006; McMahon et al., 2009). In Oregon waters, species most likely to show measurable changes in abundance or recruitment are harbor seals, Steller sea lions, California sea lions (*Zalophus californianus*), harbor porpoises (*Phocoena phocoena*), "resident" gray whales, and humpback whales.

7.4.6.3 Changes in migratory distribution and timing

Many marine mammals found in Oregon waters are migratory. For baleen whales (Mysticeti), these migrations extend from subtropical or tropical waters to subarctic or even Arctic waters. For some gray whales and humpback whales, however, the waters of Oregon are the northerly limit of migration and the primary feeding grounds. The influence of climate change on the distribution of these "resident" gray and humpback whales is likely to be dependent on changes in the distribution and abundance of prey (indirect mechanisms), rather than sea-surface temperature itself.

For non-resident gray, humpback and other migratory whales, timing of migration and period of transit through Oregon waters will likely change as a direct result of ocean warming and the retreat of Arctic ice from summer feeding grounds. Such alteration in timing, or shifts in seasonal habitat use, could lead to a mismatch between predator requirements and prey availability on the feeding grounds, as well as reproductive timing on breeding grounds (Moore, 2009). One of the best long-term records of migratory timing is that of eastern North Pacific gray whales. The southbound migration for this population has been documented from a census site in central California over the past 40 years, providing evidence of a delay in migration that coincided with the strong El Niño event that occurred in the North Pacific during 1997-1998 (Moore, 2009). This shift in timing of migration was accompanied by reports of more newborn calves offshore of California, well north of the historical concentration of calving in lagoons of Baja California. Such a shift in migratory timing should also be detectable for gray whales along the migratory corridor of the Oregon coast. A similar shift could be expected for other migratory whales such as humpbacks (Baker and Herman, 1981), fin whales (*Balaenoptera physalus*), and blue whales (*Balaenoptera musculus*), but would be much more difficult to detect given the absence of long-term records of migratory timing.

7.4.6.4 Changes in ecological interactions

Probably the major impacts of climate change will be on ecological interactions involving marine mammals, particularly due to shifts in productivity and prey availability. At a very basic level, one can expect that an increase in coastal productivity will be favorable for most marine mammals in Oregon, whereas a decline will be unfavorable. However, much will depend on which species change in productivity and the oceanographic conditions that concentrate the primary prey for each species, influences that are far less predictable (Learmonth et al., 2006).

The recent range expansion of Humboldt squid (*Dosidictus gigas*) provides an example of the complexity of collateral change in predator-prey interactions that could affect marine mammals of Oregon (see Section 7.4.4). This predatory squid is expanding its range northward, coincident with climate-linked oceanographic conditions and a reduction in competing predatory fishes

(Zeidberg and Robison, 2007). In regards to marine mammals, this squid is both a known prey item for larger sperm whales (*Physeter macrocephalus*) and beaked whales (e.g., *Ziphius cavirostris*) and a potential competitor for the most common prey of smaller cetaceans, such as harbor porpoises. The continued northward expansion of Humboldt squid into Oregon waters is likely to benefit some species of marine mammals and negatively impact others. The Humboldt squid itself, although benefiting from short-term climate and ecological change, is predicted to be threatened by longer-term increases in ocean acidity and temperature (Rosa and Seibel, 2008).

Expanding and overlapping ranges of some marine mammals could introduce further complexity to species interactions, including competition. Along parts of the California coast (and elsewhere in the world [Patterson et al., 1998]), bottlenose dolphins have been observed to attack and kill harbor porpoises (SIMoN, 2009). These fatal interactions could increase as bottlenose dolphins expand their range northward into Oregon.

7.4.6.5 Changes in infectious diseases and toxic algal blooms

Marine mammals are subject to large-scale mortality events due to infectious diseases and harmful algal blooms (HABs; Learmonth et al., 2006; Van Dolah 2005; Section 7.4.1). Rates of development, transmission, and susceptibility are all influenced by climate, with a greater incidence of disease anticipated with ocean warming. Marine mammal deaths associated with HABs and diseases appear to have increased over the past three decades, as have the frequency and geographic distribution of these events (Moore, 2009). Many HABs produce toxins known to affect both humans and marine mammals (e.g., domoic acid, Van Dolah, 2000), as are some of the disease organisms responsible for marine mammal deaths (e.g., *Toxoplasma gondii*, Gulland and Hall, 2007). Consequently, there is concern that the increase in mortality of marine mammals is the result of a general deterioration in the state of the oceans, with direct implications for human health (Gulland and Hall, 2007).

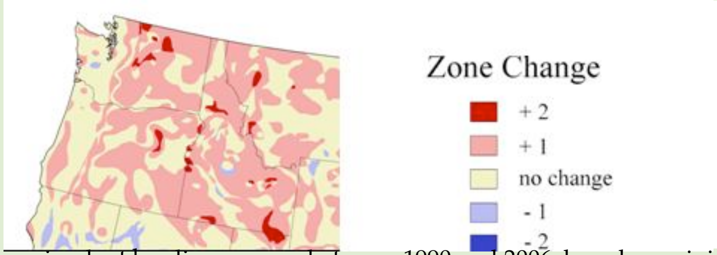
Case Study 7.1: Climate Change and Invasive Species

Globalization of trade and travel combined with technology changes over the past two centuries have accelerated the rate of species dispersal worldwide (Office of Technology Assessment, 1993; Ruiz et al., 2000). European settlement of the Pacific Northwest resulted in introduction of nonindigenous plants and fishes that established persistent, and sometimes damaging, populations. Warm water fish, such as catfish, bass, and walleye, impact threatened and endangered native salmonids (Sanderson et al., 2009). Increases in the speed and number of ships calling on Oregon ports, combined with the modern use of water as ballast that transports larvae from port to port, has resulted in an exponential increase in the rate of new aquatic invertebrate species arrivals to Oregon waters. Prior to the 1970s a new, nonindigenous aquatic invertebrate was found, on average, in the Columbia River about every five years; over the past decade, however, a new species is found about every five months (Sytsma et al., 2004).

Nonindigenous species that proliferate and cause ecological, economic, and human health problems are termed “invasive.” Total economic costs are difficult to quantify because invasive species affect nonconsumptive, indirect-use, and non-use values of ecological goods and services (Naylor, 2000; Lovell and Stone, 2005). One frequently cited assessment indicated that economic costs of invasive species in the USA are about $120 billion annually (Pimentel et al., 2005). In Oregon, just 23 noxious weeds reduce personal income in the state by $83 million each year, which is equivalent to 3329 jobs (Oregon Department of Agriculture, 2000). If left unchecked, six of these weeds would reduce personal income by another $54 million and eliminate another 2143 jobs. Quagga and zebra mussel invasion of the Columbia River was predicted to have a $23 million impact on hydropower facilities alone (Phillips et al., 2005), with a worst case scenario of $250–300 million/year from lost power production (Independent Economic Analysis Board, 2010).

The impact of climate change on invasive species is difficult to separate from natural climate cycles and the myriad of other factors that influence the rate of spread of organisms. However, changes in USDA plant hardiness zones have already been recorded in much of Oregon (see Map), and will result in concomitant shifts in terrestrial plant communities and open habitats to invasion. There is also strong fossil evidence that ocean warming has resulted in tropical species of planktonic foraminifera moving northward in the California Current (Field et al., 2006; see Chapter 1). Substantial northward migrations of 10 marine invertebrates in last thirty years coincided with increased water temperatures along the Pacific Coast—five of the 10 species exhibited range expansions into Oregon from California (Carlton, 2000). The Humboldt squid, a voracious predator that could affect commercially important fish stocks, also exhibited climate-linked, northern expansion of its range into Oregon. Moreover, this species is physiologically adaptable and its current distribution does not depend upon the higher surface water temperatures typical of the tropics (Zeidberg and Robison, 2007). Similar temperature-related phenomena have been observed in the distribution of sea squirts (Stachowicz et al., 2006), marine fishes (Perry et al., 2005), and over 100 other species around the world ranging from trees to insects and forest pests (Walther et al., 2009).

Carbon dioxide enrichment of the atmosphere will likely have direct and indirect effects on ecosystem processes and species distributions. Plants with C_3 photosynthetic biochemistry that grow in habitats that are dominated by plants with C_4 biochemistry may gain a competitive advantage with an increase in CO_2, even though there is no clear link between CO_2-responsiveness and invasiveness (Dukes, 2000).



Change in plant hardiness zones between 1990 and 2006, based on minimum annual temperature. Positive changes mean that warming conditions are favoring more warm-tolerant species (www.arborday.org/media/map_change.cfm).

Secondary effects of climate change could also influence spread and dispersal of invasive species (Sutherst, 2000). Climate change that leads to more rain and less snow at high elevations will alter seasonal periodicity in stream flow and possibly result in construction of more reservoirs to maintain adequate water reserves for human use (Fredrick and Gleick, 1999). Native fish communities are adapted to natural hydrologic regimes and changes in hydrology facilitate establishment of non-native fish species (Moyle and Marchetti, 2006; Johnson et al., 2008). Changes in the amount and distribution of precipitation could also alter fire regimes and increase the number of invasive species (D'Antonio, 2000). Melting of the polar ice cap will likely lead to shifts in shipping routes (Phillips, 2008) and changes in source and sink regions for introductions of exotic species via ballast water. Finally, climate warming will increase the pool of invasive species by facilitating the northward spread of aquaculture facilities and water gardens that are often the source of escaped invasive species that enter natural water bodies (Rahel and Olden, 2008).

Shifts in species ranges are an unavoidable and expected consequence of climate change in Oregon. The biogeography of native and invasive species in Oregon is not monitored systematically, so impacts of climate change on Oregon's plants and animals cannot yet be effectively assessed or managed. Oregon has the infrastructure in place to address invasive species issues (Oregon Invasive Species Council, 2010), but all programs are underfunded. Additional resources are required for the state to prepare for, and mitigate, the inevitable effects of climate change on invasive flora and fauna.

Case Study 7B: Climate Change, Ecological Resilience, and Natural Resource Management

The ecological effects of climate change pose immense challenges for natural resource management because the biosphere is heading toward conditions that have not been experienced previously by modern humans in any particular region: the past no longer necessarily provides reliable insight for the future. As this report should make clear, even though substantial changes are occurring and will accelerate during this century, uncertainty is immense regarding specific changes and appropriate responses. In the context of rapid change and high uncertainty, an overarching goal to ensure that ecosystems do not change catastrophically is ecological resilience (Holling, 1986; Walker and Salt, 2006).

"Ecological resilience" is the capacity of an ecosystem to absorb disturbances without shifting to a drastically different state that is undesirable—and perhaps irreversible—from a human perspective (Holling, 1973; Gunderson, 2000). Therefore, fostering resilience is a fundamental principle for ensuring that the negative effects of climate change are minimized or otherwise slowed by management policy (Holling, 1986; Walker and Salt, 2006).

The management goal of "resilience" is different from that of "stability" in a way that has important ramifications for natural resource policy in response to climate change. Whereas the goal of resilience is an ecosystem that is allowed to vary naturally—sometimes substantially—yet without crossing a threshold into a fundamentally different and undesirable state, the goal of stability is an ecosystem that does not change or, following a disturbance, returns quickly to a specific state desired by humans (Holling, 1996). History has shown repeatedly that attempting to manage fish and wildlife for optimal population levels of specific target species or maximum sustainable yield of specific fishery species is impossible in the long run because ecosystems constantly change and cannot be held in a constant state by command-and-control approaches (Holling and Meffe, 1996). When thresholds are crossed due to human alterations of key nonliving and living processes, ecosystems jump rapidly between alternate stable states that human may view as deleterious. For example, old fire-suppression policies to keep western forests static resulted in the build-up of fuel until catastrophic wildfires killed far more trees and wildlife than if naturally small and more frequent fires had been allowed to burn (Stephens and Ruth, 2005). In the ocean, overexploitation of a single predatory species, the sea otter (now extinct in Oregon), resulted in the loss of kelp forests as sea urchins overgrazed kelp in the absence of their key mammalian predator (Estes and Duggins, 1995). In each case, the new state of the ecosystem was less useful to humans than the original state that dominated before the phase shift caused by trying to manage for static equilibrium. In short, all ecosystems naturally vary through time in adaptive cycles of generation, degeneration, and regeneration (Holling, 1986). Allowing natural cycles to run their course tends to keep the system within a particular desirable regime in the long run (Folke et al., 2004).

It is important to realize that exactly what species and natural processes must be conserved to prevent the loss of resilience and sudden regime shifts typically are not predictable (Holling, 1986). This reality means that maintaining resilience requires ecosystem-based management that embodies precautionary and adaptive approaches to address unknown threats and consequences before they appear (Arkema et al., 2006). Precautionary polices do not harm ecosystem function. Adaptive management occurs when policies become hypotheses and management actions become experiments to test those hypotheses, providing feedback toward more effective approaches (Folke et al., 2005).

Experience in a variety of natural systems shows that two specific ecosystem-based policies are among the most effective at conferring ecological resilience (Walker and Salt, 2006).

> (1) *Maintaining species diversity and functional redundancy*: Ecosystems in which all native species are in their unaltered abundances and size/age classes, including multiple species that share similar ecological functions, are more resilient than systems where key species groups have been overexploited or their habitats severely altered. For example, conservation of multiple species of top predator means that the loss of any one species due to climate change does not entirely remove this essential functional group (Elmqvist et al., 2003).
>
> (2) *Allowing natural variability and modularity in processes at all scales of time and space*: Ecosystems where natural cycles and disturbances are allowed to run their course in a state of natural patchiness are more adaptable than those have been artificially and uniformly boxed-in narrow states that are vulnerable to drastic change. For an example regarding space, habitat patches in different natural states of succession (defined by time since the last natural disturbance) enhance regional species diversity and provide opportunities for degraded patches to be recolonized by adjacent patches in different successional stages (Holling, 1986). For an example regarding time, big, old, fat, fertile, female fish (BOFFFFs) have longer spawning seasons and produce more eggs than younger females, and thus are more likely to spawn at times when their young find food-rich ocean water masses and are delivered by favorable currents to nursery habitats, both of which vary unpredictably from year to year (Berkeley et al., 2004).

In practice, these policies can be implemented by (1) networks of reserves where natural processes and connectivity between sites are fostered (Bengtsson et al., 2003; McLeod et al., 2009), and (2) active management that mimics natural cycles and disturbances (Folke et al., 2005). Resilient ecosystems on land and in the sea provide “stepping stones" where species can find refuge as they shift their geographic distributions due to climate change. For more complete introductions to ecological resilience, including examples of ecosystem-based natural resource management, see Walker and Salt (2006) and Gunderson et al. (2010).

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