APPENDIX A:
STATUS OF THE SPECIES: BULL TROUT

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Appendix A
Status of the Species: Bull Trout

Listing Status

The coterminous United States population of the bull trout (*Salvelinus confluentus*) was listed as threatened on November 1, 1999 (64 FR 58910). The threatened bull trout generally occurs in the Klamath River Basin of south-central Oregon; the Jarbidge River in Nevada; the Willamette River Basin in Oregon; Pacific Coast drainages of Washington, including Puget Sound; major rivers in Idaho, Oregon, Washington, and Montana, within the Columbia River Basin; and the St. Mary-Belly River, east of the Continental Divide in northwestern Montana (Bond 1992, p. 2; Brewin and Brewin 1997, p. 215; Cavender 1978, pp. 165-166; Leary and Allendorf 1997, pp. 716-719).

Throughout its range, bull trout are threatened by the combined effects of habitat degradation, fragmentation, and alterations associated with dewatering, road construction and maintenance, mining, grazing, the blockage of migratory corridors by dams or other diversion structures, poor water quality, entrainment (a process by which aquatic organisms are pulled through a diversion or other device) into diversion channels, and introduced non-native species (64 FR 58910). Although all salmonids are likely to be affected by climate change, bull trout are especially vulnerable given that spawning and rearing are constrained by their location in upper watersheds and the requirement for cold water temperatures (Battin et al. 2007, pp. 6672-6673; Rieman et al. 2007, p. 1552). Poaching and incidental mortality of bull trout during other targeted fisheries are additional threats.

The bull trout was initially listed as three separate Distinct Population Segments (DPSs) (63 FR 31647; 64 FR 17110). The preamble to the final listing rule for the United States coterminous population of the bull trout discusses the consolidation of these DPSs with the Columbia and Klamath population segments into one listed taxon and the application of the jeopardy standard under section 7 of the Endangered Species Act (Act) relative to this species (64 FR 58910):

> Although this rule consolidates the five bull trout DPSs into one listed taxon, based on conformance with the DPS policy for purposes of consultation under section 7 of the Act, we intend to retain recognition of each DPS in light of available scientific information relating to their uniqueness and significance. Under this approach, these DPSs will be treated as interim recovery units with respect to application of the jeopardy standard until an approved recovery plan is developed. Formal establishment of bull trout recovery units will occur during the recovery planning process.

Current Status and Conservation Needs

In recognition of available scientific information relating to their uniqueness and significance, five segments of the coterminous United States population of bull trout are considered essential to the survival and recovery of this species and are identified as interim recovery units: 1) Jarbidge River, 2) Klamath River, 3) Columbia River, 4) Coastal-Puget Sound, and 5) St. Mary-

Belly River (USFWS 2002a, pp. iv, 2, 7, 98; 2004a, Vol. 1 & 2, p. 1; 2004b, p. 1). Each of these interim recovery units is necessary to maintain the bull trout's distribution, as well as its genetic and phenotypic diversity, all of which are important to ensure the species' resilience to changing environmental conditions.

A summary of the current status and conservation needs of the bull trout within these interim recovery units is provided below and a comprehensive discussion is found in the U.S. Fish and Wildlife Service's (Service) draft recovery plans for the bull trout (USFWS 2002a, pp. vi-viii; 2004a, Vol. 2 p. iii-x; 2004b, pp. iii-xii).

The conservation needs of bull trout are often generally expressed as the four "Cs": cold, clean, complex, and connected habitat. Cold stream temperatures, clean water quality that is relatively free of sediment and contaminants, complex channel characteristics (including abundant large wood and undercut banks), and large patches of such habitat that are well connected by unobstructed migratory pathways are all needed to promote conservation of bull trout at multiple scales ranging from the coterminous to local populations (a local population is a group of bull trout that spawn within a particular stream or portion of a stream system). The recovery planning process for bull trout (USFWS 2002a, pp. 49-50; 2004a, Vol 1 & 2 pp. 12-18; 2004b, pp. 60-86) has also identified the following conservation needs: 1) maintenance and restoration of multiple, interconnected populations in diverse habitats across the range of each interim recovery unit, 2) preservation of the diversity of life-history strategies, 3) maintenance of genetic and phenotypic diversity across the range of each interim recovery unit, and 4) establishment of a positive population trend. Recently, it has also been recognized that bull trout populations need to be protected from catastrophic fires across the range of each interim recovery unit (Rieman et al. 2003).

Central to the survival and recovery of bull trout is the maintenance of viable core areas (USFWS 2002a, pp. 53-54; 2004a, Vol. 1 pp. 210-218, Vol. 2. pp. 61-62; 2004b, pp. 15-30, 64-67). A core area is defined as a geographic area occupied by one or more local bull trout populations that overlap in their use of rearing, foraging, migratory, and overwintering habitat. Each of the interim recovery units listed above consists of one or more core areas. There are 121 core areas recognized across the coterminous range of the bull trout (USFWS 2002a, pp. 6, 48, 98; 2004a, Vol. 1 p. vi, Vol. 2 pp. 14, 134; 2004b, pp. iv, 2; 2005, p. ii).

Jarbidge River Interim Recovery Unit

This interim recovery unit currently contains a single core area with six local populations. Less than 500 resident and migratory adult bull trout, representing about 50 to 125 spawning adults, are estimated to occur in the core area. The current condition of the bull trout in this interim recovery unit is attributed to the effects of livestock grazing, roads, incidental mortalities of released bull trout from recreational angling, historic angler harvest, timber harvest, and the introduction of non-native fishes (USFWS 2004b). The draft bull trout recovery plan (USFWS 2004b) identifies the following conservation needs for this interim recovery unit: 1) maintain the current distribution of the bull trout within the core area, 2) maintain stable or increasing trends in abundance of both resident and migratory bull trout in the core area, 3) restore and maintain suitable habitat conditions for all life history stages and forms, and 4) conserve genetic diversity and increase natural opportunities for genetic exchange between resident and migratory forms of the bull trout. An estimated 270 to 1,000 spawning bull trout per year are needed to provide for the persistence and viability of the core area and to support both resident and migratory adult bull trout (USFWS 2004b).

Klamath River Interim Recovery Unit

This interim recovery unit currently contains three core areas and seven local populations. The current abundance, distribution, and range of the bull trout in the Klamath River Basin are greatly reduced from historical levels due to habitat loss and degradation caused by reduced water quality, timber harvest, livestock grazing, water diversions, roads, and the introduction of non-native fishes (USFWS 2002a). Bull trout populations in this interim recovery unit face a high risk of extirpation (USFWS 2002a). The draft Klamath River bull trout recovery plan (USFWS 2002a) identifies the following conservation needs for this interim recovery unit: 1) maintain the current distribution of bull trout and restore distribution in previously occupied areas, 2) maintain stable or increasing trends in bull trout abundance, 3) restore and maintain suitable habitat conditions for all life history stages and strategies, 4) conserve genetic diversity and provide the opportunity for genetic exchange among appropriate core area populations. Eight to 15 new local populations and an increase in population size from about 2,400 adults currently to 8,250 adults are needed to provide for the persistence and viability of the three core areas (USFWS 2002a).

Columbia River Interim Recovery Unit

The Columbia River interim recovery unit includes bull trout residing in portions of Oregon, Washington, Idaho, and Montana. Bull trout are estimated to have occupied about 60 percent of the Columbia River Basin, and presently occur in 45 percent of the estimated historical range (Quigley and Arbelbide 1997, p. 1177). This interim recovery unit currently contains 97 core areas and 527 local populations. About 65 percent of these core areas and local populations occur in central Idaho and northwestern Montana. The Columbia River interim recovery unit has declined in overall range and numbers of fish (63 FR 31647). Although some strongholds still exist with migratory fish present, bull trout generally occur as isolated local populations in headwater lakes or tributaries where the migratory life history form has been lost. Though still widespread, there have been numerous local extirpations reported throughout the Columbia River basin. In Idaho, for example, bull trout have been extirpated from 119 reaches in 28 streams (IDFG in litt. 1995). The draft Columbia River bull trout recovery plan (USFWS 2002c) identifies the following conservation needs for this interim recovery unit: 1) maintain or expand the current distribution of the bull trout within core areas, 2) maintain stable or increasing trends in bull trout abundance, 3) restore and maintain suitable habitat conditions for all bull trout life history stages and strategies, and 4) conserve genetic diversity and provide opportunities for genetic exchange.

This interim recovery unit currently contains 97 core areas and 527 local populations. About 65 percent of these core areas and local populations occur in Idaho and northwestern Montana. The condition of the bull trout within these core areas varies from poor to good. All core areas have been subject to the combined effects of habitat degradation and fragmentation caused by the following activities: dewatering; road construction and maintenance; mining; grazing; the blockage of migratory corridors by dams or other diversion structures; poor water quality; incidental angler harvest; entrainment into diversion channels; and introduced non-native species. The Service completed a core area conservation assessment for the 5-year status review and determined that, of the 97 core areas in this interim recovery unit, 38 are at high risk of extirpation, 35 are at risk, 20 are at potential risk, 2 are at low risk, and 2 are at unknown risk (USFWS 2005, pp. 2, Map A, pp. 73-83).

Coastal-Puget Sound Interim Recovery Unit

Bull trout in the Coastal-Puget Sound interim recovery unit exhibit anadromous[1], adfluvial, fluvial, and resident life history patterns. The anadromous life history form is unique to this interim recovery unit. This interim recovery unit currently contains 14 core areas and 67 local populations (USFWS 2004a). Bull trout are distributed throughout most of the large rivers and associated tributary systems within this interim recovery unit. Bull trout continue to be present in nearly all major watersheds where they likely occurred historically, although local extirpations have occurred throughout this interim recovery unit. Many remaining populations are isolated or fragmented and abundance has declined, especially in the southeastern portion of the interim recovery unit. The current condition of the bull trout in this interim recovery unit is attributed to the adverse effects of dams, forest management practices (e.g., timber harvest and associated road building activities), agricultural practices (e.g., diking, water control structures, draining of wetlands, channelization, and the removal of riparian vegetation), livestock grazing, roads, mining, urbanization, poaching, incidental mortality from other targeted fisheries, and the introduction of non-native species. The draft Coastal-Puget Sound bull trout recovery plan (USFWS 2004a) identifies the following conservation needs for this interim recovery unit: 1) maintain or expand the current distribution of bull trout within existing core areas, 2) increase bull trout abundance to about 16,500 adults across all core areas, and 3) maintain or increase connectivity between local populations within each core area.

St. Mary-Belly River Interim Recovery Unit

This interim recovery unit currently contains six core areas and nine local populations (USFWS 2002b). Currently, bull trout are widely distributed in the St. Mary-Belly River drainage and occur in nearly all of the waters that it inhabited historically. Bull trout are found only in a 1.2-mile reach of the North Fork Belly River within the United States. Redd count surveys of the North Fork Belly River documented an increase from 27 redds in 1995 to 119 redds in 1999. This increase was attributed primarily to protection from angler harvest (USFWS 2002b). The current condition of the bull trout in this interim recovery unit is primarily attributed to the effects of dams, water diversions, roads, mining, and the introduction of non-native fishes (USFWS 2002b). The draft St. Mary-Belly River bull trout recovery plan (USFWS 2002b)

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[1] Bull trout migrate from saltwater to freshwater to reproduce are commonly referred to as anadromous. However, bull trout and some other species that enter the marine environment are more properly termed amphidromous. Unlike strictly anadromous species, such as Pacific salmon, amphidromous species often return seasonally to fresh water as subadults, sometimes for several years, before returning to spawn (Brenkman and Corbett 2005, p. 1075; Wilson 1997, p. 5). Due to its more common usage, we will refer to bull trout has exhibiting anadromous rather than amphidromous life history patterns in this document.

identifies the following conservation needs for this interim recovery unit: 1) maintain the current distribution of the bull trout and restore distribution in previously occupied areas, 2) maintain stable or increasing trends in bull trout abundance, 3) restore and maintain suitable habitat conditions for all life history stages and forms, 4) conserve genetic diversity and provide the opportunity for genetic exchange, and 5) establish good working relations with Canadian interests because local bull trout populations in this interim recovery unit are comprised mostly of migratory fish, whose habitat is mostly in Canada.

Life History

Bull trout exhibit both resident and migratory life history strategies. Both resident and migratory forms may be found together, and either form may produce offspring exhibiting either resident or migratory behavior (Rieman and McIntyre 1993, pp. 1-18). Resident bull trout complete their entire life cycle in the tributary (or nearby) streams in which they spawn and rear. The resident form tends to be smaller than the migratory form at maturity and also produces fewer eggs (Fraley and Shepard 1989, p. 1; Goetz 1989, pp. 15-16). Migratory bull trout spawn in tributary streams where juvenile fish rear 1 to 4 years before migrating to either a lake (adfluvial form), river (fluvial form) (Fraley and Shepard 1989, pp. 135-137; Goetz 1989, pp. 22-25), or saltwater (anadromous form) to rear as subadults and to live as adults (Cavender 1978, pp. 139, 165-68; McPhail and Baxter 1996, p. 14; WDFW et al. 1997, pp. 17-18, 22-26). Bull trout normally reach sexual maturity in 4 to 7 years and may live longer than 12 years. They are iteroparous (they spawn more than once in a lifetime). Repeat- and alternate-year spawning has been reported, although repeat-spawning frequency and post-spawning mortality are not well documented (Fraley and Shepard 1989, pp. 135-137; Leathe and Graham 1982, p. 95; Pratt 1992, p. 6; Rieman and McIntyre 1996, p. 133).

The iteroparous reproductive strategy of bull trout has important repercussions for the management of this species. Bull trout require passage both upstream and downstream, not only for repeat spawning but also for foraging. Most fish ladders, however, were designed specifically for anadromous semelparous salmonids (fishes that spawn once and then die, and require only one-way passage upstream). Therefore, even dams or other barriers with fish passage facilities may be a factor in isolating bull trout populations if they do not provide a downstream passage route. Additionally, in some core areas, bull trout that migrate to marine waters must pass both upstream and downstream through areas with net fisheries at river mouths. This can increase the likelihood of mortality to bull trout during these spawning and foraging migrations.

Growth varies depending upon life-history strategy. Resident adults range from 6 to 12 inches total length, and migratory adults commonly reach 24 inches or more (Goetz 1989, pp. 29-32; Pratt 1984, p. 13). The largest verified bull trout is a 32-pound specimen caught in Lake Pend Oreille, Idaho, in 1949 (Simpson and Wallace 1982).

Habitat Characteristics

Bull trout have more specific habitat requirements than most other salmonids (Rieman and McIntyre 1993, p. 7). Habitat components that influence bull trout distribution and abundance include water temperature, cover, channel form and stability, valley form, spawning and rearing substrate, and migratory corridors (Fraley and Shepard 1989, pp. 137, 141; Goetz 1989, pp. 19-26; Bond in Hoelscher and Bjornn 1989, p. 57; Howell and Buchanan 1992, p. 1; Pratt 1992, p. 6; Rich 1996, pp. 35-38; Rieman and McIntyre 1993, pp. 4-7; Rieman and McIntyre 1995, pp. 293-294; Sedell and Everest 1991, p. 1; Watson and Hillman 1997, pp. 246-250). Watson and Hillman (1997, pp. 247-249) concluded that watersheds must have specific physical characteristics to provide the habitat requirements necessary for bull trout to successfully spawn and rear and that these specific characteristics are not necessarily present throughout these watersheds. Because bull trout exhibit a patchy distribution, even in pristine habitats (Rieman and McIntyre 1993, p. 7), bull trout should not be expected to simultaneously occupy all available habitats (Rieman et al. 1997, p. 1560).

Migratory corridors link seasonal habitats for all bull trout life histories. The ability to migrate is important to the persistence of bull trout (Gilpin, in litt. 1997, pp. 4-5; Rieman and McIntyre 1993, p. 7; Rieman et al. 1997, p. 1114). Migrations facilitate gene flow among local populations when individuals from different local populations interbreed or stray to nonnatal streams. Local populations that are extirpated by catastrophic events may also become reestablished by bull trout migrants. However, it is important to note that the genetic structuring of bull trout indicates there is limited gene flow among bull trout populations, which may encourage local adaptation within individual populations, and that reestablishment of extirpated populations may take a long time (Rieman and McIntyre 1993, p. 7; Spruell et al. 1999, pp. 118-120). Migration also allows bull trout to access more abundant or larger prey, which facilitates growth and reproduction. Additional benefits of migration and its relationship to foraging are discussed below under "Diet."

Cold water temperatures play an important role in determining bull trout habitat quality, as these fish are primarily found in colder streams (below 15 °C or 59 °F), and spawning habitats are generally characterized by temperatures that drop below 9 °C (48 °F) in the fall (Fraley and Shepard 1989, p. 133; Pratt 1992, p. 6; Rieman and McIntyre 1993, p. 7).

Thermal requirements for bull trout appear to differ at different life stages. Spawning areas are often associated with cold-water springs, groundwater infiltration, and the coldest streams in a given watershed (Baxter et al. 1997, pp. 426-427; Pratt 1992, p. 6; Rieman and McIntyre 1993, p. 7; Rieman et al. 1997, p. 1117). Optimum incubation temperatures for bull trout eggs range from 2 °C to 6 °C (35 °F to 39 °F) whereas optimum water temperatures for rearing range from about 6 °C to 10 °C (46 °F to 50 °F) (Buchanan and Gregory 1997, pp. 121-122; Goetz 1989, pp. 22-24; McPhail and Murray 1979, pp. 41, 50, 53, 55). In Granite Creek, Idaho, Bonneau and Scarnecchia (1996) observed that juvenile bull trout selected the coldest water available in a plunge pool, 8 °C to 9 °C (46 °F to 48 °F), within a temperature gradient of 8 °C to 15 °C (4 °F to 60 °F). In a landscape study relating bull trout distribution to maximum water temperatures, Dunham et al. (2003) found that the probability of juvenile bull trout occurrence does not become high (i.e., greater than 0.75) until maximum temperatures decline to 11 °C to 12 °C (52 °F to 54 °F).

Although bull trout are found primarily in cold streams, occasionally these fish are found in larger, warmer river systems throughout the Columbia River basin (Buchanan and Gregory 1997, pp. 121-122; Fraley and Shepard 1989, pp. 135-137; Rieman and McIntyre 1993, p. 2; Rieman and McIntyre 1995, p. 288; Rieman et al. 1997, p. 1114). Availability and proximity of cold water patches and food productivity can influence bull trout ability to survive in warmer rivers (Myrick et al. 2002). For example, in a study in the Little Lost River of Idaho where bull trout were found at temperatures ranging from 8 °C to 20 °C (46 °F to 68 °F), most sites that had high densities of bull trout were in areas where primary productivity in streams had increased following a fire (Gamett, pers. comm. 2002).

All life history stages of bull trout are associated with complex forms of cover, including large woody debris, undercut banks, boulders, and pools (Fraley and Shepard 1989, pp. 135-137; Goetz 1989, pp. 22-25; Hoelscher and Bjornn 1989, p. 54; Pratt 1992, p. 6; Rich 1996, pp. 35-38; Sedell and Everest 1991, p. 1; Sexauer and James 1997, pp. 367-369; Thomas 1992, pp. 4-5; Watson and Hillman 1997, pp. 247-249). Maintaining bull trout habitat requires stability of stream channels and maintenance of natural flow patterns (Rieman and McIntyre 1993, p. 7). Juvenile and adult bull trout frequently inhabit side channels, stream margins, and pools with suitable cover (Sexauer and James 1997, pp. 367-369). These areas are sensitive to activities that directly or indirectly affect stream channel stability and alter natural flow patterns. For example, altered stream flow in the fall may disrupt bull trout during the spawning period, and channel instability may decrease survival of eggs and young juveniles in the gravel from winter through spring (Fraley and Shepard 1989, pp. 135-137; Pratt 1992, p. 6; Pratt and Huston 1993, pp. 70-72). Pratt (1992, p. 6) indicated that increases in fine sediment reduce egg survival and emergence.

Bull trout typically spawn from August through November during periods of increasing flows and decreasing water temperatures. Preferred spawning habitat consists of low-gradient stream reaches with loose, clean gravel (Fraley and Shepard 1989, p. 135). Redds are often constructed in stream reaches fed by springs or near other sources of cold groundwater (Goetz 1989, p. 15; Pratt 1992, p. 8; Rieman and McIntyre 1996, p. 133). Depending on water temperature, incubation is normally 100 to 145 days (Pratt 1992, p. 8). After hatching, fry remain in the substrate, and time from egg deposition to emergence may surpass 200 days. Fry normally emerge from early April through May, depending on water temperatures and increasing stream flows (Ratliff and Howell 1992 in Howell and Buchanan 1992, pp. 10, 15; Pratt 1992, pp. 5-6).

Early life stages of fish, specifically the developing embryo, require the highest inter-gravel dissolved oxygen (IGDO) levels, and are the most sensitive life stage to reduced oxygen levels. The oxygen demand of embryos depends on temperature and on stage of development, with the greatest IGDO required just prior to hatching.

A literature review conducted by the Washington Department of Ecology (WDOE 2002) indicates that adverse effects of lower oxygen concentrations on embryo survival are magnified as temperatures increase above optimal (for incubation). In a laboratory study conducted in Canada, researchers found that low oxygen levels retarded embryonic development in bull trout (Giles and Van der Zweep 1996, pp. 54-55). Normal oxygen levels seen in rivers used by bull trout during spawning ranged from 8 to 12 mg/L (in the gravel), with corresponding instream levels of 10 to 11.5 mg/L (Stewart et al. 2007). In addition, IGDO concentrations, water velocities in the water column, and especially the intergravel flow rate, are interrelated variables that affect the survival of incubating embryos (ODEQ 1995). Due to a long incubation period of 220+ days, bull trout are particularly sensitive to adequate IGDO levels. An IGDO level below 8 mg/L is likely to result in mortality of eggs, embryos, and fry.

Migratory forms of bull trout may develop when habitat conditions allow movement between spawning and rearing streams and larger rivers, lakes or nearshore marine habitat where foraging opportunities may be enhanced (Brenkman and Corbett 2005, pp. 1073, 1079-1080; Frissell 1993, p. 350; Goetz et al. 2004, pp. 45, 55, 60, 68, 77, 113-114, 123, 125-126). For example, multiple life history forms (e.g., resident and fluvial) and multiple migration patterns have been noted in the Grande Ronde River (Baxter 2002). Parts of this river system have retained habitat conditions that allow free movement between spawning and rearing areas and the mainstem Snake River. Such multiple life history strategies help to maintain the stability and persistence of bull trout populations to environmental changes. Benefits to migratory bull trout include greater growth in the more productive waters of larger streams, lakes, and marine waters; greater fecundity resulting in increased reproductive potential; and dispersing the population across space and time so that spawning streams may be recolonized should local populations suffer a catastrophic loss (Frissell 1999, pp. 15-16; MBTSG 1998, pp. iv, 48-50; Rieman and McIntyre 1993, pp. 18-19; USFWS 2004a, Vol. 2, p. 63). In the absence of the migratory bull trout life form, isolated populations cannot be replenished when disturbances make local habitats temporarily unsuitable. Therefore, the range of the species is diminished, and the potential for a greater reproductive contribution from larger fish with higher fecundity is lost (Rieman and McIntyre 1993, pp. 1-18).

Diet

Bull trout are opportunistic feeders, with food habits primarily a function of size and life-history strategy. A single optimal foraging strategy is not necessarily a consistent feature in the life of a fish, because this strategy can change as the fish progresses from one life stage to another (i.e., juvenile to subadult). Fish growth depends on the quantity and quality of food that is eaten (Gerking 1994), and as fish grow, their foraging strategy changes as their food changes, in quantity, size, or other characteristics. Resident and juvenile migratory bull trout prey on terrestrial and aquatic insects, macrozooplankton, and small fish (Boag 1987, p. 58; Donald and Alger 1993, pp. 239-243; Goetz 1989, pp. 33-34). Subadult and adult migratory bull trout feed on various fish species (Brown 1994, p. 21; Donald and Alger 1993, p. 242; Fraley and Shepard 1989, p. 135; Leathe and Graham 1982, p. 95). Bull trout of all sizes other than fry have been found to eat fish up to half their length (Beauchamp and VanTassell 2001). In nearshore marine areas of western Washington, bull trout feed on Pacific herring (*Clupea pallasi*), Pacific sand lance (*Ammodytes hexapterus*), and surf smelt (*Hypomesus pretiosus*) (Goetz et al. 2004, p. 114; WDFW et al. 1997, p. 23).

Bull trout migration and life history strategies are closely related to their feeding and foraging strategies. Migration allows bull trout to access optimal foraging areas and exploit a wider variety of prey resources. Optimal foraging theory can be used to describe strategies fish use to choose between alternative sources of food by weighing the benefits and costs of capturing one source of food over another. For example, prey often occur in concentrated patches of abundance ("patch model") (Gerking 1994). As the predator feeds in one patch, the prey population is reduced, and it becomes more profitable for the predator to seek a new patch rather than continue feeding on the original one. This can be explained in terms of balancing energy acquired versus energy expended. For example, in the Skagit River system, anadromous bull trout make migrations as long as 121 miles between marine foraging areas in Puget Sound and headwater spawning grounds, foraging on salmon eggs and juvenile salmon along their migration route (WDFW et al. 1997). Anadromous bull trout also use marine waters as migration corridors to reach seasonal habitats in non-natal watersheds to forage and possibly overwinter (Brenkman and Corbett 2005, p. 1079; Goetz et al. 2004, pp. 36, 60).

Changes in Status of the Coastal-Puget Sound Interim Recovery Unit

Although the status of bull trout in Coastal-Puget Sound interim recovery unit has been improved by certain actions, it continues to be degraded by other actions, and it is likely that the overall status of the bull trout in this population segment has not improved since its listing on November 1, 1999. Improvement has occurred largely through changes in fishing regulations and habitat-restoration projects. Fishing regulations enacted in 1994 either eliminated harvest of bull trout or restricted the amount of harvest allowed, and this likely has had a positive influence on the abundance of bull trout. Improvement in habitat has occurred following restoration projects intended to benefit either bull trout or salmon, although monitoring the effectiveness of these projects seldom occurs. On the other hand, the status of this population segment has been adversely affected by a number of Federal and non-Federal actions, some of which were addressed under section 7 of the Act. Most of these actions degraded the environmental baseline; all of those addressed through formal consultation under section 7 of the Act permitted the incidental take of bull trout.

Section 10(a)(1)(B) permits have been issued for Habitat Conservation Plans (HCP) completed in the Coastal-Puget Sound population segment. These include: 1) the City of Seattle's Cedar River Watershed HCP, 2) Simpson Timber HCP (now Green Diamond Resources), 3) Tacoma Public Utilities Green River HCP, 4) Plum Creek Cascades HCP, 5) Washington State Department of Natural Resources (WSDNR) State Trust Lands HCP, 6) West Fork Timber HCP, and 7) WSDNR Forest Practices HCP. These HCPs provide landscape-scale conservation for fish, including bull trout. Many of the covered activities associated with these HCPs will contribute to conserving bull trout over the long-term; however, some covered activities will result in short-term degradation of the baseline. All HCPs permit the incidental take of bull trout.

Changes in Status of the Columbia River Interim Recovery Unit

The overall status of the Columbia River interim recovery unit has not changed appreciably since its listing on June 10, 1998. Populations of bull trout and their habitat in this area have been affected by a number of actions addressed under section 7 of the Act. Most of these actions resulted in degradation of the environmental baseline of bull trout habitat, and all permitted or analyzed the potential for incidental take of bull trout. The Plum Creek Cascades HCP, Plum Creek Native Fish HCP, Storedahl Daybreak Mine HCP, and WSDNR Forest Practices HCP addressed portions of the Columbia River population segment of bull trout.

Changes in Status of the Klamath River Interim Recovery Unit

Improvements in the Threemile, Sun, and Long Creek local populations have occurred through efforts to remove or reduce competition and hybridization with non-native salmonids, changes in fishing regulations, and habitat-restoration projects. Population status in the remaining local populations (Boulder-Dixon, Deming, Brownsworth, and Leonard Creeks) remains relatively unchanged. Grazing within bull trout watersheds throughout the recovery unit has been curtailed. Efforts at removal of non-native species of salmonids appear to have stabilized the Threemile and positively influenced the Sun Creek local populations. The results of similar efforts in Long Creek are inconclusive. Mark and recapture studies of bull trout in Long Creek indicate a larger migratory component than previously expected.

Although the status of specific local populations has been slightly improved by recovery actions, the overall status of Klamath River bull trout continues to be depressed. Factors considered threats to bull trout in the Klamath Basin at the time of listing – habitat loss and degradation caused by reduced water quality, past and present land use management practices, water diversions, roads, and non-native fishes – continue to be threats today.

Changes in Status of the Saint Mary-Belly River Interim Recovery Unit

The overall status of bull trout in the Saint Mary-Belly River interim recovery unit has not changed appreciably since its listing on November 1, 1999. Extensive research efforts have been conducted since listing, to better quantify populations of bull trout and their movement patterns. Limited efforts in the way of active recovery actions have occurred. Habitat occurs mostly on Federal and Tribal lands (Glacier National Park and the Blackfeet Nation). Known problems due to instream flow depletion, entrainment, and fish passage barriers resulting from operations of the U.S. Bureau of Reclamation's Milk River Irrigation Project (which transfers Saint Mary-Belly River water to the Missouri River Basin) and similar projects downstream in Canada constitute the primary threats to bull trout and to date they have not been adequately addressed under section 7 of the Act. Plans to upgrade the aging irrigation delivery system are being pursued, which has potential to mitigate some of these concerns but also the potential to intensify dewatering. A major fire in August 2006 severely burned the forested habitat in Red Eagle and Divide Creeks, potentially affecting three of nine local populations and degrading the baseline.

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APPENDIX B
STATUS OF THE SPECIES: MARBLED MURRELET

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Appendix B
Status of the Species: Marbled Murrelet

The marbled murrelet (*Brachyramphus marmoratus*) (murrelet) was listed by the U.S. Fish and Wildlife Service (Service) as a threatened species in Washington, Oregon, and California in 1992. The primary reasons for listing included extensive loss and fragmentation of the older-age forests that serve as nesting habitat for murrelets, and human-induced mortality in the marine environment from gillnets and oil spills (57 FR 45328 [Oct. 1, 1992]). Although some threats such as gillnet mortality and loss of nesting habitat on Federal lands have been reduced since the 1992 listing, the primary threats to species persistence continue (75 FR 3424 [Jan. 21, 2010]).

Life History

The murrelet is a small, fast-flying seabird in the Alcidae family that occurs along the Pacific coast of North America. Murrelets forage for small schooling fish or invertebrates in shallow, nearshore, marine waters and primarily nest in coastal older-aged coniferous forests. The murrelet lifespan is unknown, but is expected to be in the range of 10 to 20 years based on information from similar alcid species (De Santo and Nelson 1995, pp. 36-37). Murrelet nesting is asynchronous and spread over a prolonged season. In Washington, the murrelet breeding season extends from April 1 to September 23. Egg laying and incubation occur from April to early August and chick rearing occurs between late May and September, with all chicks fledging by late September (Hamer et al. 2003; USFWS 2012a).

Murrelets lay a single-egg which may be replaced if egg failure occurs early in the nesting cycle, but this is rare (Nelson 1997, p. 17). During incubation, one adult sits on the nest while the other forages at sea. Adults typically incubate for a 24-hour period, then exchange duties with their mate at dawn. Chicks hatch between May and August after 30 days of incubation. Hatchlings appear to be brooded by an adult for several days (Nelson 1997, p. 18). Once the chick attains thermoregulatory independence, both adults leave the chick alone at the nest for the remainder of the rearing period, except during feedings. Both parents feed the chick, which receives one to eight meals per day (Nelson 1997, p. 18). Most meals are delivered early in the morning while about a third of the food deliveries occur at dusk and intermittently throughout the day (Nelson and Hamer 1995, p. 62).

Murrelets and other fish-eating alcids exhibit wide variations in nestling growth rates. The nestling stage of murrelet development can vary from 27 to 40 days before fledging (De Santo and Nelson 1995, p. 45). The variations in alcid chick development are attributed to constraints on feeding ecology, such as unpredictable and patchy food distributions, and great distances between feeding and nesting sites (Øyan and Anker-Nilssen 1996, p. 830). Food limitation during nesting often results in poor growth, delayed fledging, increased mortality of chicks, and nest abandonment by adults (Øyan and Anker-Nilssen 1996, p. 836).

Murrelets are believed to be sexually mature at 2 to 4 years of age (Nelson 1997, p. 19). Adult birds may not nest every year, especially when food resources are limited. Recent monitoring efforts in Washington indicated that only 20 percent of monitored murrelet nesting attempts were successful, and only a small portion of the 158 tagged adult birds actually attempted to nest (13 percent) (Raphael and Bloxton 2009, p. 165). The low number of adults attempting to nest is not unique to Washington. Some researchers suspect that the portion of non-breeding adults in murrelet populations can range from about 5 percent to 70 percent depending on the year, but most population modeling studies suggest a range of 5 to 20 percent (McShane et al. 2004, p. 3-5).

Murrelets in the Marine Environment

Marbled murrelets spend most (>90 percent) of their time at sea. Their preferred marine habitat includes sheltered, nearshore waters within 3 miles of shore, although they occur farther offshore in areas of Alaska and during the nonbreeding season (Huff et al. 2006, p. 19). They generally forage in pairs on the water, but they also forage solitarily or in small groups.

Breeding Season

The murrelet is widely distributed in nearshore waters along the west coast of North America. It occurs primarily within 5 km of shore (Alaska, within 50 km), and primarily in protected waters, although its distribution varies with coastline topography, river plumes, riptides, and other physical features (Nelson 1997, p. 3). Murrelet marine distribution is strongly associated with the amount and configuration of terrestrial nesting habitat (Raphael et al. 2015c, p. 17). In other words, they tend to be distributed in marine waters adjacent to areas of suitable breeding habitat. Non-breeding adults and subadults are thought to occur in similar areas as breeding adults. This species does occur farther offshore, but in much reduced numbers (Strachan et al. 1995, p. 247). Their offshore occurrence is probably related to current upwelling and plumes during certain times of the year that tend to concentrate their prey species.

Winter Range

The winter range of the murrelet is poorly documented, but they are present near breeding sites year-round in most areas (Nelson 1997, p. 3). Murrelets exhibit seasonal redistributions during non-breeding seasons. Generally more dispersed and found farther offshore in winter in some areas, although highest concentrations still occur close to shore and in protected waters (Nelson 1997, p. 3). In some areas, murrelets move from the outer exposed coasts of of Vancouver Island and the Straits of Juan de Fuca into the sheltered and productive waters of northern and eastern Puget Sound. Less is known about seasonal movements along the outer coasts of Washington, Oregon, and California (Ralph et al. 1995, p. 9). The farthest offshore records of murrelet distribution are 60 km off the coast of northern California in October, 46 km off the coast of Oregon in February (Adams et al. 2014) and at least 300 km off the coast in Alaska (Piatt and Naslund 1995, p. 287). Known areas of winter concentration include and southern and eastern end of Strait of Juan de Fuca (primarily Sequim, Discovery, and Chuckanut Bays), San Juan Islands and Puget Sound, WA (Speich and Wahl 1995, p. 314).

Foraging and Diet

Murrelets dive and swim through the water by using their wings in pursuit of their prey; their foraging and diving behavior is restricted by physiology. They usually feed in shallow, nearshore water <30 m (98 ft) deep, which seems to provide them with optimal foraging conditions for their generalized diet of small schooling fish and large, pelagic invertebrates: Pacific sand lance (*Ammodytes hexapterus*), northern anchovy (*Engraulis mordax*), Pacific herring (*Clupea harengus*), surf smelt (*Hypomesus* sp.), euphausiids, mysids, amphipods, and other species (Nelson 1997, p. 7). However, they are assumed to be capable of diving to a depth of 47 m (157 ft) based on their body size and diving depths observed for other Alcid species (Mathews and Burger 1998, p. 71).

Contemporary studies of murrelet diets in the Puget Sound–Georgia Basin region indicate that Pacific sand lance now comprise the majority of the murrelet diet (Gutowsky et al. 2009, p. 251). Historically, energy-rich fishes such as herring and northern anchovy comprised the majority of the murrelet diet (Becker and Beissinger 2006, p. 470; Gutowsky et al. 2009, p. 247). This is significant because sandlance have the lowest energetic value of the fishes that murrelets commonly consume. For example, a single northern anchovy has nearly six times the energetic value of a sandlance of the same size (Gutowsky et al. 2009, p. 251), so a murrelet would have to eat six sandlance to get the equivalent energy of a single anchovy. Reductions in the abundance of energy-rich forage fish species is likely a contributing factor in the poor reproduction in murrelets (Becker and Beissinger 2006, p. 470).

The duration of dives appears to depend upon age (adults vs. juveniles), water depth, visibility, and depth and availability of prey. Dive duration has been observed ranging from 8 seconds to 115 seconds, although most dives are between 25 to 45 seconds (Day and Nigro 2000; Jodice and Collopy 1999; Thoresen 1989; Watanuki and Burger 1999). Diving bouts last over a period of 27 to 33 minutes (Nelson 1997, p. 9). They forage in deeper waters when upwelling, tidal rips, and daily activity of prey concentrate prey near the surface (Strachan et al. 1995). Murrelets are highly mobile and some make substantial changes in their foraging sites within the breeding season. For example, Becker and Beissinger (2003, p. 243) found that murrelets responded rapidly (within days or weeks) to small-scale variability in upwelling intensity and prey availability by shifting their foraging behavior and habitat selection within a 100-km (62-mile) area.

For more information on murrelet use of marine habitats, see literature reviews in McShane et al. 2004 and USFWS 2009.

<u>Murrelets in the Terrestrial Environment</u>

Murrelets are dependent upon older-age forests, or forests with an older tree component, for nesting habitat (Hamer and Nelson 1995, p. 69). Specifically, murrelets prefer high and broad platforms for landing and take-off, and surfaces which will support a nest cup (Hamer and Nelson 1995, pp. 78-79). In Washington, murrelet nests have been found in live conifers, specifically, western hemlock (*Tsuga heterophylla*), Sitka spruce (*Picea sitchensis*), Douglas-fir (*Pseudotsuga menziesii*), and western red cedar (*Thuja plicata*) (Hamer and Nelson 1995; Hamer and Meekins 1999). Most murrelets appear to nest within 37 miles of the coast, although occupied behaviors have been recorded up to 52 miles inland, and murrelet presence has been detected up to 70 miles inland in Washington (Huff et al. 2006, p. 10). Nests occur primarily in large, older-aged trees. Overall, nests have been found in trees greater than 19 inches in diameter-at-breast and greater than 98 ft tall. Nesting platforms include limbs or other branch deformities that are greater than 4 inches in diameter, and are at greater than 33 ft above the ground. Substrate such as moss or needles on the nest platform is important for protecting the egg and preventing it from falling off (Huff et al. 2006, p. 13).

Murrelets do not form dense colonies which is atypical of most seabirds. Limited evidence suggests they may form loose colonies in some cases (Ralph et al. 1995). The reliance of murrelets on cryptic coloration to avoid detection suggests they utilize a wide spacing of nests in order to prevent predators from forming a search image (Ralph et al. 1995). Individual murrelets are suspected to have fidelity to nest sites or nesting areas, although this is has only been confirmed with marked birds in a few cases (Huff et al. 2006, p. 11). There are at least 15 records of murrelets using nest sites in the same or adjacent trees in successive years, but it is not clear if they were used by the same birds (McShane et al. 2004, p. 2-14). At the landscape scale, murrelets do show fidelity to foraging areas and probably to specific watersheds for nesting (McShane et al. 2004, p. 2-14). Murrelets have been observed visiting nesting habitat during non-breeding periods in Washington, Oregon, and California which may indicate adults are maintaining fidelity and familiarity with nesting sites and/or stands (Naslund 1993; O'Donnell et al. 1995, p. 125).

Loss of nesting habitat reduces nest site availability and displaces any murrelets that may have had nesting fidelity to the logged area (Raphael et al. 2002, p. 232). Murrelets have demonstrated fidelity to nesting stands and in some areas, fidelity to individual nest trees (Burger et al. 2009, p. 217). Murrelets returning to recently logged areas may not breed for several years or until they have found suitable nesting habitat elsewhere (Raphael et al. 2002, p. 232). The potential effects of displacement due to habitat loss include nest site abandonment, delayed breeding, failure to initiate breeding in subsequent years, and failed breeding due to increased predation risk at a marginal nesting location (Divoky and Horton 1995, p. 83; Raphael et al. 2002, p. 232). Each of these outcomes has the potential to reduce the nesting success for individual breeding pairs, and could ultimately result in the reduced recruitment of juvenile birds into the local population (Raphael et al. 2002, pp. 231-233).

Detailed information regarding the life history and conservation needs of the murrelet are presented in the *Ecology and Conservation of the Marbled Murrelet* (Ralph et al. 1995), the Service's 1997 *Recovery Plan for the Marbled Murrelet* (USFWS 1997), and in subsequent 5-year status reviews (McShane et al. 2004; USFWS 2009).

Distribution

Murrelets are distributed along the Pacific coast of North America, with birds breeding from central California through Oregon, Washington, British Columbia, southern Alaska, westward through the Aleutian Island chain, with presumed breeding as far north as Bristol Bay (Nelson 1997, p. 2). The federally-listed murrelet population in Washington, Oregon, and California is classified by the Service as a distinct population segment (75 FR 3424). The coterminous United States population of murrelets is considered significant as the loss of this distinct population segment would result in a significant gap in the range of the taxon and the loss of unique genetic characteristics that are significant to the taxon (75 FR 3430).

Murrelets spend most of their lives in the marine environment where they consume a diversity of prey species, including small fish and invertebrates. Murrelets occur primarily in nearshore marine waters within 5 km of the coast, but have been documented up to 300 km offshore in winter off the coast of Alaska (Nelson 1997, p. 3). The inland nesting distribution of murrelets is strongly associated with the presence of mature and old-growth conifer forests. Murrelets have been detected >100 km inland in Washington (70 miles), while the inland distribution in the southern portion of the species range is associated with the extent of the hemlock/tanoak vegetation zone which occurs up to 16-51 km inland (10-32 miles) (Evans Mack et al. 2003, p. 4).

The distribution of murrelets in marine waters during the summer breeding season is highly variable along the Pacific coast, with areas of high density occurring along the Strait of Juan de Fuca in Washington, the central Oregon coast, and northern California (Raphael et al. 2015c, p. 20). Low-density areas or gaps in murrelet distribution occur in central California, and along the southern Washington coast (Raphael et al. 2015c, p. 21). Analysis of various marine and terrestrial habitat factors indicate that the amount and configuration of inland nesting habitat is the strongest factor that influences the marine distribution of murrelets during the nesting season (Raphael et al. 2015c, p. 17). Local aggregations or "hot spots" of murrelets in nearshore marine waters are strongly associated with landscapes that support large, contiguous areas of mature and old-growth forest.

Distribution of Nesting Habitat

The loss of nesting habitat was a major cause of the murrelets decline over the past century and may still be contributing as nesting habitat continues to be lost to fires, logging, and wind storms (Miller et al. 2012, p. 778). Due mostly to historic timber harvest, only a small percentage (~11 percent) of the habitat-capable lands within the listed range of the murrelet currently contain potential nesting habitat (Raphael et al. 2015b, p. 118). Monitoring of murrelet nesting habitat within the Northwest Forest Plan area indicates nesting habitat declined from an estimated 2.53 million acres in 1993 to an estimated 2.23 million acres in 2012, a decline of about 12.1 percent (Raphael et al. 2015b, p. 89). Fire has been the major cause of nesting habitat loss on Federal lands, while timber harvest is the primary cause of loss on non-Federal lands (Raphael et al. 2015b, p. 90). While most (60 percent) of the potential habitat is located on Federal reserved-land allocations, a substantial amount of nesting habitat occurs on non-federal lands (34 percent) (Table 1).

Table 1. Estimates of higher-quality murrelet nesting habitat by State and major land ownership within the area of the Northwest Forest Plan – derived from 2012 data.

State	Habitat capable lands (1,000s of acres)	Habitat on Federal reserved lands (1,000s of acres)	Habitat on Federal non-reserved lands (1,000s of acres)	Habitat on non-federal lands (1,000s of acres)	Total potential nesting habitat (all lands) (1,000s of acres)	Percent of habitat capable land that is currently in habitat
WA	10,851.1	822.4	64.7	456	1,343.1	12 %
OR	6,610.4	484.5	69.2	221.1	774.8	12 %
CA	3,250.1	24.5	1.5	82.9	108.9	3 %
Totals	20,711.6	1,331.4	135.4	760	2,226.8	11 %
Percent		60 %	6 %	34 %	100 %	-

Source: (Raphael et al. 2015b, pp. 115-118)

Population Status

The 1997 *Recovery Plan for the Marbled Murrelet* (USFWS 1997) identified six Conservation Zones throughout the listed range of the species: Puget Sound (Conservation Zone 1), Western Washington Coast Range (Conservation Zone 2), Oregon Coast Range (Conservation Zone 3), Siskiyou Coast Range (Conservation Zone 4), Mendocino (Conservation Zone 5), and Santa Cruz Mountains (Conservation Zone 6) (Figure 1). Recovery zones are the functional equivalent of recovery units as defined by Service policy (USFWS 1997, p. 115). The subpopulations in each Zone are not discrete. There is some movement of murrelets between Zones as indicated by radio-telemetry studies (e.g., Bloxton and Raphael 2006, p. 162), but the degree to which murrelets migrate between Zones is unknown. For the purposes of consultation, the Service treats each of the Conservation Zones as separate sub-populations of the listed murrelet population.

Population Status and Trends

Population estimates for the murrelet are derived from marine surveys conducted during the nesting season as part of the Northwest Forest Plan effectiveness monitoring program. Surveys from 2001 to 2013 indicated that the murrelet population in Conservation Zones 1 through 5 (Northwest Forest Plan area) declined at a rate of -1.2 percent per year (Falxa et al. 2015, pp. 7-8). While the overall trend estimate across this time period is negative, the evidence of a detectable linear decline is not conclusive because the confidence intervals for the estimated trend overlap zero (95% confidence interval [CI]:-2.9 to 0.5 percent) (Falxa et al. 2015, pp. 7-8) (Table 2). This differs from the declines previously reported at the Northwest Forest Plan-scale for the 2001 to 2010 period. This difference was the result of high population estimates for 2011 through 2013 compared to the previous several years, which reduced the slope of the trend and increased variability (Falxa and Raphael 2015, p. 4).

Population monitoring from 2001 to 2013 indicates strong evidence for a linear decline for murrelet subpopulations in Washington, while trends in Oregon and northern California indicate potentially stable or increasing subpopulations with no conclusive evidence of a positive or negative trend over the monitoring period (Falxa et al. 2015, p. 26). While the direct causes for subpopulation declines in Washington are unknown, potential factors include the loss of nesting habitat, including cumulative and time-lag effects of habitat losses over the past 20 years (an individual murrelets potential lifespan), changes in the marine environment reducing the availability or quality of prey, increased densities of nest predators, and emigration (Miller et al. 2012, p. 778).

The most recent population estimate for the entire Northwest Forest Plan area in 2013 was 19,700 murrelets (95 percent CI: 15,400 to 23,900 birds) (Falxa et al. 2015, p. 7). The largest and most stable murrelet subpopulations now occur off the Oregon and northern California coasts, while subpopulations in Washington have experienced the greatest rates of decline. Murrelet zones are now surveyed on an every other-year basis, so the last year that a range-wide estimate for all zones combined is 2013 (Table 2). Subsequent surveys in Washington, Oregon, and California have been completed during the 2014 and 2015 seasons. Summaries of these more recent surveys are presented in Table 3.

The murrelet subpopulation in Conservation Zone 6 (central California- Santa Cruz Mountains) is outside of the Northwest Forest Plan area and is monitored separately by the University of California as part of an oil-spill compensation program (Henry et al. 2012, p. 2). Surveys in Zone 6 indicate a small subpopulation of murrelets with no clear trends. Population estimates from 2001 to 2014 have fluctuated from a high of 699 murrelets in 2003, to a low of 174 murrelets in 2008 (Henry and Tyler 2014, p. 3). In 2014, surveys indicated an estimated population of 437 murrelets in Zone 6 (95% CI: 306-622) (Henry and Tyler 2014, p. 3) (Table 3).

Table 2. Summary of murrelet population estimates and trends (2001-2013) at the scale of Conservation Zones and States (estimates combined across Zones within the Northwest Forest Plan area).

Zone	Year	Estimated number of murrelets	95% CI Lower	95% CI Upper	Average density (at sea) (murrelets /km^2)	Average annual rate of change (%)	95% CI Lower	95% CI Upper	Cumulative change over 10 years (%)
1	2013	4,395	2,298	6,954	1.26	-3.9	-7.6	0.0	-32.8
2	2013	1,271	950	1,858	0.77	-6.7	-11.4	-1.8	-50.0
3	2013	8,841	6,819	11,276	5.54	+1.3	-1.1	+3.8	+6.2
4	2013	6,046	4,531	9,282	5.22	+1.5	-0.9	+4.0	+16.1
5	2013	71	5	118	0.08	-1.0	-8.3	+6.9	-9.6
Zones 1-5	2013	19,662	15,398	23,927	2.24	-1.2	-2.9	+0.5	-11.3
Zone 6	2013	628	386	1,022	na	na	na	na	na
WA	2013	5,665	3,217	8,114	1.10	-5.1	-7.7	-2.5	-37.6
OR	2013	9,819	6,158	13,480	4.74	0.3	-1.8	2.5	+3.0
CA	2013	4,178	3,561	4,795	2.67	2.5	-1.1	6.2	+28.0

Sources: (Falxa et al. 2015, pp. 41-43; Henry and Tyler 2014, p. 3).

Table 3. Summary of the most recent murrelet population estimates by Zone (2014-2015).

Zone	Year	Estimated number of murrelets	Estimated population 95% CI Lower	Estimated population 95% CI Upper	Average annual rate of decline (2001-2015)
1	2015	4,290	2,783	6,492	-5.3 %
2	2015	3,204	1,883	5,609	-2.8 %
3	2014	8,841	6,819	11,276	nc
4	2015	8,743	7,409	13,125	nc
5	2013	71	5	118	nc
6	2014	437	306	622	nc

Sources: (Henry and Tyler 2014, p. 3; Lance and Pearson 2016, pp. 4-5; NWFPEMP 2016, pp. 2-3).

Factors Influencing Population Trends

Murrelet populations are declining in Washington, stable in Oregon, and stable in California where there is a non-significant but positive population trend (Raphael et al. 2015a, p. 163). Murrelet population size and distribution is strongly and positively correlated with the amount and pattern (large contiguous patches) of suitable nesting habitat and population trend is most strongly correlated with trend in nesting habitat although marine factors also contribute to this trend (Raphael et al. 2015a, p. 156). From 1993 to 2012, there was a net loss of about 2 percent of potential nesting habitat from on federal lands, compared to a net loss of about 27 percent on nonfederal lands, for a total cumulative net loss of about 12.1 percent across the Northwest Forest Plan area (Raphael et al. 2015b, p. 66). Cumulative habitat losses since 1993 have been greatest in Washington, with most habitat loss in Washington occurring on non-Federal lands due to timber harvest (Raphael et al. 2015b, p. 124) (Table 4).

Table 4. Distribution of higher-suitability murrelet nesting habitat by Conservation Zone, and summary of net habitat changes from 1993 to 2012 within the Northwest Forest Plan area.

Conservation Zone	1993	2012	Change (acres)	Change (percent)
Zone 1 - Puget Sound/Strait of Juan de Fuca	829,525	739,407	-90,118	-10.9 %
Zone 2 - Washington Coast	719,414	603,777	-115,638	-16.1 %
Zone 3 - Northern to central Oregon	662,767	610,583	-52,184	-7.9 %
Zone 4 - Southern Oregon - northern California	309,072	256,636	-52,436	-17 %
Zone 5 - north-central California	14,060	16,479	+2,419	+17.2 %

Source: (Raphael et al. 2015b, p. 121).

The decline in murrelet populations from 2001 to 2013 is weakly correlated with the decline in nesting habitat, with the greatest declines in Washington, and the smallest declines in California, indicating that when nesting habitat decreases, murrelet abundance in adjacent marine waters may also decrease. At the scale of Conservation Zones, the strongest correlation between habitat loss and murrelet decline is in Zone 2, the zone where both murrelet habitat and murrelet abundance has declined the greatest. However these relationships are not linear, and there is much unexplained variation (Raphael et al. 2015a, p. 163). While terrestrial habitat amount and configuration (i.e., fragmentation) and the terrestrial human footprint (i.e., cities, roads, development) appear to be strong factors influencing murrelet distribution in Zones 2-5; terrestrial habitat and the marine human footprint (i.e., shipping lanes, boat traffic, shoreline development) appear to be the most important factors that influence the marine distribution and abundance of murrelets in Zone 1 (Raphael et al. 2015a, p. 163).

As a marine bird, murrelet survival is dependent on their ability to successfully forage in the marine environment. Despite this, it is apparent that the location, amount, and landscape pattern of terrestrial nesting habitat are strongest predictors of the spatial and temporal distributions of murrelets at sea during the nesting season (Raphael et al. 2015c, p. 20). Various marine habitat features (e.g., shoreline type, depth, temperature, etc.) apparently have only a minor influence on murrelet distribution at sea. Despite this relatively weak spatial relationship, marine factors, and especially any decrease in forage species, likely play an important role in explaining the apparent population declines, but the ability to model these relationships is currently limited (Raphael et al. 2015c, p. 20).

Population Models

Prior to the use of survey data to estimate trend, demographic models were more heavily relied upon to generate predictions of trends and extinction probabilities for the murrelet population (Beissinger 1995; Cam et al. 2003; McShane et al. 2004; USFWS 1997). However, murrelet population models remain useful because they provide insights into the demographic parameters and environmental factors that govern population stability and future extinction risk, including stochastic factors that may alter survival, reproductive, and immigration/emigration rates.

In a report developed for the *5-year Status Review of the Marbled Murrelet in Washington, Oregon, and California* (McShane et al. 2004, p. 3-27 to 3-60), models were used to forecast 40-year murrelet population trends. A series of female-only, multi-aged, discrete-time stochastic Leslie Matrix population models were developed for each conservation zone to forecast decadal population trends over a 40-year period with extinction probabilities beyond 40 years (to 2100). The authors incorporated available demographic parameters (Table 5) for each conservation zone to describe population trends and evaluate extinction probabilities (McShane et al. 2004, p. 3-49).

McShane et al. (2004) used mark-recapture studies conducted in British Columbia by Cam et al. (2003) and Bradley et al. (2004) to estimate annual adult survival and telemetry studies or at-sea survey data to estimate fecundity. Model outputs predicted -3.1 to -4.6 percent mean annual rates of population change (decline) per decade the first 20 years of model simulations in murrelet Conservation Zones 1 through 5 (McShane et al. 2004, p. 3-52). Simulations for all zone populations predicted declines during the 20 to 40-year forecast, with mean annual rates of -2.1 to -6.2 percent per decade (McShane et al. 2004, p. 3-52). While these modeled rates of decline are similar to those observed in Washington (Falxa and Raphael 2015, p. 4), the simulated projections at the scale of Zones 1-5 do not match the potentially stable or increasing populations observed in Oregon and California during the 2001-2013 monitoring period.

Table 5. Rangewide murrelet demographic parameter values based on four studies all using Leslie Matrix models.

Demographic Parameter	Beissinger 1995	Beissinger and Nur 1997*	Beissinger and Peery (2007)	McShane et al. 2004
Juvenile Ratio (Ŕ)	0.10367	0.124 or 0.131	0.089	0.02 - 0.09
Annual Fecundity	0.11848	0.124 or 0.131	0.06-0.12	-
Nest Success	-	-	0.16-0.43	0.38 - 0.54
Maturation	3	3	3	2 - 5
Estimated Adult Survivorship	85 % – 90%	85 % – 88 %	82 % - 90 %	83 % – 92 %

*In U.S. Fish and Wildlife (1997).

Reproduction

Generally, estimates of murrelet fecundity are directed at measures of breeding success, either from direct assessments of nest success in the terrestrial environment, marine counts of hatch-year birds, or computer models. Telemetry estimates are typically preferred over marine counts for estimating breeding success due to fewer biases (McShane et al. 2004, p. 3-2). However, because of the challenges of conducting telemetry studies, estimating murrelet reproductive rates with an index of reproduction, referred to as the juvenile ratio (Ŕ),[1] continues to be important, despite the debate over use of this index (see discussion in Beissinger and Peery 2007, p. 296).

Although difficult to obtain, nest success rates[2] are available from telemetry studies conducted in California (Hebert and Golightly 2006; Peery et al. 2004) and Washington (Bloxton and Raphael 2006). In northwest Washington, Bloxton and Raphael (2005, p. 5) documented a nest success rate of 0.20 (2 chicks fledging from 10 nest starts). In central California, murrelet nest success is 0.16 (Peery et al. 2004, p. 1098) and in northern California it is 0.31 to 0.56 (Hebert and Golightly 2006, p. 95). No studies or published reports from Oregon are available.

Unadjusted and adjusted values for estimates of murrelet juvenile ratios suggest extremely low breeding success in northern California (0.003 to 0.008 - Long et al. 2008, pp. 18-19), central California (0.035 and 0.032 - Beissinger and Peery 2007, pp. 299, 302), and in Oregon (0.0254 - 0.0598 - Crescent Coastal Research 2008, p. 13). Estimates for **Ŕ** (adjusted) in the San Juan Islands in Washington have been below 0.15 every year since surveys began in 1995, with three of those years below 0.05 (Raphael et al. 2007, p. 16).

[1] The juvenile ratio (**Ŕ**) for murrelets is derived from the relative abundance of hatch-year (HY; 0-1 yr-old) to after-hatch-year (AHY; 1+ yr-old) birds (Beissinger and Peery 2007, p. 297) and is calculated from marine survey data.
[2] Nest success here is defined by the annual number of known hatchlings departing from the nest (fledging) divided by the number of nest starts.

These estimates of **Ŕ** are assumed to be below the level necessary to maintain or increase the murrelet population. Demographic modeling suggests murrelet population stability requires a minimum reproductive rate of 0.18 to 0.28 (95 % CI) chicks per pair per year (Beissinger and Peery 2007, p. 302; USFWS 1997). Even the lower levels of the 95 percent confidence interval from USFWS (1997) and Beissinger and Peery (2007, p. 302) is greater than the current range of estimates for Ŕ (0.02 to 0.13 chicks per pair) for any of the Conservation Zones (Table 4).

The current estimates for **Ŕ** also appear to be well below what may have occurred prior to the murrelet population decline. Beissinger and Peery (2007, p. 298) performed a comparative analysis using historic data from 29 bird species to predict the historic **Ŕ** for murrelets in central California, resulting in an estimate of 0.27 (95% CI: 0.15 - 0.65). Therefore, the best available scientific information of murrelet fecundity from model predictions and trend analyses of survey-derived population data appear to align well. Both indicate that the murrelet reproductive rate is generally insufficient to maintain stable population numbers throughout all or portions of the species' listed range.

Summary: Murrelet Abundance, Distribution, Trend, and Reproduction

Although murrelets are distributed throughout their historical range, the area of occupancy within their historic range appears to be reduced from historic levels. The distribution of the species also exhibits five areas of discontinuity: a segment of the border region between British Columbia, Canada and Washington; southern Puget Sound, WA; Destruction Island, WA to Tillamook Head, OR; Humboldt County, CA to Half Moon Bay, CA; and the entire southern end of the breeding range in the vicinity of Santa Cruz and Monterey Counties, CA (McShane et al. 2004, p. 3-70).

A statistically significant decline was detected in Conservation Zones 1 and 2 for the 2001-2014 period (Table 2). The overall population trend from the combined 2001-2013 population estimates (Conservation Zones 1 - 5) indicate a decline at a rate of -1.2 percent per year (Falxa et al. 2015, pp. 7-8). This decline across the listed range is most influenced by the significant declines in Washington, while subpopulations in Oregon and California are potentially stable.

The current range of estimates for **Ŕ**, the juvenile to adult ratio, is assumed to be below the level necessary to maintain or increase the murrelet population. Whether derived from marine surveys or from population modeling (**Ŕ** = 0.02 to 0.13, Table 4), the available information is in general agreement that the current ratio of hatch-year birds to after-hatch year birds is insufficient to maintain stable numbers of murrelets throughout the listed range. The current estimates for **Ŕ** also appear to be well below what may have occurred prior to the murrelet population decline (Beissinger and Peery 2007, p. 298).

Considering the best available data on abundance, distribution, population trend, and the low reproductive success of the species, the Service concludes the murrelet population within the Washington portion of its listed range currently has little or no capability to self-regulate, as indicated by the significant, annual decline in abundance the species is currently undergoing in Conservation Zones 1 and 2. Populations in Oregon and California are apparently more stable, but threats associated with habitat loss and habitat fragmentation continue to occur in those areas. The Service expects the species to continue to exhibit further reductions in the distribution and abundance into the foreseeable future, due largely to the expectation that the variety of environmental stressors present in the marine and terrestrial environments (discussed in the *Threats to Murrelet Survival and Recovery* section) will continue into the foreseeable future.

Threats to Murrelet Survival and Recovery

When the murrelet was listed under the Endangered Species Act in 1992, several anthropogenic threats were identified as having caused the dramatic decline in the species:

- habitat destruction and modification in the terrestrial environment from timber harvest and human development caused a severe reduction in the amount of nesting habitat
- unnaturally high levels of predation resulting from forest "edge effects" ;
- the existing regulatory mechanisms, such as land management plans (in 1992), were considered inadequate to ensure protection of the remaining nesting habitat and reestablishment of future nesting habitat; and
- manmade factors such as mortality from oil spills and entanglement in fishing nets used in gill-net fisheries.

The regulatory mechanisms implemented since 1992 that affect land management in Washington, Oregon, and California (for example, the Northwest Forest Plan) and new gill-netting regulations in northern California and Washington have reduced the threats to murrelets (USFWS 2004, pp. 11-12). However, additional threats were identified in the Service's 2009, 5-year review for the murrelet (USFWS 2009, pp. 27-67). These stressors are due to several environmental factors affecting murrelets in the marine environment. These stressors include:

- Habitat destruction, modification, or curtailment of the marine environmental conditions necessary to support murrelets due to:
    - elevated levels of polychlorinated biphenyls in murrelet prey species;
    - changes in prey abundance and availability;
    - changes in prey quality;
    - harmful algal blooms that produce biotoxins leading to domoic acid and paralytic shellfish poisoning that have caused murrelet mortality; and
    - climate change in the Pacific Northwest.
- Manmade factors that affect the continued existence of the species include:
    - derelict fishing gear leading to mortality from entanglement;
    - disturbance in the marine environment (from exposures to lethal and sub-lethal levels of high underwater sound pressures caused by pile-driving, underwater detonations, and potential disturbance from high vessel traffic).

Since the time of listing, the murrelet population has continued to decline due to lack of successful reproduction and recruitment. The murrelet Recovery Implementation Team identified five major mechanisms that appear to be contributing to this decline (USFWS 2012b, pp. 10-11):

- Ongoing and historic loss of nesting habitat.
- Predation on murrelet eggs and chicks in their nests.
- Changes in marine conditions, affecting the abundance, distribution, and quality of murrelet prey species.
- Post-fledging mortality (predation, gill-nets, oil-spills).
- Cumulative and interactive effects of factors on individuals and populations.

Climate Change

In the Pacific Northwest, mean annual temperatures rose 0.8° C (1.5° F) in the 20th century and are expected to continue to warm from 0.1° to 0.6° C (0.2° to 1° F) per decade (Mote and Salathe 2010, p. 29). Climate change models generally predict warmer, wetter winters and hotter, drier summers and increased frequency of extreme weather events in the Pacific Northwest (Salathé et al. 2010, pp. 72-73). Predicted climate changes in the Pacific Northwest have implications for forest disturbances that affect the quality and distribution of murrelet habitat. Both the frequency and intensity of wildfires and insect outbreaks are expected to increase over the next century in the Pacific Northwest (Littell et al. 2010, p. 130).

One of the largest projected effects on Pacific Northwest forests is likely to come from an increase in fire frequency, duration, and severity. Westerling et al. (2006, pp. 940-941) analyzed wildfires and found that since the mid-1980s, wildfire frequency in western forests has nearly quadrupled compared to the average of the period from 1970-1986. The total area burned is more than 6.5 times the previous level and the average length of the fire season during 1987-2003 was 78 days longer compared to 1978-1986 (Westerling et al. 2006, p. 941). The area burned annually by wildfires in the Pacific Northwest is expected to double or triple by the 2080s (Littell et al. 2010, p. 140). Wildfires are now the primary cause of murrelet habitat loss on Federal lands, with over 21,000 acres of habitat loss attributed to wildfires from 1993 to 2012 (Raphael et al. 2015b, p. 123). Climate change is likely to further exacerbate some existing threats such as the projected potential for increased habitat loss from drought related fire, mortality, insects and disease, and increases in extreme flooding, landslides and windthrow events in the short-term (10 to 30 years).

Within the marine environment, effects on the murrelet food supply (amount, distribution, quality) provide the most likely mechanism for climate change impacts to murrelets. Studies in British Columbia (Norris et al. 2007) and California (Becker and Beissinger 2006) have documented long-term declines in the quality of murrelet prey, and one of these studies (Becker and Beissinger 2006, p. 475) linked variation in coastal water temperatures, murrelet prey quality during pre-breeding, and murrelet reproductive success. These studies indicate that murrelet recovery may be affected as long-term trends in ocean climate conditions affect prey resources and murrelet reproductive rates. While seabirds such as the murrelet have life-history strategies adapted to variable marine environments, ongoing and future climate change could present changes of a rapidity and scope outside the adaptive range of murrelets (USFWS 2009, p. 46).

Conservation Needs of the Species

Reestablishing an abundant supply of high quality murrelet nesting habitat is a vital conservation need given the extensive removal during the 20th century. However, there are other conservation imperatives. Foremost among the conservation needs are those in the marine and terrestrial environments to increase murrelet fecundity by increasing the number of breeding adults, improving murrelet nest success (due to low nestling survival and low fledging rates), and reducing anthropogenic stressors that reduce individual fitness or lead to mortality.

The overall reproductive success (fecundity) of murrelets is directly influenced by nest predation rates (reducing nestling survival rates) in the terrestrial environment and an abundant supply of high quality prey in the marine environment during the breeding season (improving potential nestling survival and fledging rates). Anthropogenic stressors affecting murrelet fitness and survival in the marine environment are associated with commercial and tribal gillnets, derelict fishing gear, oil spills, and high underwater sound pressure (energy) levels generated by pile-driving and underwater detonations (that can be lethal or reduce individual fitness).

General criteria for murrelet recovery (delisting) were established at the inception of the Plan and they have not been met. More specific delisting criteria are expected in the future to address population, demographic, and habitat based recovery criteria (USFWS 1997, p. 114-115). The general criteria include:

- documenting stable or increasing population trends in population size, density, and productivity in four of the six Conservation Zones for a 10-year period and
- implementing management and monitoring strategies in the marine and terrestrial environments to ensure protection of murrelets for at least 50 years.

Thus, increasing murrelet reproductive success and reducing the frequency, magnitude, or duration of any anthropogenic stressor that directly or indirectly affects murrelet fitness or survival in the marine and terrestrial environments are the priority conservation needs of the species. The Service estimates recovery of the murrelet will require at least 50 years (USFWS 1997)

Recovery Plan

The Marbled Murrelet Recovery Plan outlines the conservation strategy with both short- and long-term objectives. The Plan places special emphasis on the terrestrial environment for habitat-based recovery actions due to nesting occurring in inland forests.

In the short-term, specific actions identified as necessary to stabilize the populations include protecting occupied habitat and minimizing the loss of unoccupied but suitable habitat (USFWS 1997, p. 119). Specific actions include maintaining large blocks of suitable habitat, maintaining and enhancing buffer habitat, decreasing risks of nesting habitat loss due to fire and windthrow, reducing predation, and minimizing disturbance. The designation of critical habitat also contributes towards the initial objective of stabilizing the population size through the maintenance and protection of occupied habitat and minimizing the loss of unoccupied but suitable habitat.

Long-term conservation needs identified in the Plan include:

- increasing productivity (abundance, the ratio of juveniles to adults, and nest success) and population size;
- increasing the amount (stand size and number of stands), quality, and distribution of suitable nesting habitat;
- protecting and improving the quality of the marine environment; and
- reducing or eliminating threats to survivorship by reducing predation in the terrestrial environment and anthropogenic sources of mortality at sea.

Recovery Zones in Washington

Conservation Zones 1 and 2 extend inland 50 miles from marine waters. Conservation Zone 1 includes all the waters of Puget Sound and most waters of the Strait of Juan de Fuca south of the U.S.-Canadian border and the Puget Sound, including the north Cascade Mountains and the northern and eastern sections of the Olympic Peninsula. Conservation Zone 2 includes marine waters within 1.2 miles (2 km) off the Pacific Ocean shoreline, with the northern terminus immediately south of the U.S.-Canadian border near Cape Flattery along the midpoint of the Olympic Peninsula and extending to the southern border of Washington (the Columbia River) (USFWS 1997, pg. 126).

Lands considered essential for the recovery of the murrelet within Conservation Zones 1 and 2 are 1) any suitable habitat in a Late Successional Reserve (LSR), 2) all suitable habitat located in the Olympic Adaptive Management Area, 3) large areas of suitable nesting habitat outside of LSRs on Federal lands, such as habitat located in the Olympic National Park, 4) suitable habitat on State lands within 40 miles off the coast, and 5) habitat within occupied murrelet sites on private lands (USFWS 1997).

Summary

At the range-wide scale, murrelet populations have declined at an average rate of 1.2 percent per year since 2001. The most recent population estimate for the entire Northwest Forest Plan area in 2013 was 19,700 murrelets (95 percent CI: 15,400 to 23,900 birds) (Falxa et al. 2015, p. 7). The largest and most stable murrelet subpopulations now occur off the Oregon and northern California coasts, while subpopulations in Washington have experienced the greatest rates of decline (-4.4 percent per year; 95% CI: -6.8 to -1.9%) (Lance and Pearson 2016, p. 5).

Monitoring of murrelet nesting habitat within the Northwest Forest Plan area indicates nesting habitat declined from an estimated 2.53 million acres in 1993 to an estimated 2.23 million acres in 2012, a decline of about 12.1 percent (Raphael et al. 2015b, p. 89). Murrelet population size is strongly and positively correlated with amount of nesting habitat, suggesting that conservation of remaining nesting habitat and restoration of currently unsuitable habitat is key to murrelet recovery (Raphael et al. 2011, p. iii).

The species decline has been largely caused by extensive removal of late-successional and old growth coastal forest which serves as nesting habitat for murrelets. Additional factors in its decline include high nest-site predation rates and human-induced mortality in the marine environment from disturbance, gillnets, and oil spills. In addition, murrelet reproductive success is strongly correlated with the abundance of marine prey species. Overfishing and oceanographic variation from climate events have likely altered both the quality and quantity of murrelet prey species (USFWS 2009, p. 67).

Although some threats have been reduced, most continue unabated and new threats now strain the ability of the murrelet to successfully reproduce. Threats continue to contribute to murrelet population declines through adult and juvenile mortality and reduced reproduction. Therefore, given the current status of the species and background risks facing the species, it is reasonable to assume that murrelet populations in Conservation Zones 1 and 2 and throughout the listed range have low resilience to deleterious population-level effects and are at high risk of continual declines. Activities which degrade the existing conditions of occupied nest habitat or reduce adult survivorship and/or nest success of murrelets will be of greatest consequence to the species. Actions resulting in the further loss of occupied nesting habitat, mortality to breeding adults, eggs, or nestlings will reinforce the current murrelet population decline throughout the coterminous United States.

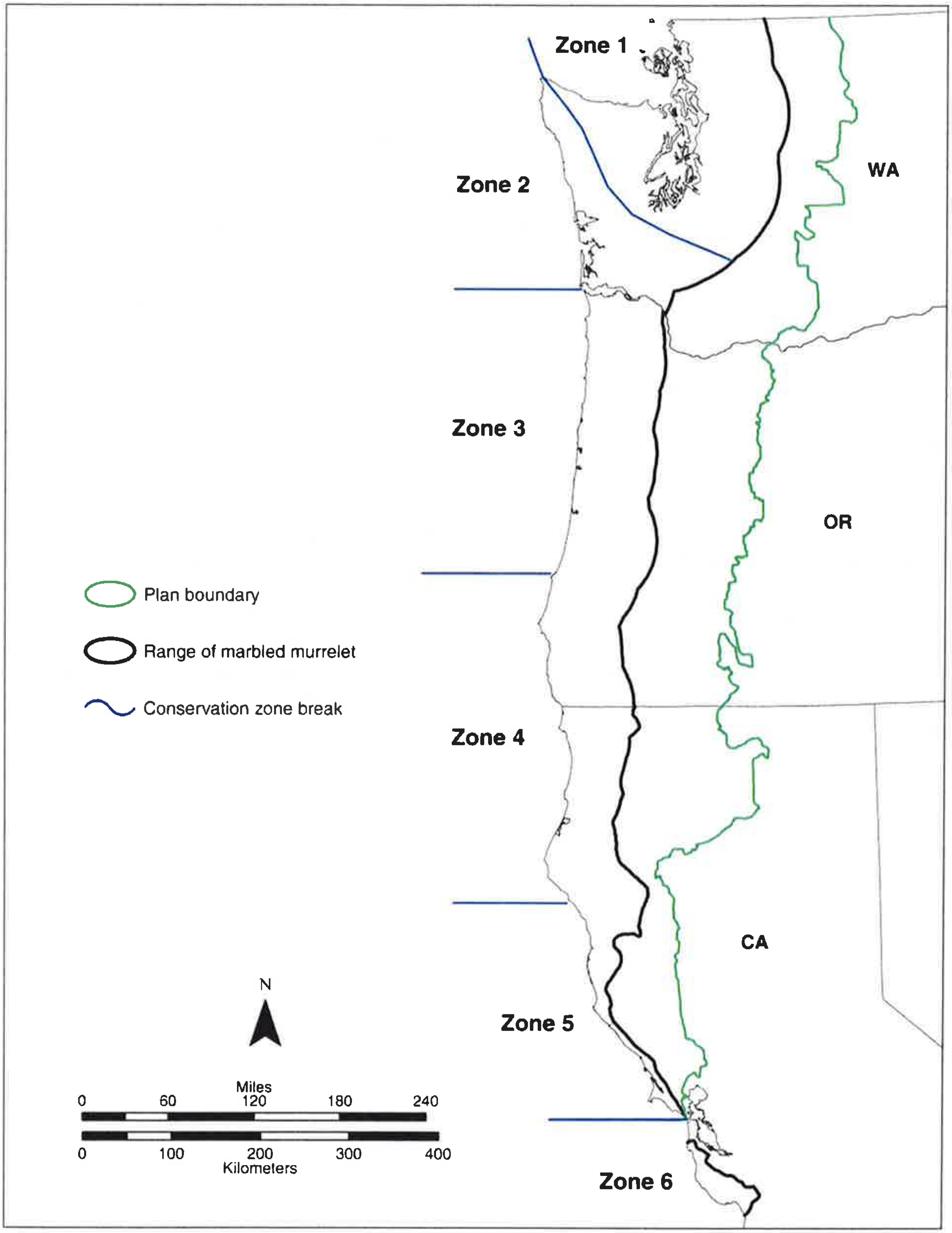

Figure 1. The six geographic areas identified as Conservation Zones in the recovery plan for the marbled murrelet (USFWS 1997). Note: "Plan boundary" refers to the Northwest Forest Plan. Figure adapted from Huff et al. (2006, p. 6).

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APPENDIX C
STATUS OF THE DESIGNATED CRITICAL HABITAT FOR BULL TROUT

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Appendix C
Status of the Designated Critical Habitat for Bull Trout

Legal Status

Current Designation

The U.S. Fish and Wildlife Service (Service) published a final critical habitat designation for the coterminous United States population of the bull trout on October 18, 2010 (70 FR 63898); the rule became effective on November 17, 2010. A justification document was also developed to support the rule and is available on our website (http://www.fws.gov/pacific/bulltrout). The scope of the designation involved the species' coterminous range, including six draft recovery units [Mid-Columbia, Saint Mary, Columbia Headwaters, Coastal, Klamath, and Upper Snake (75 FR 63927)]. The Service's 1999 coterminous listing rule identified five interim recovery units (50 CFR Part 17, pg. 58910), which includes the Jarbidge River, Klamath River, Columbia River, Coastal-Puget Sound, and Saint Mary-Belly River population segments (also considered as interim recovery units). Our five year review recommended re-evaluation of these units based on new information (USFWS 2008, p. 9). However, until the bull trout draft recovery plan is finalized, the current five interim recovery units will be used for purposes of section 7 jeopardy analyses and recovery planning. The adverse modification analysis in this biological opinion does not rely on recovery units, relying instead on the listed critical habitat units and subunits.

Rangewide, the Service designated reservoirs/lakes and stream/shoreline miles as bull trout critical habitat (Table 1). Designated bull trout critical habitat is of two primary use types: 1) spawning and rearing, and 2) foraging, migration, and overwintering (FMO).

Table 1. Stream/shoreline distance and reservoir/lake area designated as bull trout critical habitat by state.

State	Stream/Shoreline Miles	Stream/Shoreline Kilometers	Reservoir /Lake Acres	Reservoir /Lake Hectares
Idaho	8,771.6	14,116.5	170,217.5	68,884.9
Montana	3,056.5	4,918.9	221,470.7	89,626.4
Nevada	71.8	115.6	-	-
Oregon	2,835.9	4,563.9	30,255.5	12,244.0
Oregon/Idaho	107.7	173.3	-	-
Washington	3,793.3	6,104.8	66,308.1	26,834.0
Washington (marine)	753.8	1,213.2	-	-
Washington/Idaho	37.2	59.9	-	-
Washington/Oregon	301.3	484.8	-	-
Total	19,729.0	31,750.8	488,251.7	197,589.2

The 2010 revision increases the amount of designated bull trout critical habitat by approximately 76 percent for miles of stream/shoreline and by approximately 71 percent for acres of lakes and reservoirs compared to the 2005 designation.

This rule also identifies and designates as critical habitat approximately 1,323.7 km (822.5 miles) of streams/shorelines and 6,758.8 ha (16,701.3 acres) of lakes/reservoirs of unoccupied habitat to address bull trout conservation needs in specific geographic areas in several areas not occupied at the time of listing. No unoccupied habitat was included in the 2005 designation. These unoccupied areas were determined by the Service to be essential for restoring functioning migratory bull trout populations based on currently available scientific information. These unoccupied areas often include lower main stem river environments that can provide seasonally important migration habitat for bull trout. This type of habitat is essential in areas where bull trout habitat and population loss over time necessitates reestablishing bull trout in currently unoccupied habitat areas to achieve recovery.

The final rule continues to exclude some critical habitat segments based on a careful balancing of the benefits of inclusion versus the benefits of exclusion. Critical habitat does not include: 1) waters adjacent to non-Federal lands covered by legally operative incidental take permits for habitat conservation plans (HCPs) issued under section 10(a)(1)(B) of the Endangered Species Act of 1973, as amended (Act), in which bull trout is a covered species on or before the publication of this final rule; 2) waters within or adjacent to Tribal lands subject to certain commitments to conserve bull trout or a conservation program that provides aquatic resource protection and restoration through collaborative efforts, and where the Tribes indicated that inclusion would impair their relationship with the Service; or 3) waters where impacts to national security have been identified (75 FR 63898). Excluded areas are approximately 10 percent of the stream/shoreline miles and 4 percent of the lakes and reservoir acreage of designated critical habitat. Each excluded area is identified in the relevant Critical Habitat Unit (CHU) text, as identified in paragraphs (e)(8) through (e)(41) of the final rule. See Tables 2 and 3 for the list of excluded areas. It is important to note that the exclusion of waterbodies from designated critical habitat does not negate or diminish their importance for bull trout conservation. Because exclusions reflect the often complex pattern of land ownership, designated critical habitat is often fragmented and interspersed with excluded stream segments.

Table 2. Stream/shoreline distance excluded from bull trout critical habitat based on Tribal ownership or other plan.

Ownership and/or Plan	Kilometers	Miles
Lewis River Hydro Conservation Easements	7.0	4.3
DOD – Dabob Bay Naval	23.9	14.8
HCP – Cedar River (City of Seattle)	25.8	16.0
HCP – Washington Forest Practices Lands	1,608.30	999.4
HCP – Green Diamond (Simpson)	104.2	64.7
HCP – Plum Creek Central Cascades (WA)	15.8	9.8
HCP – Plum Creek Native Fish (MT)	181.6	112.8
HCP–Stimson	7.7	4.8
HCP – WDNR Lands	230.9	149.5
Tribal – Blackfeet	82.1	51.0
Tribal – Hoh	4.0	2.5
Tribal – Jamestown S'Klallam	2.0	1.2
Tribal – Lower Elwha	4.6	2.8

Ownership and/or Plan	Kilometers	Miles
Tribal – Lummi	56.7	35.3
Tribal – Muckleshoot	9.3	5.8
Tribal – Nooksack	8.3	5.1
Tribal – Puyallup	33.0	20.5
Tribal – Quileute	4.0	2.5
Tribal – Quinault	153.7	95.5
Tribal – Skokomish	26.2	16.3
Tribal – Stillaguamish	1.8	1.1
Tribal – Swinomish	45.2	28.1
Tribal – Tulalip	27.8	17.3
Tribal – Umatilla	62.6	38.9
Tribal – Warm Springs	260.5	161.9
Tribal – Yakama	107.9	67.1
Total	3,094.9	1,923.1

Table 3. Lake/Reservoir area excluded from bull trout critical habitat based on Tribal ownership or other plan.

Ownership and/or Plan	Hectares	Acres
HCP – Cedar River (City of Seattle)	796.5	1,968.2
HCP – Washington Forest Practices Lands	5,689.1	14,058.1
HCP – Plum Creek Native Fish	32.2	79.7
Tribal – Blackfeet	886.1	2,189.5
Tribal – Warm Springs	445.3	1,100.4
Total	7,849.3	19,395.8

Conservation Role and Description of Critical Habitat

The conservation role of bull trout critical habitat is to support viable core area populations (75 FR 63898:63943 [October 18, 2010]). The core areas reflect the metapopulation structure of bull trout and are the closest approximation of a biologically functioning unit for the purposes of recovery planning and risk analyses. CHUs generally encompass one or more core areas and may include FMO areas, outside of core areas, that are important to the survival and recovery of bull trout.

Thirty-two CHUs within the geographical area occupied by the species at the time of listing are designated under the final rule. Twenty-nine of the CHUs contain all of the physical or biological features identified in this final rule and support multiple life-history requirements. Three of the mainstem river units in the Columbia and Snake River basins contain most of the physical or biological features necessary to support the bull trout's particular use of that habitat, other than those physical biological features associated with Primary Constituent Elements (PCEs) 5 and 6, which relate to breeding habitat.

The primary function of individual CHUs is to maintain and support core areas, which 1) contain bull trout populations with the demographic characteristics needed to ensure their persistence and contain the habitat needed to sustain those characteristics (Rieman and McIntyre 1993, p. 19); 2) provide for persistence of strong local populations, in part, by providing habitat conditions that encourage movement of migratory fish (Rieman and McIntyre 1993, pp. 22-23; MBTSG 1998, pp. 48-49); 3) are large enough to incorporate genetic and phenotypic diversity, but small enough to ensure connectivity between populations (Hard 1995, pp. 314-315; Healey and Prince 1995, p. 182; Rieman and McIntyre 1993, pp. 22-23; MBTSG 1998, pp. 48-49); and 4) are distributed throughout the historic range of the species to preserve both genetic and phenotypic adaptations (Hard 1995, pp. 321-322; Rieman and McIntyre 1993, p. 23; Rieman and Allendorf 2001, p. 763; MBTSG 1998, pp. 13-16).

The Olympic Peninsula and Puget Sound CHUs are essential to the conservation of anadromous[1] bull trout, which are unique to the Coastal-Puget Sound population segment. These CHUs contain marine nearshore and freshwater habitats, outside of core areas, that are used by bull trout from one or more core areas. These habitats, outside of core areas, contain PCEs that are critical to adult and subadult foraging, overwintering, and migration.

Primary Constituent Elements for Bull Trout

Within the designated critical habitat areas, the PCEs for bull trout are those habitat components that are essential for the primary biological needs of foraging, reproducing, rearing of young, dispersal, genetic exchange, or sheltering. Based on our current knowledge of the life history, biology, and ecology of this species and the characteristics of the habitat necessary to sustain its essential life-history functions, we have determined that the following PCEs are essential for the conservation of bull trout.

1. Springs, seeps, groundwater sources, and subsurface water connectivity (hyporheic flows) to contribute to water quality and quantity and provide thermal refugia.

2. Migration habitats with minimal physical, biological, or water quality impediments between spawning, rearing, overwintering, and freshwater and marine foraging habitats, including but not limited to permanent, partial, intermittent, or seasonal barriers.

3. An abundant food base, including terrestrial organisms of riparian origin, aquatic macroinvertebrates, and forage fish.

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[1] Bull trout migrate from saltwater to freshwater to reproduce are commonly referred to as anadromous. However, bull trout and some other species that enter the marine environment are more properly termed amphidromous. Unlike strictly anadromous species, such as Pacific salmon, amphidromous species often return seasonally to fresh water as subadults, sometimes for several years, before returning to spawn (Brenkman and Corbett 2005, p. 1075; Wilson 1997, p. 5). Due to its more common usage, we will refer to bull trout has exhibiting anadromous rather than amphidromous life history patterns in this document.

4. Complex river, stream, lake, reservoir, and marine shoreline aquatic environments, and processes that establish and maintain these aquatic environments, with features such as large wood, side channels, pools, undercut banks and unembedded substrates, to provide a variety of depths, gradients, velocities, and structure.

5. Water temperatures ranging from 2 °C to 15 °C (36 °F to 59 °F), with adequate thermal refugia available for temperatures that exceed the upper end of this range. Specific temperatures within this range will depend on bull trout life-history stage and form; geography; elevation; diurnal and seasonal variation; shading, such as that provided by riparian habitat; streamflow; and local groundwater influence.

6. In spawning and rearing areas, substrate of sufficient amount, size, and composition to ensure success of egg and embryo overwinter survival, fry emergence, and young-of-the-year and juvenile survival. A minimal amount of fine sediment, generally ranging in size from silt to coarse sand, embedded in larger substrates, is characteristic of these conditions. The size and amounts of fine sediment suitable to bull trout will likely vary from system to system.

7. A natural hydrograph, including peak, high, low, and base flows within historic and seasonal ranges or, if flows are controlled, minimal flow departure from a natural hydrograph.

8. Sufficient water quality and quantity such that normal reproduction, growth, and survival are not inhibited.

9. Sufficiently low levels of occurrence of non-native predatory (e.g., lake trout, walleye, northern pike, smallmouth bass); interbreeding (e.g., brook trout); or competing (e.g., brown trout) species that, if present, are adequately temporally and spatially isolated from bull trout.

The revised PCE's are similar to those previously in effect under the 2005 designation. The most significant modification is the addition of a ninth PCE to address the presence of nonnative predatory or competitive fish species. Although this PCE applies to both the freshwater and marine environments, currently no non-native fish species are of concern in the marine environment, though this could change in the future.

Note that only PCEs 2, 3, 4, 5, and 8 apply to marine nearshore waters identified as critical habitat. Also, lakes and reservoirs within the CHUs also contain most of the physical or biological features necessary to support bull trout, with the exception of those associated with PCEs 1 and 6. Additionally, all except PCE 6 apply to FMO habitat designated as critical habitat.

Critical habitat includes the stream channels within the designated stream reaches and has a lateral extent as defined by the bankfull elevation on one bank to the bankfull elevation on the opposite bank. Bankfull elevation is the level at which water begins to leave the channel and move into the floodplain and is reached at a discharge that generally has a recurrence interval of

1 to 2 years on the annual flood series. If bankfull elevation is not evident on either bank, the ordinary high-water line must be used to determine the lateral extent of critical habitat. The lateral extent of designated lakes is defined by the perimeter of the waterbody as mapped on standard 1:24,000 scale topographic maps. The Service assumes in many cases this is the full-pool level of the waterbody. In areas where only one side of the waterbody is designated (where only one side is excluded), the mid-line of the waterbody represents the lateral extent of critical habitat.

In marine nearshore areas, the inshore extent of critical habitat is the mean higher high-water (MHHW) line, including the uppermost reach of the saltwater wedge within tidally influenced freshwater heads of estuaries. The MHHW line refers to the average of all the higher high-water heights of the two daily tidal levels. Marine critical habitat extends offshore to the depth of 10 meters (m) (33 ft) relative to the mean lower low-water (MLLW) line (zero tidal level or average of all the lower low-water heights of the two daily tidal levels). This area between the MHHW line and minus 10 m MLLW line (the average extent of the photic zone) is considered the habitat most consistently used by bull trout in marine waters based on known use, forage fish availability, and ongoing migration studies and captures geological and ecological processes important to maintaining these habitats. This area contains essential foraging habitat and migration corridors such as estuaries, bays, inlets, shallow subtidal areas, and intertidal flats.

Adjacent shoreline riparian areas, bluffs, and uplands are not designated as critical habitat. However, it should be recognized that the quality of marine and freshwater habitat along streams, lakes, and shorelines is intrinsically related to the character of these adjacent features, and that human activities that occur outside of the designated critical habitat can have major effects on physical and biological features of the aquatic environment.

Activities that cause adverse effects to critical habitat are evaluated to determine if they are likely to "destroy or adversely modify" critical habitat by no longer serving the intended conservation role for the species or retaining those PCEs that relate to the ability of the area to at least periodically support the species. Activities that may destroy or adversely modify critical habitat are those that alter the PCEs to such an extent that the conservation value of critical habitat is appreciably reduced (75 FR 63898:63943; USFWS 2004, Vol. 1. pp. 140-193, Vol. 2, pp. 69-114). The Service's evaluation must be conducted at the scale of the entire critical habitat area designated, unless otherwise stated in the final critical habitat rule (USFWS and NMFS 1998, pp. 4-39). Thus, adverse modification of bull trout critical habitat is evaluated at the scale of the final designation, which includes the critical habitat designated for the Klamath River, Jarbidge River, Columbia River, Coastal-Puget Sound, and Saint Mary-Belly River population segments. However, we consider all 32 CHUs to contain features or areas essential to the conservation of the bull trout (75 FR 63898:63901, 63944). Therefore, if a proposed action would alter the physical or biological features of critical habitat to an extent that appreciably reduces the conservation function of one or more critical habitat units for bull trout, a finding of adverse modification of the entire designated critical habitat area may be warranted (75 FR 63898:63943).

Current Critical Habitat Condition Rangewide

The condition of bull trout critical habitat varies across its range from poor to good. Although still relatively widely distributed across its historic range, the bull trout occurs in low numbers in many areas, and populations are considered depressed or declining across much of its range (67 FR 71240). This condition reflects the condition of bull trout habitat. The decline of bull trout is primarily due to habitat degradation and fragmentation, blockage of migratory corridors, poor water quality, past fisheries management practices, impoundments, dams, water diversions, and the introduction of nonnative species (63 FR 31647, June 10 1998; 64 FR 17112, April 8, 1999).

There is widespread agreement in the scientific literature that many factors related to human activities have impacted bull trout and their habitat, and continue to do so. Among the many factors that contribute to degraded PCEs, those which appear to be particularly significant and have resulted in a legacy of degraded habitat conditions are as follows: 1) fragmentation and isolation of local populations due to the proliferation of dams and water diversions that have eliminated habitat, altered water flow and temperature regimes, and impeded migratory movements (Dunham and Rieman 1999, p. 652; Rieman and McIntyre 1993, p. 7); 2) degradation of spawning and rearing habitat and upper watershed areas, particularly alterations in sedimentation rates and water temperature, resulting from forest and rangeland practices and intensive development of roads (Fraley and Shepard 1989, p. 141; MBTSG 1998, pp. ii - v, 20-45); 3) the introduction and spread of nonnative fish species, particularly brook trout and lake trout, as a result of fish stocking and degraded habitat conditions, which compete with bull trout for limited resources and, in the case of brook trout, hybridize with bull trout (Leary et al. 1993, p. 857; Rieman et al. 2006, pp. 73-76); 4) in the Coastal-Puget Sound region where amphidromous bull trout occur, degradation of mainstem river FMO habitat, and the degradation and loss of marine nearshore foraging and migration habitat due to urban and residential development; and 5) degradation of FMO habitat resulting from reduced prey base, roads, agriculture, development, and dams.

Effects of Climate Change on Bull Trout Critical Habitat

One objective of the final rule was to identify and protect those habitats that provide resiliency for bull trout use in the face of climate change. Over a period of decades, climate change may directly threaten the integrity of the essential physical or biological features described in PCEs 1, 2, 3, 5, 7, 8, and 9. Protecting bull trout strongholds and cold water refugia from disturbance and ensuring connectivity among populations were important considerations in addressing this potential impact. Additionally, climate change may exacerbate habitat degradation impacts both physically (e.g., decreased base flows, increased water temperatures) and biologically (e.g., increased competition with non-native fishes).

Consulted on Effects for Critical Habitat

The Service has formally consulted on the effects to bull trout critical habitat throughout its range. Section 7 consultations include actions that continue to degrade the environmental baseline in many cases. However, long-term restoration efforts have also been implemented that provide some improvement in the existing functions within some of the critical habitat units.

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APPENDIX D
EXCERPTS FROM CITED LITERATURE

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Appendix D
Excerpts from Cited Literature

The body of this Opinion cites numerous articles and reports. Excerpts from many of these articles and reports are included here (Appendix D). Within this appendix, articles and reports are organized alphabetically by first author and year of publication.

Agness *et al.* (2008) have reported:

- "Many marine species now experience unprecedented levels of disturbance from vessel traffic, though the effects of this disturbance on most seabirds are poorly known. One such species is the Kittlitz's murrelet (*Brachyramphus brevirostris*), a relatively rare alcid that spends much of its time at sea (Day *et al.* 1999) … During summer, the potential for vessel disturbance of Kittlitz's murrelets in Glacier Bay is high … Under current (2006) regulations, 2 cruise ships, 6 large tour boats, and ≤ 25 private recreational motor-vessels are permitted to enter park waters each day through the summer season. Vessels overlap in space and time with Kittlitz's murrelets in their usual foraging areas, so there is potential for adverse effects on this species." (p. 347)

- "We investigated the potential effects of vessel activity on density and behavior … in near-shore areas of Glacier Bay to evaluate whether vessel activity causes (1) a decline in the species' near-shore density, (2) a change in group size, and (3) a change in the behavior of individuals at sea." (p. 347)

- "Because of high wing-loading, flight is energetically costly in this species (Pennycuick 1987). Chick-rearing has a high energetic cost for Kittlitz's murrelets, because of long-distance flight to inland nest sites (≤ 75 km inland; Day *et al.* 1983) … Therefore, we examined whether … murrelets that are provisioning chicks have different behavioral responses … than those not engaged in provisioning. Only individuals that are rearing chicks hold a single fish crosswise in the bill for later delivery to chicks (Carter and Sealy 1987) … We considered the effects of vessel activity on the behavior of fish-holding Kittlitz's murrelets compared with those not holding fish." (p. 347)

- "We also collected data on the vessel (speed and size) … We used a daily vessel rate (vessels h^{-1}) to capture variation in vessel activity at the daily time-scale. To ensure that the vessel rate accurately reflected daily vessel activity, only data from 36 full sampling days (≥ 9 h day^{-1}) were used." (p. 347)

- "Near-shore density. Vessel activity caused a decline in near-shore density at the short-term time-scale … When vessel effects were considered, model fit improved, which indicates that vessel rate helped predict murrelet density … [but] vessel activity did not result in a decrease in near-shore density at the daily time-scale." (p. 349)

- "Group size. Vessel activity did not change group size at the short-term time-scale … [or] daily time-scale … [instead] breeding stage (second split) and tidal magnitude (third split) were important predictors of murrelet group size." (p. 349)

- "Behaviors. At the immediate time-scale, we found that Kittlitz's murrelets changed behavior in the presence of vessels … such that the proportion of individuals flying increased, loafing decreased, and diving behavior did not immediately change … murrelets not holding fish (i.e., nonbreeders) had greater flight response … from cruise ships and tour boats than from small, medium, or large recreational vessels … Fish-holders (i.e., breeders) had the greatest flight response … from slow vessels with 'far' (400 - 1,000 m) approach distance … Fish-holders most commonly responded to vessels by diving, regardless of vessel speed, approach distance, or vessel size … vessel activity caused changes in behavior at the daily time-scale. Individuals spent more time loafing and less time diving when there was no vessel traffic on a given day than when vessel traffic was low, moderate, or high." (pp. 350, 351)

- "[However,] Environmental and biological factors had more influence than vessels on density near shore, group size, and behavior … vessels influenced density near shore and behavior, but they were not the sole or the most influential factor." (pp. 351, 352)

- "Vessel activity did not cause declines to persist at the daily time-scale, where environmental and biological factors had the greatest influence, which suggests only temporary disturbance of murrelets by vessels … Although Kittlitz's murrelets moved an unknown distance away to accommodate vessel traffic, they eventually returned within the day in greater numbers … for reasons that remain unclear to us … We conclude that vessel activity does not constitute a loss of suitable habitat for the Kittlitz's murrelet, because density rebounded over the course of a day." (p. 352)

- "We did not detect effects of vessel activity on the group size of Kittlitz's murrelets at short-term or daily time-scales, which indicates that group dynamics were not affected." (p. 352)

- "Kittlitz's murrelets increased diving effort on days with vessel activity by a factor of three … [and] flying effort during vessel activity increased more than 30-fold … Negative effects on the birds' daily energy budgets can occur when vessel activity reduces foraging behavior and increases energetically costly behavior such as flight. Other studies have shown that such behavioral changes may constitute significant energy loss at high rates of vessel traffic (diving ducks: Korschgen *et al.* 1985; American Coot [*Fulica americana*]: Schummer and Eddleman 2003). Therefore, it is possible that Kittlitz's murrelets suffer a net energy loss as a consequence of vessel activity." (p. 352)

- "Dive response may be a better indicator of disturbance for fish-holders. Dive behavior was not observed among fish-holders in the absence of vessels … Given that fast vessel speed caused the greatest disturbance (i.e., dive response) for fish-holders … vessel travel at slower speeds enforced with speed limits (i.e., ≤ 6 km h^{-1}) could prevent disturbance of fish-holders." (Agness *et al.* 2008, p. 352)

The Virginia Eastern Shorekeepers (Ayers 2006) looked at the distribution of lost, discarded, and abandoned clam nets on the Atlantic barrier islands, and made observations regarding their effects on substrates, vegetation, and nesting and migratory birds:

- "The objective was to locate, assess, and document the extent of discarded plastic netting used in the clam aquaculture industry on the barrier beaches of the Eastern Shore of Virginia … [with] photo- documentation, mapped locations, and observed effects … on the coastal system." (p. 3)

- "Nets are used solely to protect clams from large predators … Most of the netting … is an oriented polyethylene or polypropylene mesh imbedded with a UV additive to extend outdoor life." (p. 5)

- "In most cases, the clam net … was carried or moved on and around the beach as part of the wrack line … In most cases, partially buried nets observed during one survey were gone in the next, with evidence of high tide washing over the area and moving the net." (p. 10)

- "The nets provide adequate and cost effective protection from most predators … [However,] To be effective, the nets must remain intact … Even a small tear of a few inches can allow some predators to devastate entire beds of clams … Growers have developed effective ways of securing their nets … Despite the care given to ensure that nets are properly placed, nets are still damaged or destroyed by man-made and naturally occurring events." (p. 12)

- "Man-made events, primarily nets struck by boats or boat propellers, … are the most frustrating to growers who feel they are … avoidable … Some shallow water beds are damaged by passing boats several times a season … Often it appears to be a recreational boat operating in unfamiliar waters … Although there are no specific guidelines for growers to mark their grounds, most have some type of marking … Some growers mark every bed, while others place a minimal amount of marks out." (p. 12)

- "Natural events can have an even larger impact … Storms, strong currents … [and] wave action can … erode sand … above average tides and currents can also erode and cover beds with sand … nets are [frequently] torn." (p. 13)

- "The aquaculture industry reports some netting is lost during storm and unusual tide events … The quantity reported as lost appears significantly less than the actual netting deposited along the shoreline … Discounting weather, the vast majority of the growers believe the net is being abandoned by less the ten percent of the total growers (personal conversation, M. Peirson, P. Terry, T. Walker)." (p. 15)

- "Today it is common practice for the larger growers to send crews out to recover abandoned net, regardless of the origin … The larger growers … condemn the practice of discarding net … [and] indicate that a relatively small number of growers are creating a negative image for the rest of the industry." (Ayers 2006, p. 15)

Banas and Cheng (2015, pp. 59-69 *In* Washington Sea Grant 2015) used an oceanographic circulation model developed for the south Puget Sound to investigate the potential influences of shellfish aquaculture on water quality and trophic status:

- "A new, high-resolution (200 meter) circulation model for south Puget Sound was developed, both to illuminate water connectivity and residence-time patterns with application to south Puget Sound shellfish aquaculture." (p. 59)

- "Results suggest a strong gradient in residence time from the central, deep channels to the small, western inlets, creating a potential for localized effects on water quality that a bulk analysis would not resolve … A map of 'drawdown time' – the time required for cultured shellfish to reduce the standing stock of phytoplankton by 50 percent, given their inlet-scale densities – was estimated and compared with the map of residence time … Results suggest that Henderson Inlet, Eld Inlet, Totten Inlet, Hammersley Inlet, Oakland Bay, and upper Case Inlet have combinations of long residence time and high densities of aquacultured filter-feeders such that aquaculture operations there may potentially control local phytoplankton concentrations." (p. 59)

- "Overall, these results suggest that while tidal flushing of south Puget Sound is quite efficient on average, the gradient in residence time from the central, deep channels to the small, western inlets is quite strong, potentially creating localized effects on water quality." (p. 62)

- "In general, the balance of (i) local phytoplankton production, (ii) hydrodynamic import and export, and (iii) filter feeder consumption rates controls the carrying capacity of a shallow estuary for filter-feeder production (Cloern 1982, Dame and Prins 1988, Peterson and Black 1987) … The same balance determines the potential for benthic filter feeders to act as a brake on eutrophication." (p. 62)

- "A benthic clearance rate … was estimated for each inlet … based on multiplying cultured shellfish density … by shellfish clearance rate … Clearance rates were then summed across species to obtain the total water filtered by region." (p. 65)

- "If [drawdown time is much lower than residence time], then it is possible for benthic grazing to constitute the dominant loss term, and the phytoplankton budget is likely a balance between local growth and local pelagic and benthic grazing … The criterion for potential local control by benthic grazers is met in Henderson, Eld, Totten, Hammersley, and upper Case Inlets, and Oakland Bay." (pp. 65, 66)

- "Based on [our] results, one might hypothesize that the small inlets of western south Puget Sound experience noticeable food competition between cultured bivalves and other consumers of phytoplankton. One might also hypothesize that these inlets are at noticeably lower risk of eutrophication than they would be in the absence of shellfish aquaculture." (Banas and Cheng 2015, pp. 66 *In* Washington Sea Grant 2015)

Beck *et al.* (2001) have argued that "…a better understanding of the habitats that serve as nurseries for marine species, and the factors that create site-specific variability in nursery quality, will improve conservation and management":

- "Nearshore estuarine and marine ecosystems—e.g., seagrass meadows, marshes, and mangrove forests—serve many important functions in coastal waters … Most notably,they have extremely high primary and secondary productivity and support a great abundance and diversity of fish and invertebrates. " (p. 633)

- "The nursery-role concept was first applied nearly a century ago to motile invertebrates and fishes with complex life cycles, in which larvae are transported to estuaries, metamorphose, grow to subadult stages, and then move to adult habitats offshore." (p. 634)

- "In early papers the estuary as a whole was considered to be the nursery … In subsequent works, however, the focus shifted to specific areas within estuaries as nurseries, especially wetlands … and seagrass meadows, because evidence suggested that they supported much greater densities of organisms than adjacent unvegetated … substrates (Williams 1955, Hutchings and Recher 1974, Turner 1977, Orth *et al.* 1984, Minello 1999)." (p. 634)

- "Comparisons are often limited to vegetated versus unvegetated habitats (Edgar and Shaw 1995, Gray *et al.* 1996) … Generally, an area has been called a nursery if a juvenile fish or invertebrate species occurs at higher densities, avoids predation more successfully, or grows faster there than in a different habitat." (p. 634)

- "The evidence usually indicates that the density of fish and invertebrates is higher in vegetated than in unvegetated habitats (for reviews see Orth *et al.* 1984, Heck *et al.* 1997, Able 1999, Minello 1999)." (p. 634)

- "The few studies that have focused on differences in juvenile survival … indicate that survival of a species is generally greater in vegetated than in unvegetated habitats (Orth *et al.* 1984, Heck and Crowder 1991, Able 1999) … [But] Even fewer studies have focused on the effects … [to] growth of fish and invertebrates (Heck *et al.* 1997, Phelan *et al.* 2000) … In seagrass meadows, evidence regarding growth is, surprisingly, equivocal … Only about half of the studies report that the growth rate of individuals is higher in seagrass habitats than in adjacent habitats (Heck *et al.* 1997)." (p. 634)

- "There is growing recognition that there are exceptions to the nursery-role concept … For example, few commercially important species of fish and invertebrates appear to rely exclusively on seagrass meadows … (Heck *et al.* 1995) … (Able and Fahay 1998) … Instead, most of these species use seagrass meadows opportunistically but can survive well in unvegetated areas." (p. 635)

- "The underlying premise of most studies … is that some nearshore, juvenile habitats contribute disproportionally to the production of individuals that recruit to adult populations … The ecological processes operating in nursery habitats, as compared with other habitats, must support greater contributions to adult recruitment from any combination of four factors: (1) density, (2) growth, (3) survival of juveniles, and (4) movement to adult habitats." (p. 635)

- "It is more important to conserve, abate the loss, restore, or otherwise manage habitats that contribute disproportionately to the production of adults." (p. 636)

- "Comparisons among … nursery habitats have usually involved only vegetated and unvegetated habitats, even though individual species may use many different habitats (Minello 1999) … To determine which, if any, habitats serve as nurseries, all of a species' juvenile habitats should be surveyed." (p. 637)

- "Some portions of juvenile habitats will be nurseries, but not all juvenile habitats can be nurseries … If many habitats are examined, it should be possible to identify and focus on those that make the greatest contribution to adult recruitment, that is, the best nursery habitats." (p. 637)

- "In the overwhelming majority of studies, a habitat is suggested to be a nursery largely because it supports high densities of juveniles relative to another habitat … Although a habitat may support high densities of juveniles, if these individuals never reach adult populations, then that habitat does not function as a productive nursery … In most studies the unstated premise has been that, all else being equal, habitats with higher densities of juveniles are likely to make a greater contribution to the production of adults than habitats with lower densities of juveniles … This correlation, which is rarely tested,may hold in many cases, but there are likely to be important exceptions … Density is only one of four factors that must be considered to determine whether a habitat serves as a nursery." (pp. 637, 638)

- "The nursery value of seagrass meadows … may vary geographically … Many biotic and abiotic factors can influence the nursery value of habitats for a species [including predation, competition, food availability, water depth, disturbance and tidal regime, location, fragmentation, and connectivity]… For example, Heck and Crowder (1991) found that predation on target species in seagrass beds was lower in more structurally complex beds, which suggests that more complex beds may serve as better nurseries for many species because they increase survivorship." (p. 638)

- "Larval supply and presettlement processes also can affect the initial density and condition (e.g., size) of juveniles within a habitat (Grimes and Kingsford 1996, Roy 1998) … In general, presettlement processes are rarely considered when evaluating how well habitats function as nurseries … greater attention needs to be paid to their interaction with postsettlement processes." (p. 638)

- "Landscape-level factors also can affect the nursery value of sites within habitats … For example, the relative location of seagrass beds in an estuary can affect the density of fish species … Relative location, with respect to large water movements such as upwelling or retention zones, has also been shown to strongly influence larval delivery (Roy 1998), thus playing a crucial role in setting initial juvenile densities within a habitat." (p. 638)

- "[For seagrasses] There is undeniable evidence of their importance … They provide many ecosystem services and serve many important functions (Costanza *et al.* 1997) … Seagrasses and wetlands are highly productive, and this production enters coastal food webs through many different pathways, not just as fish moving to adult habitats." (p. 639)

- "Ideally, all four factors—density, growth, survival, and movement—would be examined in a study of … nursery habitats, but doing so may be difficult … Researchers must consider multiple habitats … Although most species are found in more than one or two habitats, surprisingly few studies make comparisons among more than two potential nursery habitats." (Beck *et al.* 2001, p. 639)

Bendell and Wan (2011) used high resolution aerial photography and Geographic Information Systems to evaluate the effects of intensive, landscape-scale shellfish activities on patterns of avian habitat utilization:

- "Here we apply aerial photography with Geographic Information Systems (GIS), to map the cumulative anthropogenic footprint of an industry in a spatially defined ecologically important region of the British Columbian [BC] coast … The approach applied here was successful in accurately detailing the cumulative extent of the anthropogenic activity on the foreshore which could have not been achieved at a coarser resolution … Information was then effectively applied to visualize and assess the potential impact of … development of the foreshore on bird distribution within the spatially identified region." (p. 417)

- "Low resolution photography coupled with GIS has been used to successfully characterize and quantify habitat types (e.g., Sheppard *et al.* 2006; Higinbotham *et al.* 2004) … Here we apply high resolution aerial photography coupled with GIS … to evaluate the consequences of anthropogenic activity on other ecological uses within [a] spatially defined region." (p. 418)

- "The case study presented here is unique in that the region under study is an Important Bird Area … of global significance (Booth 2001) … The Baynes Sound region supports globally important populations of the Western Grebe (*Aechmophorus occidentalis*), the White-winged (*Melanitta fusca*) and Surf Scoter (*Melanitta perspicillata*), and the Pacific Loon (*Gavia pacifica*) (Booth 2001) … It also serves as a major centre for the BC shellfish aquaculture industry with half of the industries economies being generated from this region (British Columbia Ministry of Sustainable Resource Management (BCMSRM) 2002)). " (p. 418)

- "On the west coast of BC … there has been [an] attempt by industry and the federal and provincial governments to aggressively expand shellfish aquaculture, with the Manila clam (*Venerupis philippinarum*), and Pacific oyster (*Crassostrea gigas*), the main product farmed … Baynes Sound has a long history of shellfish aquaculture dating back to the 1900's (BCMSRM 2002) … [But] The number of leases and the numbers of approved species for farming on the individual leases has greatly increased since 1984 … In addition to shellfish aquaculture, increasing urban development also results in habitat loss within this region." (pp. 418, 419)

- "Use of the foreshore … for aquaculture purposes precludes the use of this region for ecologically important roles such as providing key habitat for spawning activities (e.g., the Pacific sand lance (*Ammodytes hexapterus*)), foraging by wildlife, and as nurseries … This stretch of shallow coastline is the most intensely farmed shellfish area in the province accounting for over half of the total production of shellfish in BC (BCMSRM 2002)." (p. 419)

- "This region is … key habitat and serves a number of ecological roles … supporting numerous intertidal species … [it provides] a primary food source for clam feeding sea ducks (Bendell-Young 2006; Whiteley and Bendell-Young 2007) … [and] is also important for shore birds such as the Dunlin (*Calidris alpina*) which by contrast forages on polychaetes within the intertidal (Dierschke *et al.* 1999; Shepherd and Lank 2004)." (p. 421)

- "After the maximum and relevant intertidal were digitized, regions of the intertidal covered by anti-predator netting were determined … A multi-step analysis by GIS modelling was applied to the four layers (maximum intertidal, viable intertidal, antipredator netting, and oyster grow-out beds) to determine that region of the foreshore not compromised by shellfish farming activities." (p. 422)

- "In this case, cumulative effects include the use of the foreshore for oyster grow-out as well as coverage with anti-predator netting … We use the information obtained by spatially characterizing the anthropogenic footprint to assess its role in influencing the distribution of shore and water birds such as the dunlin, grebe, and scoter." (p. 423)

- "Areas of high bird use in 1980 versus 2003-2005 were contrasted for 1) White-winged Scoter, 2) Surf Scoter, 3) Bufflehead, 4) Pacific Loon, 5) Western Grebe, and 6) Dunlin … All are dependent on the habitat of the foreshore in someway, e.g., for food such as mussels, clams, small fish, invertebrates, and plants." (p. 424)

- "In Baynes Sound, netted areas … [and] oyster grow-out beds occupy 27 percent and 34 percent of the intertidal area respectively … The amount of foreshore habitat in Baynes Sound used for shellfish farming is … 56 percent of the viable intertidal." (p. 424)

- "There were distinct differences in the locations of high bird use in 1980 as compared to 2003-2005 … In 2003-2005 birds were located all along the coastline, with no one particular region of high use … Although numbers cannot be directly compared as counting techniques differed between the two surveys, differences in abundance for the Pacific Loon and Western Grebe [were obvious and] note comment … For the Pacific Loon, in 1980, maximum counts of 400 were recorded for polygon 45 … During 2003-2005 [the] greatest average numbers of 50 were recorded for polygon 25 … In 1980, maximum counts of 14,000 for the Western Grebe were recorded for polygon 41 … For 2003-2005 the maximum average of 200 was recorded for polygon 33." (pp. 425, 426)

- "Other surveys within the same geographic region, Puget Sound, south of Baynes Sound also note a 95 percent decline in numbers of Western Grebe (Nysewander *et al.* 2005)." (p. 429)

- "Within Baynes Sound, the primary change in intertidal use during this 30 year period has been the development of the foreshore within polygons 33–46 for aquaculture, with the true extent of its footprint determined by high resolution aerial photography coupled with GIS … As the majority of overwintering birds are now found within the Courtenay River Estuary (Comox Harbour) or are distributed along the coastline with no one significant region of high bird use, it would appear that key habitat historically used by these species is no longer available." (p. 429)

- "Although scoters are still observed in polygons where farming occurs, they also have been displaced from historic regions of high bird use and presumably high food availability to areas where food availability has not been compromised by the shellfish industry, i.e., polygons 2–23." (p. 429)

- "Aerial photography with GIS identified that polygons 36–46 [are] under intense use by aquaculture … Prior to 1980 these regions were relatively unaltered and areas of high bird use … During 2003-2005 this was no longer the case, with birds being displaced to Comox Harbour." (Bendell and Wan 2011, p. 429)

Bostrom, Jackson, and Simenstad (2006) reviewed and synthesized a large body of literature describing the landscape ecology of seagrasses and their effects on associated fauna:

- "Seagrasses comprise some of the most heterogeneous landscape structures of shallow-water estuarine/marine ecosystems in the world … However, while knowledge at the molecular, organism, patch, and community scale is pervasive, understanding of seagrass landscape ecology is more fragmentary and has not been synthesized …The growth and recruitment dynamics of seagrasses as well as man-made and/or natural disturbances create complex spatial configurations of seagrass over broad (metres to kilometres) spatial scales." (p. 383)

- "Patterns (e.g., abundance, diversity, biomass) and processes (e.g., recruitment, predation, flows and productivity) at a specific site can only be fully understood by including broad-scale … variables and landscape attributes … We review landscape patterns and [the] processes that cause them, and then present models for faunal distribution." (pp. 383, 384)

- "Internal regulatory mechanisms … [include] the capacity of seagrasses to occupy space by clonal growth … [and via] sexual reproduction and dispersal … Plant performance in some seagrass species can vary by position of the plant position in the patch, with higher shoot density, above-ground biomass, and leaf area index at the centre of the patch (Brun *et al.*, 2003)." (pp. 384, 385)

- "External regulatory mechanisms … [include] hydrodynamic activity … geomorphology … water depth … [and] exposure." (p. 385)

- "The landscape mosaic model … [takes] into account that organisms rarely show a preference for a specific structured habitat, i.e. seagrass, oyster reefs, macroalgae, and mangrove … An alternative view is to see the species/process/question-specific landscape as a mosaic of different habitats (McGarigal and Cushman, 2002) … [The model] proposes that optimal foraging, movement, and fitness strategies vary for different animals within a mosaic." (p. 386)

- "To summarize general tendencies across seagrass landscape studies … we used as a metric the proportion of studies reporting significant … and non-significant … results, without taking into account the statistical power of individual studies (Mazzerolle and Villard, 1999) … To detect possible effects of patch and landscape variables on the most commonly reported faunal groups and/or processes we also used the total number of significant results, because many papers reported significant or non-significant results for several different sampling occasions and/or for several taxa." (p. 386)

- "A total of 33 papers published between 1994 and 2004 met our search criteria … skewed towards the temperate northern latitudes … *Zostera* spp. … [were among] the most studied landscape-forming genera/species … 50 percent of the papers examined the role of patch size and 43percent examined edge effects, i.e., possible differences in response variables between the seagrass boundary and the interior parts of a patch or meadow." (pp. 391, 392)

- "Although patches within seagrass landscapes are rarely symmetrical, but occur in a variety of shapes, our understanding of the role of patch shape, orientation, and quality (food availability) for associated animals is still based on a very limited number (<10 percent) of studies." (p. 392)

- "About 50 percent of all studies focused on some aspect of seagrass ecosystem configuration based on a variety of partly correlating metrics, including fragmentation, proximity, connectivity, isolation, fractal dimension, total linear edge, number of patches, edge contrast, and patch orientation … At its simplest, fragmentation is usually observed as a reduction in seagrass cover and a decrease in patch size over time, causing an increase in the proportion of habitat edge and distance between patches, i.e. decreased connectivity and increased amount of unvegetated corridors." (p. 393)

- "The majority (>80 percent) of studies focused on invertebrates … Mollusca (almost exclusively bivalves) was the most studied taxon (34 percent), followed by epifaunal and infaunal assemblages (28 percent and 25 percent, respectively), [and] crabs and fish (21 percent each) … The most common response variables describing faunal population and community structure in relation to patch and landscape variables were density (>65 percent) and number of species/taxa (25 percent), followed by composition, biomass, and diversity, each contributing by about 10 percent … These studies tended to capture the broad-scale effect of landscape structure on faunal community composition, but studies at different scales were required to address the role of landscape attributes in the functional performance of individuals or species." (p. 393)

- "The three most commonly studied explanatory variables, i.e. patch size … edge effects, and fragmentation, and the five most commonly studied animal response variables, i.e. density, number of species/taxa, growth, predation and mortality, were chosen for closer examination … In two thirds of the studies examined, seagrass patch size was a significant predictor of [faunal] density (n = 7), growth (n = 5), and mortality (n = 4), respectively … However, half of the studies examined showed non-significant results for the same response variables, mainly due to confounding effects of sites, seasons, and target taxa … This exemplifies the difficulty in linking effects of seagrass landscape pattern to faunal structure." (p. 393)

- "Seagrass habitat fragmentation effects on decapods, fish, and bivalves have been inconclusive, with about equal proportions of significant (56 percent) and non-significant (44 percent) results, respectively … Examples of responses of fish densities to fragmentation are few (n = 2) and show both higher and lower densities in fragmented seagrass landscapes compared to more continuous landscapes (Hovel *et al.*, 2002; Salita *et al.*, 2003) … Total number of species of fish and decapods has been demonstrated to show a negative relationship with increasing fragmentation, while non-significant patterns have been demonstrated for infaunal density, taxa richness, and diversity … Decapod studies have shown either negative (density) or non-significant (density, size) responses to habitat edges … One study reported significantly lower densities of total macrofauna and fish along edges (Uhrin and Holmquist, 2003)." (p. 394)

- "In general, we found that a landscape variable by itself seldom explained adequately the variance in response variables … rather they influenced faunal distributions and dynamics indirectly, for example by altering … water flow, physical disturbance, and sediment characteristics … predation pressure … movement and behavior … [and] reproduction strategies … Covarying mechanisms typically explained faunal distributions and dynamics … Covariation makes it difficult to determine differences between local and landscape phenomena." (pp. 395, 396)

- "We found mixed effects of fragmentation in seagrass landscapes, with about equal proportions of significant … and non-significant effects … suggesting that seagrass fragmentation is not necessarily detrimental for associated animals." (p. 396)

- "Studies in terrestrial landscapes have demonstrated critical thresholds in fragmentation, where mobility and diversity patterns change dramatically and nonlinearly (Gardner and Milne, 1987; Rosen, 1989) … Demonstration of such threshold responses … [in seagrass landscapes] warrants further investigation." (p. 396)

- "Broad-scale movement of marine invertebrates occurs predominantly by means of passive dispersal of larval reproductive stages, eggs, and juveniles over vast areas … This implicates the important role of increased connectivity between marine populations." (p. 396)

- "In accordance with terrestrial studies suggesting minor effects of fragmentation on migratory and edge species (Bender *et al.*, 1998), studies of actively moving crustaceans indicate that fragmented seagrass supports more decapods than does continuous seagrass (Eggleston *et al.*, 1998; Loneragan *et al.*, 1998; Hovel and Lipcius, 2001)." (p. 396)

- "In accordance with Turner *et al.* (2001), it might be summarized that effects of spatial patterns/fragmentation on organisms are not likely to be important if habitat patches are abundant … and well connected, edge effects are not central to the process/species under study, and movement between suitable habitats is relatively unlimited." (p. 397)

- "In this review, landscape variables were seldom significant predictors of invertebrate response … Rather, patch scale and landscape scale variables interacted and covaried in 60 percent of the studies, with usually strong effects of within patch plant characteristics on animal responses ... Consequently, the influence of the seagrass landscape scale on ecosystem function only occasionally appears to override local scale variability … The literature surveyed suggests that seagrass landscapes support highly dynamic communities where results were seldom consistent over time within the same region (Irlandi *et al.*, 1999; Bologna and Heck, 2000, 2002; Bell *et al.*, 2001; Hovel and Lipcius, 2001; Salita *et al.*, 2003) or across sites (Irlandi, 1996; Hovel *et al.*, 2002; Eggleston *et al.*, 1999) … In particular, invertebrates appeared less sensitive to landscape variables than vertebrates." (p. 397)

- "Critical questions regarding how mobile seagrass fauna perceives and responds to patchiness have only recently started to be explored … While a landscape might appear fragmented to one species it could be perceived as continuous by another." (p. 398)

- "The importance of unvegetated strips as corridors for large mobile predators (e.g., Irlandi *et al.*, 1995) is likely to vary depending on target species and water depth … In very shallow seagrass landscapes, where the leaf canopy reach the water surface, unvegetated corridors may provide the only avenue for movement/foraging in an unstructured environment, while in deeper seagrass landscapes the space above the leaf canopy can also be utilized by mobile fauna." (p. 398)

- "Surprisingly, given their inability to rapidly adjust to predation and other dynamic influences in seagrass landscapes, infaunal assemblages showed usually weak responses to landscape variables, leaving much of the variability unexplained (Tanner, 2003; Bowden *et al.*, 2001; Turner *et al.*, 1999) … Infaunal communities are … least affected by fragmentation … and show species-specific effects and/or small shifts in community composition rather than dramatic changes in density (Frost *et al.*, 1999) … In general, infaunal assemblages appear to be primarily controlled by sediment stability and grain size … (Bostrom and Bonsdorff, 1997, 2000; Bowden *et al.*, 2001)." (p. 398)

- "The value of seagrass … is certainly recognized as a desirable factor to be managed as 'critical nursery habitat' … although validation of the causative factors or seagrass landscape attributes that actually account for enhanced survival to recruitment is lacking (Beck et al., 2001) … [But] In contrast to previous assumptions, it has been demonstrated that many taxa have limited larval dispersal abilities, implying that such fauna will respond negatively to increasing fragmentation, and that maintenance of connectivity among habitat patches is indeed an important management issue (Ruckelshaus and Hays, 1998)." (p. 398)

- "Nonlinear relationships between ensemble faunal variables and landscape metrics were identified by a number of studies, and are to be expected when assessing species with different perception of the seagrass landscape … This may also account for the lack of relationships in some studies and the opposing results of comparable studies … In order to contrast patterns across regions and to allow the synergistic development of our knowledge in this field, we need to standardise our use of landscape metric and terms in relation to seagrass landscapes … Perhaps the more daunting need is a much better understanding of the various processes operating at various scales and possible cascading effects across scales that influence fauna-environment relationships in seagrass landscapes … It is obvious from this literature that they are complex, difficult to predict, and still relatively under-studied." (Bostrom, Jackson, and Simenstad 2006, p. 399)

Brown and Thuesen (2011) assessed the biodiversity of mobile benthic fauna in cultured south Puget Sound geoduck beds:

- "Both sites were commercial-scale geoduck farming operations and were representative of typical geoduck farms in Puget Sound in both scale and design … These two farm sites were in two different stages of production throughout the sampling period … The geoduck site in Eld Inlet was structured with … PVC tubes, with net toppers serving as predator protection … The Nisqually Reach site had no structure and contained only geoduck in grow-out phase … These two stages of geoduck aquaculture were examined because they represent the two most distinct stages of geoduck production, those with and those without geoduck tubes." (p. 772)

- "Traps yielded 1,161 individuals from 15 species of mobile benthic animals during the course of the study … The graceful crab, *C. gracilis*, accounted for 76.3 percent of all specimens … There were no significant differences in species richness between the geoduck aquaculture sites and control sites, as observed using Mao Tau accumulation curves … Using Coleman rarefaction analysis, species richness was significantly higher ($P < 0.05$) in the structured geoduck site … compared with its control site … However, there was no significant difference observed between the [un-structured] geoduck grow-out site … [and] its control." (p. 773)

- "[At the structured Eld Inlet site] low species evenness was observed … *C. gracilis* constituted 94.0 percent of all specimens … [At the un-structured Nisqually Reach site] there was greater species evenness … *C. gracilis* was the most abundant species, comprising 35.0 percent of the individuals … However, the staghorn sculpin, *Leptocottus armatus*, and red rock crab, *Cancer productus*, each made up 26.5 percent of the individuals." (p. 773)

- "In southern Puget Sound, even small differences in habitats can demonstrate broad variability in community member assemblages, as evidenced by the differences between the study sites in Eld Inlet and Nisqually Reach … The results in the current study indicate that intertidal geoduck aquaculture can increase the local biodiversity of mobile benthic fauna … However, the effects were subtle and not consistent between the two locations." (pp. 774, 775)

- "In Eld Inlet, both the geoduck farm and the natural control site were dominated by one species, *C. gracilis*, and Simpson's biodiversity indices were very low and not significantly different between the two sites … [At] the Nisqually Reach site, where all predator protection had been removed, biodiversity as measured using Simpson's index was higher than in the control site, and seasonal shifts in the numbers of organisms influenced results … Although it remains inconclusive, the trend in the Coleman rarefaction analyses … indicates that, with further sampling, species richness in the control site would be significantly higher than at the geoduck farm site … The conflicting results … may simply be the result of the temporal and spatial heterogeneity of marine organisms in southern Puget Sound." (p. 775)

- "Additional studies are needed to look at the impact of geoduck aquaculture on smaller animals and infaunal organisms … Another method of geoduck husbandry uses a single large predator net … to protect against predators, and the effects of this method on mobile benthic communities should also be investigated." (Brown and Thuesen 2011, p. 775)

Burkett (1995, pp. 233-240) reviewed marbled murrelet food habits and prey ecology, including the works of Sealy (1975c), Krasnow and Sanger (1982), Sanger (1983, 1987b), Carter (1984), Vermeer (1992), and others:

- Sealy (1975c) found that sand lance (*Ammodytes hexapterus*) made up 67 percent of the food items in the diet of adult and subadult marbled murrelets. Euphausiids, "…a group of small crustaceans which make up part of the zooplankton ('krill') found in the marine environment…" (p. 233), were the next most important food item (27 percent of the items).

- "Newly fledged young selected different prey than adult/subadult[s] … [and] The difference in adult and juvenile diets can be partially explained by looking at the difference in abundance of prey items taken by the adult/subadult [marbled] murrelets over the course of a breeding season." (p. 224)

- "Sealy (1975c) concluded that [marbled] murrelets seldom feed more than 500 m from shore, usually in water less than 30 m deep. His work demonstrated that euphausiids made up only a small part of the overall diet during the breeding season, but were dominant during the early part of the breeding season." (p. 224)

- Krasnow and Sanger (1982) calculated an Index of Relative Importance value for the foods consumed by marbled murrelets. "During the 1976/1977 winter, fish, primarily of the family osmeridae [smelt, including capelin], were the most important prey, followed by euphausiids … and mysids." (p. 224)

- "Krasnow and Sanger (1982) reported that murrelets fed primarily in shallow water but obtained their prey throughout the water column. Sanger (1987b) noted that the ability of murrelets to forage at least part of the time near the bottom assures a broader trophic spectrum than a food supply originating with phytoplankton productivity in the water column alone." (p. 228)

- "The results of Krasnow and Sanger's (1982) study … pointed to the importance of local differences in the relative availability of major prey species within the same year." "Marbled murrelets, tufted puffins (*Fratercula cirrhata*), sooty shearwaters (*Puffinus griseus*), and black-legged kittiwakes [*Rissa tridactyla*] exploited a similar suite of prey. Sand lance and euphausiids were taken during spring, capelin during early summer, and sand lance during late summer. The authors attributed this chronology to the probable seasonal occurrence and distribution of prey as did Sealy (1975c) and Carter (1984) in their study areas." (p. 228)

- Sanger (1983, 1987b) found that winter survival may be enhanced by the ability to alter the 'normal' diet of pelagic fishes to include demersal crustaceans, seasonally linking themselves to a detrital-based food chain.

- Carter (1984) found that breeding adults fed primarily on sand lance and Pacific herring, including larval and juvenile fish. Molting and hatch-year birds also fed primarily on herring, sand lance, and northern anchovy. Euphausiids were absent.

- "The importance of herring … in Carter's (1984) study correlates with the local abundance and availability of juvenile herring. He suggested that [marbled] murrelets fed opportunistically on available prey and noted that juvenile herring were abundant only in localized areas near spawning grounds (Hourston in Carter 1984). This conclusion is further strengthened by the work of Vermeer (1992)." (p. 230)

- "The massive presence of herring … and the predictable nature of this occurrence, has resulted in annual utilization of this resource by many seabirds and other animals (Vermeer 1992) … Vermeer's (1992) study is another example of opportunistic foraging behavior … and another demonstration of the importance of local differences." (p. 230)

- In Washington, "During the summers of 1968 and 1969, Cody (1973) collected information on seabird breeding activity, prey species, and foraging patterns off the west coast of the Olympic Peninsula ... Marbled murrelets holding fish before their evening flights inland were … seen to carry only anchovy (*Engraulis*) and sand lance (*Ammodytes*) in their bills, and it was presumed these fish were for nestlings (Carter and Sealy 1987a) … Additional work by Cody in Carter (1984) at the San Juan Islands again revealed anchovy as nestling prey." (p. 232)

- "Historically, the Pacific sardine migrated extensively... The migration was complex, and timing and extent of movement were affected to some degree by oceanographic conditions (Hart in Anonymous 1993) ... The fishery began in central California in the late 1800's ... [but] declined, beginning in the late 1940's ... to extremely low levels in the 1970's ... The regulatory history of the sardine fishery might best be described as 'too little too late' ... It was not until 1967, well after the fishery had collapsed, that the California legislature passed an 'emergency' bill ... Since the early 1980's, sardines have been taken incidentally [in west coast commercial fisheries] ... The low occurrence of sardines in the diet of [marbled] murrelets is interesting given the wide geographic distribution of this fish ... It may represent an overall lower abundance due to overfishing, competition, and natural influences ... [but] Because of the natural fluctuations in anchovies and sardines ... [marbled] murrelets probably evolved to use this resource in proportion to availability ... The periodic lows in anchovy and sardine populations would probably not adversely affect the [marbled] murrelet as long as alternative forage fish remained available." (pp. 237, 238)

- "From the studies discussed above, some variability in reproductive success of the [marbled] murrelet can be expected because of the naturally dynamic nature of their prey base and the marine environment. Anthropogenic influences can compound prey fluctuations; thus, marine research and management should be designed to minimize or avoid adverse changes in seabird reproduction and marine trophic-level interactions." (Burkett 1995, p. 240)

Carter, McAllister, and Isleib (1995) describe accidental capture and mortality in commercial gill nets as one of the major threats to marbled murrelet populations:

- "There has been mounting concern about the impacts of gill-net mortality on the marbled murrelet (*Brachyramphus marmoratus*)(Carter and Morrison 1992, Carter and Sealy 1984, DeGange and others 1993, Marshall 1988a, Sealy and Carter 1984). [Marbled] murrelets become tangled and drown in gill nets while swimming under water ... Other forms of net fishing tend to be much less destructive to birds. Seine fishing is known at times to cause mortality ... Drift [gill] nets are about 900-1200 ft (275-365 m) long and are fished as a single unit." (p. 271)

- In Alaska, "Isleib (1982) observed marbled murrelets feeding close to nets ... Young of the year showed little fear of vessels. Isleib usually observed murrelets swimming along the nets in singles or pairs, frequently diving, often surfacing on one side and then the other of the net ... pursuing small feed fishes, including juvenile herring, sand lance (*Ammodytes hexapterus*), capelin (*Mallotus villosus*), needlefish (*Strongylura exilis*), and various salmon fry ... Murrelets are caught at varying depths in the nets, from the surface to 10 meters, mostly 3 to 5 meters down. Beyond 60 meters deep, murrelets do not appear to be caught ... [Isleib] felt that the numbers had increased in the past 20 years due to several factors: the vessels are continuously fishing around the clock; the use of finer web [or mesh]; and more boats are actively fishing (Isleib 1982). He observed that [marbled] murrelets are killed throughout the fishing season, with most (80+ percent) killed at night ... [marbled] murrelets are captured in the same locations year after year throughout the season. Young of the year, first noted in mid-July, are killed in a higher proportion to their respective numbers than adults" (p. 272)

- "It is difficult to estimate the true magnitude of impact, but when actively foraging aggregations of [marbled] murrelets overlap with gill-net gear, the potential for mortality is high (Carter and Sealy 1984)." (p. 274)

- "On five occasions in late summer, McAllister retrieved and released live [marbled] murrelets from encircled nets near Cape Chacon ... [They] were not able to escape over the floats, including juveniles and adults undergoing prebasic molt." (p. 274)

- In British Columbia, "Carter and Sealy (1984) estimated a minimum of 175-250 [marbled] murrelets were killed in 1980, representing 6.2 percent of the breeding population or 7.8 percent of the potential fall population. They pointed out that the long-term impacts of such mortality could be great, but the degree of impact depended upon continued high fishing effort in Barkley Sound ... Marbled murrelets were not recovered from purse seines in Barkley Sound in 1979-1982, although hundreds of common murres (*Uria aage*) were recovered (Carter, unpubl. data in DeGange and others 1993). Similarly, murrelets were not observed among floating carcasses of common murres off Carmanah Point north of Cape Flattery on the west coast of Vancouver Island ... in August 1979 (Carter, unpubl. data in Vermeer and Sealy 1984; DeGange and others 1993)" (p. 278)

- In Washington, "Speich and Wahl (1989) reported that western grebes (*Aechmophorus occidentalis*), common murres, and marbled murrelets were frequently killed, based on reports by local fishermen (Speich, pers. comm.; Wahl, pers. comm.) ... Because significant mortality of [marbled] murrelets was recorded in nearby Barkley Sound, British Columbia (see above), it is reasonable to assume that [marbled] murrelet mortality occurs in Washington waters." (p. 280)

- "Beached Birds. Kaiser (1993) reported two dead juvenile [marbled] murrelets and hundreds of other seabirds, especially common murres and rhinoceros auklets, washed ashore in Boundary Bay, British Columbia, in August 1993. Boundary Bay is located just across the border from areas where high numbers of [marbled] murrelets and gill-net fishing areas co-occur." (p. 281)

- "Grays Harbor. No marbled murrelets have been recorded as killed in gill nets in Grays Harbor during observer programs in summer and fall 1991, 1992, and 1993 for non-tribal fisheries (Jefferies and Brown 1993, WDFW 1994). Between 4 and 10 percent of nets were monitored each season and year. Bycatch included common murres, rhinoceros auklets, and loons. Some unidentified alcids and birds were recorded which may have included [marbled] murrelets." (p. 281)

- "Willapa Bay. No marbled murrelet bycatch was observed in Willapa Bay during observer programs in summer and fall 1991, 1992, and 1993 for non-tribal fisheries (Jefferies and Brown 1993, WDFW 1994). Between 1 and 13 percent of nets were monitored each season and year. Bycatch included common murres, cormorants, loons, grebes, and other alcids. Some unidentified alcids and birds were recorded which may have included [marbled] murrelets." (p. 281)

- "Columbia River. No marbled murrelets have been recorded as killed in gill nets in the Columbia River during observer programs in winter 1991, 1992 and 1993 (Jefferies and Brown 1993). Bycatch included common murres, cormorants, western and unidentified grebes, and surf scoters (*Melanitta perspicillata*). Some unidentified alcids and birds were reported which may have included [marbled] murrelets." (p. 281)

- "With available information, it is not yet possible to accurately determine the extent of mortality on marbled murrelets in Washington … Additional information on mortality must be derived from tribal and non-tribal fisheries, especially within and north of the San Juan Islands, northern Puget Sound, along the northern side of the Olympic Peninsula, and in the Cape Flattery area … The large amount of fishing effort that occurs throughout this area is likely to cause mortality on the scale of tens to hundreds of [marbled] murrelets [per year] at a minimum." (p. 281)

- "Gill-net fishing occurs widely and it is likely that: (1) several thousand to tens of thousands of [marbled] murrelets are killed annually in Alaska; (2) hundreds to thousands are probably killed annually in British Columbia; and (3) tens to hundreds may be killed annually in Washington." (p. 271)

- "Gill-net mortality alone may have already been an important factor of the decline in Alaska and British Columbia populations … Lower numbers of birds killed in central California and Washington also have had relatively large impacts on these small populations and may have contributed significantly to their potential future extirpation (see Carter and Erickson 1992)." (p. 283)

- "Even the very few dead [marbled] murrelets reported anecdotally or from observer programs are significant … few people (aside from fishermen) could report mortalities, carcasses are discarded shortly after death and either sink or are taken by predators soon thereafter, fishermen typically do not divulge knowledge of such mortality due to fear of affecting their livelihoods, and only a small fraction of nets are examined in certain localities during monitoring programs … We feel that the large size of gill-net fisheries, and their extensive coverage of almost all coastal areas throughout the range of the marbled murrelet, places gill-net mortality among the most significant problems for the species." (Carter, McAllister, and Isleib 1995, p. 283)

Coen *et al.* (2007) have reviewed ecosystem services provided by oysters and other molluscs (e.g., mussels):

- "Oysters and other molluscs (e.g. mussels) … provide services far beyond the mere top-down control of phytoplankton blooms, such as (1) seston filtration, (2) benthic–pelagic coupling, (3) creation of refugia from predation, (4) creation of feeding habitat for juveniles and adults of mobile species, and for sessile stages of species that attach to molluscan shells, and (5) provision of nesting habitat." (p. 303)

- "Grabowski and Peterson (2007) have identified 7 categories of ecosystem services provided by oysters: (1) production of oysters; (2) water filtration and concentration of biodeposits (largely as they affect local water quality); (3) provision of habitat for epibenthic fishes …; (4) sequestration of carbon; (5) augmentation of fishery resources in general; (6) stabilization of benthic or intertidal habitat (e.g., marsh); and (7) increase of landscape diversity." (p. 304)

- "Studies comparing invertebrate faunal abundance and diversity between restored and non-restored oyster reefs (e.g. Luckenbach *et al.* 2005, Rodney and Paynter 2006, L. D. Coen *et al.* unpubl.), between oyster reefs or reef mimics, and soft bottom habitats (e.g. Posey *et al.* 1999, Tolley and Volety 2005), and among oyster reefs of varying complexity (e.g. Coen and Luckenbach 2000, Luckenbach *et al.* 2005), consistently find higher abundances, biomass, and species richness on the structurally more complex reef habitats … Densities of decapods and meiofauna on oyster reefs are similar to those in other structured habitats (e.g. Glancy *et al.* 2003, Hosack *et al.* 2006)." (p. 305)

- "Abundance, biomass, and species richness of finfish species are higher at oyster reefs than in unstructured estuarine habitats (reviewed in Coen *et al.* 1999, ASMFC 2007) … Some of these species … are obligate reef residents … while other species are either facultative residents or transient associates (discussed in Breitburg 1999, Coen *et al.* 1999, ASMFC 2007)." (p. 305)

- "Oysters are predominantly intertidal, forming a protective breakwater that retards shoreline … erosion (Meyer *et al.* 1997; Grizzle *et al.* 2002; Coen and Bolton-Warberg 2005; ASMFC 2007; NRC 2007) … Fringing oysters … constitute an alternative to the hard bulk-heading of shorelines (Meyer *et al.* 1997; Coen and Bolton-Warberg 2005; NRC 2007)." (p. 305)

- "Filter-feeders enhance seagrass production … via a positive feedback loop (Reusch *et al.* 1994; Peterson and Heck 1999, 2001a,b; C. C. Wall *et al.* unpubl.). In their recent modeling paper, Cerco and Noel (2007) assess the impact of a 10 percent increase in oyster biomasss in Chesapeake Bay … and suggest that the enhancement of submerged aquatic vegetation would be the greatest direct beneficiary of oyster restoration." (Coen *et al.* 2007, p. 305)

Collie *et al.* (2000) published a meta-analysis looking at the effects of towed bottom-fishing gear on benthic communities:

- "Fishing gears used to catch demersal fish and shellfish often disturb both the seabed and the organisms living within or on it … The potential impact of this disturbance has become a subject of heated debate (Malakoff 1998) … The results of any single study are highly specific with respect to fishing gear, disturbance regime, habitat, and environment … Viewing each study in isolation makes it difficult to draw general conclusions." (p. 785)

- "We extracted summary data from a population of fishing impact studies and [undertook] a meta-analysis of this combined data set to ask the following questions … Are there consistent patterns in the responses of benthic organisms to fishing disturbance? … How does the magnitude of this response vary with habitat, depth, disturbance type, and among taxa? … [and] How does the recovery rate of organisms vary with these same factors? … Using this approach, the results from each study are regarded as independent replicates, permitting ecological questions to be examined on a much larger scale than would otherwise be possible." (pp. 785, 786)

- "We found 57 different manipulations or observations of the effects of fishing disturbance on benthic fauna and communities, extracted from 39 separate publications … [they examine] … gear type … regime [or] number of discrete periods of disturbance … [and] habitat … The 'biogenic' category includes seagrass meadows or reef-forming organisms such as mussel beds, [and] sponge or coral reefs." (p. 786)

- "For … the initial impacts of fishing we examined the effect of each variable on the response of benthic organisms … within a generalized linear modelling framework (McCullagh and Nelder 1989) … We also employed tree-based regression modelling." (pp. 786, 788)

- "Most (89 percent) of the studies were undertaken at depths less than 60 m; of these 13 (23 percent) were intertidal … All the intertidal studies were conducted at small spatial scales (<50 m) … The largest scale studies were those that compared commercially-fished grounds with closed areas or areas of different fishing intensity … We used the 'regime' variable to distinguish experimental studies (acute disturbance) from the 12 studies comparing fished and unfished areas (chronic disturbance)." (p. 789)

- "Effects on the total number of individuals and total number of species … Dredging had a more negative impact than trawling, which is not surprising as dredges tend to penetrate deeper into the sediments than trawls … The mean response for number of species was … a 27 percent reduction … Larger impacts were observed in mud and gravel habitats than in sand … Intertidal dredging had the most negative impact on species richness." (p. 790)

- "Effects on populations … Gear type was highly significant, with intertidal dredging having the most negative impact, followed by scallop dredging, and inter-tidal raking … Habitat and regime were almost significant at the 5 percent level … The most negative impacts occurred in muddy sand and gravel habitats." (pp. 790, 791)

- "The variable 'Class' also had a significant effect on the response to disturbance …The largest negative impacts were observed for Anthoza and Malacostraca; their means … correspond to a 75 percent reduction in density … The other arthropod class, maxillipoda (copepods and ostracods), was less negatively affected … Among the echinoderms, the holothurians and ophiuroids were more negatively impacted than the echinoids and asteroids … Bivalves appeared to be less sensitive to fishing disturbance than gastropod molluscs … Polychaetes were more negatively affected than oligochaetes, which appeared to be the least sensitive class … None of the predicted means were positive … Taxa differed in their response to disturbance, but on average, none increased in abundance." (p. 791)

- "The genera least impacted by disturbance were bivalves … Many of these bivalves are small in size or have particularly well armoured shells that protect them from physical damage." (p. 792)

- "Patterns of recovery … Depth and scale were either insignificant or had inconsistent effects among models … With respect to gear type, the plots suggest that the source of the statistically significant interaction term is the greater initial impact for intertidal dredging … Intertidal dredging gives the greatest initial responses because it is the most efficient gear … [often] completely removing the … fauna." (pp. 792, 793)

- "Despite the obvious limitations of our analyses, consistent patterns have emerged that would otherwise be unsupported by single studies … On average, the immediate impact of fishing disturbance was to remove about half the individuals … However, the magnitude of the response varied significantly with gear type, habitat, and among taxa … With respect to gear type, our results are broadly consistent with expectations – intertidal dredging has more marked initial effects." (p. 793)

- "Our expectations for a habitat effect were that initial responses and rates of recovery from … impacts would be related to, and could be predicted from, the physical stability of the sea bed … It makes intuitive sense that animals living in unconsolidated sediments are adapted to periodic sediment resuspension and smothering … However, our … results were somewhat inconsistent among analyses … It does appear that responses in sand habitats were usually less negative than in the other habitats, but a clear ranking for expected impacts did not emerge." (pp. 793, 794)

- "The most consistently interpretable result was with respect to faunal vulnerability, with a ranking of initial impacts that seems broadly congruent with expectations based on morphology and behavior." (p. 795)

- "Recovery … The small spatial scale of most of the … studies make it likely that much of the recolonization was through immigration into disturbed patches, rather than reproduction within patches … It should be noted, that while we might accurately predict the recovery rate for small-bodied taxa such as polychaetes, which dominate the data set … communities often contain one or two long-lived and therefore vulnerable species … Given the effects observed in many studies, we anticipate a shift from communities dominated by relatively high biomass species towards dominance by high abundances of small-sized organisms." (pp. 795)

- "It is clear that intensively fished areas are likely to be maintained in a permanently altered state, inhabited by fauna adapted to frequent physical disturbance … This is, of course, much more likely for the most stable types of habitats containing structural biogenic components … It is for these habitats that the paucity of data is most apparent and where recovery rates will be longest." (p. 795)

- "An important consequence … is the reduction in habitat complexity (architecture) that accompanies the removal of sessile epifauna, which appears to have important consequences for fish communities (see, for example, Sainsbury *et al.* 1997) … Our current understanding of the functional role of many of the larger-bodied long-lived species (e.g. as habitat features, bioturbators, etc.) is limited and should be addressed." (p. 795)

- "With respect to the design of future studies … [we] will be best served by abandoning short-term, small-scale pulse experiments … Instead, the scientific community should be arguing for support to undertake much larger scale press and relaxation experiments … The results … [would be] clearly interpretable in terms of real world intensities of fishing disturbance … [and] the experiments would be conducted in the very habitats (i.e. real fishing grounds) about which the question of recovery is actually being posed." (Collie *et al.* 2000, p. 796)

Dealteris *et al.* (2004) assessed the structural habitat complexity inherent to submerged aquatic vegetation, shallow nonvegetated seabeds, and shellfish aquaculture gear, and the abundance, composition, and diversity of associated benthic communities:

- "The habitat value of modified rack and bag, shellfish aquaculture gear (SAG) … submerged aquatic vegetation (SAV) … and a shallow nonvegetated seabed (NVSB) was comparatively evaluated over a 1-year period." (p. 867)

- "Shellfish aquaculture gear … has habitat value at least equal to and possibly superior to submerged aquatic vegetation." (pp. 867, 873)

- "There is abundant evidence that indicates … [natural oyster] reef communities are extremely diverse and show differences in species abundances as compared with adjacent nonvegetated, sand flat habitats … Oyster reef habitats are not only highly diverse but [also] include species absent in adjacent soft-bottom environments (Coen *et al.* 1999b)." (p. 867)

- "Shellfish aquaculture gear may serve as an artificial reef habitat by virtue of its inherent structural complexity and extensive time spent on the seafloor throughout the year." (p. 868)

- "Habitat structure, described in terms of emergent surface area … varied as a function of habitat type and season … The log transformed average emergent surface area varied significantly … There were significant differences ($P < 0.05$) between each of the 3 habitats (SAG>SAV>NVSB)." (p. 869)

- "The mean Shannon-Weiner Index values of species diversity were highly significantly different between habitats ($P < 0.001$) and between seasons ($P < 0.01$) … The SAG habitat was not significantly different from the SAV habitat ($P > 0.05$), however both of these habitats were highly significantly different ($P < 0.01$) from the NVSB." (pp. 869, 870)

- "The SAG habitat showed consistently lower Smith and Wilson species evenness values than either the SAV or NVSB because a few species tended to dominate this habitat … The SAG habitat was significantly lower in species evenness than either the SAV or NVSB habitats." (p. 870)

- "There was a highly significant difference ($P < 0.001$) in species abundance between each habitat (SAG>SAV>NVSB) … Thirteen crustacean species were identified … The greatest abundances occurred in the SAG habitat, followed by the SAV habitat, and then the NVSB habitat … Seven mollusk species were identified … The greatest abundances occurred in the SAG habitat, followed by the SAV habitat, and then the NVSB habitat … Sessile invertebrate species were present in both SAG and SAV habitats … [but] NVSB habitat was devoid of … sessile invertebrates." (p. 870)

- "We believe that the observed differences in species composition and abundances are influenced by differences in habitat composition, structure, and complexity … There was a highly significant difference in emergent surface area … that was strongly correlated with abundance of organisms." (pp. 872, 873)

- "The SAV emergent surface varied throughout the year due to seasonal growth and mortality patterns … The surface area of the … [SAG] remained constant … The SAV does support epiphytic and sessile invertebrate growth, but not to the extent of the SAG … The high prevalence of [encrusting] sessile invertebrate communities on the SAG … increases habitat complexity … The SAG … provides 3-dimensional structural complexity." (p. 873)

- "The SAG habitat had consistently lower evenness than the other ecotypes because of the hyperdominance of several species within the aquaculture gear … In contrast, the SAV habitat was rarely dominated by a few species, but rather supported a more equal distribution of organisms." (p. 873)

- "The species evenness data clearly show that whereas the abundances may be greater in the SAG habitat, the SAG habitat is dominated by a few species." (p. 873)

- "The aquaculture gear used to grow cultured bivalves has intrinsic habitat complexity and shares many of the characteristics that artificial reefs possess." (Dealteris *et al.* 2004, p. 873)

DNR 2014a, pp. 1-32 through 1-42, 1-44 through 1-51, and 1-51 through 1-54.

Physical, Chemical, and Biological Characteristics

Unless cited to indicate otherwise, the following content is taken with minimal editing from the DNR's Aquatic Lands HCP planning document (DNR 2014a, pp. 1-32 through 1-42):

(p. 1-32) "Saltwater systems in the Pacific Northwest are influenced by mixed semidiurnal tides, two high and two low tides each lunar day with unequal amplitude. Tidal range increases from north to south, with tidal ranges in the north Puget Sound of less than 3 meters (10 ft), and more than 5 meters (16 ft) near Olympia, Washington (Komar 1997).

Locally, tidal currents and wind events also affect inland circulation patterns. Wind flow is predominantly from south-southwest during the winter, before gradually reversing direction in the spring (Williams *et al.* 2001). Wave conditions are generally mild, with both wave height and period limited by fetch (Williams *et al.* 2001). Wind significantly influences the oceanography of interior waters by generating surface waves, mixing surface waters, and forcing surface drift currents (Thomson 1994).

Stratification is greatest during the summer because of the combined effects of solar heating and river discharge, and lowest in the winter because of seasonal cooling and increased wind-induced mixing from storms (Thomson 1994). Many of the deeper regions exhibit persistent density stratification based on salinity and temperature (Williams *et al.* 2001). By comparison, seasonal stratification in the Strait of Juan de Fuca is relatively uncommon and the waters are well-mixed vertically."

(pp. 1-32 thru 1-34) "Resource cycling is fueled primarily by energy from benthic and terrestrial vegetation; the type and source of vegetative inputs influence both the species present and their ecological function (Simenstad and Wissmar 1985; Valiela 1984). While benthic habitats in the nearshore generally lie within the photic zone, the lower depth of light penetration is highly dependent on water clarity.

The bathymetry of the nearshore ecosystem varies with the characteristics of the surrounding landscape. In Puget Sound [and Hood Canal], much of this ecosystem occurs as a narrow fringe along the edge of the steep-sided fjord, interspersed with shallow inlets and back-bay areas. The characteristics of these shallow areas vary from north to south. Estuaries and tidally influenced rivers are concentrated in the north (for example, Bellingham, Skagit, and Port Susan Bays); inlets predominate at the southern end of Puget Sound (including the Henderson, Budd, and Hammersley Inlets)(Washington DNR 2005a).

Water circulation and local bathymetry have a significant influence on the character of the nearshore system. Because of the proximity of the continental shelf, strong seasonal upwelling occurs along the coast of Washington and results in the movement of nutrient-rich waters into the photic zone and the nearshore ecosystem. This stimulates phytoplankton growth and thereby provides habitat and food for zooplankton. Tidal exchange also transports these highly productive waters into tidally influenced rivers and shallow embayments, providing foraging and refuge habitat for juvenile salmonids and other fish (Emmett *et al.* 2000). During periods of low circulation, or stratification, the nearshore is most affected by the upper water column, which is generally warmer and nutrient poor in the summer and is less saline in the winter due to increased river flows.

Glaciation shaped the general geomorphology [of the Puget Sound and Hood Canal](Burns 1985). Present-day sediment processes are responsible for forming and maintaining unconsolidated nearshore features such as dunes, marsh plains, and unvegetated beaches. Sediment transport in the nearshore is generally the result of waves and wave currents. Wave approach patterns determine the type of currents and resulting sediment movement. When waves approach the beach parallel to the shoreline, a series of rip currents develop causing erosion in pockets along the beach, while waves approaching at an angle form a longshore current or littoral drift. These currents can move along the shore for hundreds of miles; the direction of the prevailing winds determines the direction that the sediment is transported (Komar 1997). Sediment transport processes vary in their predominant direction and intensity, and are influenced by the complexities of tidal currents, wind-influenced wave patterns, and shoreline geomorphology."

(pp. 1-35, 1-36) "Saltwater-nearshore temperature varies dramatically both seasonally and spatially. Solar energy heats the water and intertidal substrate at low tides, which results in a dramatic seasonal variation in water temperature. Saltwater-nearshore temperatures generally range from 6 to 9 degrees Celsius (43 to 48 degrees Fahrenheit) during winter, and 16 to 19 degrees Celsius in summer (61 to 66 degrees Fahrenheit)(Thom and Albright 1990). Summer temperatures in shallow embayments with restricted circulation reach 20 to 25 degrees Celsius (68 to 77 degrees Fahrenheit) during warm sunny days. Infrequent, long, cold periods can drive temperatures to as low as 2 degrees Celsius (36 degrees Fahrenheit), especially in shallow systems, and very shallow water will occasionally freeze.

River and stream flows can also affect temperature in the nearshore. Typically, warming of freshwater during summer will increase water temperature in the nearshore. In winter, freshwater flows can cool nearshore water temperatures. Winds that blow offshore cause vertical mixing of the water column and can create upwelling, which brings colder, deeper water from offshore into the nearshore environment. Stratification of the water column in the nearshore typically results in a warm surface layer during summer and a cold surface layer in winter. The most protected water and shallowest sites show the greatest extremes in temperature, whereas sites most exposed, deep and open to circulation show the least extremes.

Salinity varies seasonally and spatially in the nearshore. Salinity is determined by the relative amounts of freshwater inputs from rivers and streams and saline ocean water. Winds and currents cause vertical and horizontal mixing of fresh and salt water. Nearshore areas dominated by rivers can have periods of very low salinity. In central Puget Sound, salinity observations at the mouths of rivers can vary between 15 parts per thousand in winter-spring, to 31 parts per thousand in late summer and early autumn.

Inorganic nutrients in the nearshore typically include the macronutrients nitrate, nitrite, ammonia and phosphate. These arrive in the nearshore by ocean inputs through upwelling, and freshwater inputs through overland flows of rainwater, rivers and streams. These macronutrients are important to the support of phytoplankton, seaweed, seagrass, and marsh plant growth in nearshore areas; low macronutrient concentrations can limit productivity. An overabundance of one or more of these nutrients can result in abnormal abundances of phytoplankton or seaweeds, the decay of which can create areas of low dissolved oxygen, also known as hypoxia. Plant use and uptake also affects the seasonal concentrations of nutrients. Nitrate concentrations in central Puget Sound vary from a high of 35 micromoles per liter in winter, to a low of less than 5 micromoles per liter in early summer (Thom and Albright 1990).

Dissolved oxygen concentrations in the nearshore are spatially and temporally variable. Because the water column is shallow, and often overlies very productive habitats, periods of high productivity can result in oxygen levels greater than 100 percent of the theoretical maximum oxygen concentration possible in water—this phenomenon is called supersaturation. In central Puget Sound, nearshore dissolved oxygen concentrations are typically greatest and most variable in spring and summer (11 to 16 milligrams per liter); the least variation occurs in autumn and winter (7 to 9 milligrams per liter; Thom and Albright 1990). Oxygen demand by sediment-associated microbes and chemical processes can be great in embayments with low circulation (where sediments are high in organic matter concentration), and in areas with very high densities of large infauna such as clams."

(pp. 1-40, 1-41) "Water clarity is affected by plankton concentration and suspended sediments. Secchi depth, a measure of water clarity, varies between 4 meters (13 ft) and more than 11 meters (36 ft), with the clearest waters often occurring during calm periods in winter, and after the large phytoplankton blooms in spring and summer have died off (Newton *et al.* 2002). In addition to phytoplankton blooms, widespread reduction in water clarity can occur during storms from suspension of fine sediment particles, or plumes of turbid water from larger rivers.

Nitrogen and phosphorus come from three primary sources: upwelling of nutrient rich water, input from land sources, and recycling of nutrients in surface waters and sediments (Harris 1986). Rich, oceanic waters are the primary source of nutrients for the inland region; anthropogenic sources are considered negligible in well-flushed basins (Williams *et al.* 2001). Inland primary productivity rates are generally considered to be very high, relative to those in other temperate estuaries. Inland primary productivity rates are primarily affected by sunlight, stratification, and water residence time (Williams *et al.* 2001). Because all of these factors are highly variable in time and space, primary productivity and abundance can occur in extremes, characterized by phytoplankton blooms. Intense blooms largely occur in the spring and fall, with smaller blooms in summer, and sparse growth in the winter.

Both inland and coastal offshore dissolved oxygen concentrations reflect the influence of dense, high salinity, naturally low-oxygenated oceanic waters (Newton *et al.* 2002). Concentrations range between 5 and 3 milligrams per liter."

(pp. 1-36 thru 1-38) "The nearshore is home to many species of planktonic invertebrates and fishes and is responsible for much of the primary production in nearshore and offshore waters. Water column phytoplankton communities can be divided into three main groups: dinoflagellates, diatoms, and microflagellates. Diatoms are typically the most abundant group, particularly during algal spring blooms. Dinoflagellates are more common in calmer, low-energy environments (Strickland 1983). Zooplankton consume phytoplankton and form the prey base for many species of fish that inhabit the nearshore, particularly juvenile salmon.

Other species that feed primarily on zooplankton include juvenile and adult Pacific herring (*Clupea pallasi*), southern euchalon (*Thaleichthys pacificus*), stickleback (*Gasterosteus* spp.), sand lance (*Ammodytes hexapterus*), juvenile salmon (*Onchorhynchus* spp.), Pacific cod (*Gadus macrocephala*), Pacific hake (*Merluccius productus*), walleye pollock (*Theragra chalcogramma*), lingcod (*Ophiodon elongatus*), sablefish (*Anoplopoma fimbria*), and spiny dogfish (*Squalus acanthias*)(Williams *et al.* 2001). Several species of mammals and birds also depend on the nearshore, including harbor seals (*Phoca vitulina*), killer whale or orca (*Orcinus orca*), grey whales (*Eschrichtius robustus*), river and sea otters (*Lontra canadensis* and *Enhydra lutri* respectively), loons (*Gavia* spp.), grebes (*Podicipedidae*), cormorants (*Phalacrocorax* spp.), and several species of ducks and marine seabirds (Long 1982).

Benthic nearshore habitats are divided into two general types: consolidated and unconsolidated. The specific nature of the habitat and its associated communities are influenced by substrates and vegetation (Dethier 1990; Williams and Thom 2001). [Consolidated habitats include rocky shore assemblages and seaweed assemblages. Unconsolidated habitats include eelgrass meadows, flats, and sub-estuaries (or tidally-influenced rivers).]

Rocky shores include those areas of the intertidal and shallow subtidal zone that are dominated by bedrock or boulder substrates. This habitat type is generally defined by relatively large-sized or abundant taxa dominated by kelp beds and other seaweed, or benthic invertebrates.

Seaweeds are macroscopic algae [organized] within three taxonomic subgroups based on dominant photosynthetic pigmentation: red, green, and brown algae. Seaweeds occur throughout the photic zone, reaching their greatest abundance in areas where salinity is routinely above 15 parts per thousand, with the greatest numbers of species occurring at salinities in the range of 31 to 35 (Thom 1980).

Kelp (Laminariales) and other seaweeds that grow attached to rock generally dominate consolidated habitats in areas of bedrock and boulders. The distribution of these seaweeds occurs along a vertical-depth gradient and is controlled by a variety of species-specific factors, such as light requirements, tolerance for desiccation, thermal and physical stress, competition with other native and non-native plants, and life-history strategies. Red algae are often found in the deepest waters because of their ability to use the wavelengths and energy levels of light that are found at these depths.

Floating kelps, such as bull kelp (*Nereocystis luetkeana*) and giant kelp (*Macrocystis integrifolia*), can form extensive canopies at or near the surface and are most common in high-energy environments. In Washington, floating kelp beds are found on approximately 11 percent of the shoreline, primarily in the Northwest Coast ecoregion (Washington DNR 2002). Kelp beds are used by sea otters and a variety of fish and invertebrate species for rearing, feeding, and predator avoidance. In some areas, herring may lay eggs on kelp. Benthic diatoms are also an important photosynthetic component of rocky consolidated habitats, and their primary productivity rates can be as high as that in beds of eelgrass (*Zostera marina*)(Thom *et al.* 1989).

In unconsolidated habitats, the primary vegetation is comprised of rooted flowering plants called seagrasses. Six species of seagrasses occur in Washington; eelgrasses (*Z. marina* and the exotic *Z. japonica*) are the most widespread. Eelgrass is generally found in monotypic stands, or meadows. These meadows harbor some of the richest assemblages of animals among all aquatic habitats in the state (Phillips 1984). They provide important feeding and refuge habitat for salmonids, crabs, and birds, and provide spawning habitat for herring (Baldwin and Lovvorn 1994; Holsman *et al.* 2003; McMillan *et al.* 1995; Phillips 1984; Thom *et al.* 1989); Wilson and Atkinson 1995; McIntyre and Barr 1997). While the vertical extent of eelgrass is controlled by light penetration and desiccation, it generally grows at depths of approximately plus 0.3 meters (0.9 ft) to minus 10 meters (33 ft) relative to MLLW (Thom *et al.* 1998; Thom *et al.* 2003).

Mud or tidal flats consist of gently sloping lands that contain fine to coarse unconsolidated sediments. Deposition of fine material is largely influenced by riverine sediment load or by deposition of material eroded from the surrounding bluffs. Benthic diatoms are generally the major source of primary production in many flats; eelgrass, however, and other attached vegetation and drift seaweeds (ulvoids) may be present. Unconsolidated sediments provide habitat for a variety of infauna (worms, small crustaceans, and bivalves) that are important prey for shorebirds, fishes, and both marine and terrestrial mammals. These sediments are also home to recreationally and commercially important stocks of clams, crabs, sturgeon (*Acipenser* spp.) and flatfish (*Pleuronectidae*), including geoduck clam, native littleneck clam, and Dungeness crab (*Metacarcinus magister*).

Rivers and streams that enter into larger estuarine and tidal systems can form distinct habitats. At their mouths, these tidally-influenced waters form deltas, which include channels through the mud flats that may contain water even at the lowest tides. Sub-estuaries are characterized by salinity concentrations that vary with river flows; estuarine character extends up river to the limit of tidal influence. Sub-estuaries also contain riparian habitat, dune habitat, tidal marshes, seaweed assemblages, eelgrass meadows, and limited rocky shore habitat. Sub-estuaries and tidally-influenced rivers provide the transition between freshwater and saltwater for migratory salmonids. Recent studies indicate that juvenile salmonids spend considerable time in these habitats as they migrate to the ocean (Beamer *et al.* 2005)."

(pp. 1-41, 1-42) "Consolidated habitats are primarily found in scattered pockets off the coast of the Olympic Peninsula, in the San Juan Archipelago, off the west coast of Whidbey Island and Admiralty Inlet, and in the Tacoma Narrows channel. High-energy, consolidated habitats are predominantly characterized by non-motile invertebrate species – such as anemones (*Metridium senile* and *Urticina* spp.), purple-hinged rock scallops (*Hinnites giganteus*), and giant acorn barnacles (*Balanus nubilus*)(Dethier 1990) – and mobile species, such as sea urchins (*Strongylocentrotus* spp.), rockfish (*Sebastes* spp.), gobies (*Coryphopterus* spp.), lingcod (*Ophiodon elongatus*), and sculpin (*Artiedius* spp.). Low-energy, consolidated habitats are characterized by polychaete worms (*Serpulid* spp.), squat lobsters (*Munida quadrispina*), a variety of planktivorous invertebrates (e.g., anemones), orange cup coral (*Balanophyllia elegans*), rockfish, longfin sculpin (*Jordania zonope*), and gobies.

Unconsolidated, soft bottom is the predominant benthic habitat. The biological communities associated with high-energy, unconsolidated habitats are influenced by both substrate composition and size. Mixes of cobble and finer material, such as gravel, shell hash, and sand, are typically inhabited by horse mussels (*Modiolus modiolus*) and barnacles (*Balanus* spp.). Cobble substrates are generally dominated by sea urchins and rock scallops. Mixed-coarse substrates support a variety of infauna, including small bivalves – such as the hundred line cockle (*Nemocardium centifilosum*) – and amphipods such as the Bay ghost shrimp (*Callianassa californiensis*) and the stout coastal shrimp (*Heptacarpus brevirostris*). Sandy, unconsolidated habitats in high-energy regimes support small bivalves (for example, *Tellina* spp. and *Macoma* spp.), amphipods (including *Rhepoxynius abronius* and *Eohaustorius washingtonianus*), and polychaetes (such as *Maldane glebifex* and *Chaetozone setosa*)(Dethier 1990). Low-energy, unconsolidated habitats typically support sea pens (*Ptilosarcus gurneyi*), sea whips (*Virgularia* spp.), tubeworms (chaetopterid polychaetes), many bivalve species, and mobile crustaceans such as Dungeness crab and kelp crabs (*Pugettia* spp.)(Dethier 1990)."

<u>Existing Conditions</u>

Unless cited to indicate otherwise, the following content is taken with minimal editing from the DNR's Aquatic Lands HCP planning document (DNR 2014a, pp. 1-44 through 1-51):

(pp. 1-44, 1-45) "The DOE has conducted annual marine water quality monitoring at stations in Puget Sound and in coastal areas (Grays Harbor and Willapa Bay) since 1967. The program collects data on dissolved oxygen, nutrients, and fecal coliform bacteria. The following discussion is a synthesis of material published by the DOE (Newton *et al.* 2002) and the Puget Sound Action Team (PSAT 2007).

While water quality varies seasonally and across years, general patterns in the levels of fecal coliform, nitrogen, ammonium, dissolved oxygen, and stratification can be used as indicators. For the 1998 to 2000 sampling period, the DOE reported that while water quality appeared to be generally good for the Puget Sound basin, several sites experienced decreases in overall water quality, including low dissolved oxygen, increases in fecal coliform bacteria, or a sensitivity to eutrophication based on stratification or nutrient conditions (Newton *et al.* 2002). The eight areas of highest concern were southern Hood Canal, Budd Inlet, Penn Cove, Commencement Bay, Elliott Bay, Possession Sound, Saratoga Passage, and Sinclair Inlet. For the coastal estuaries, the primary water quality issue reported was chronic fecal coliform bacteria contamination in Grays Harbor and in Willapa Bay, adjacent to the Willapa River (*Newton et al.* 2002). In 2005 all the sites sampled in Puget Sound were of concern for at least one parameter, with eight sites (Budd Inlet, South Hood Canal, Saratoga Passage, Possession Sound, Penn Cove, Commencement Bay, Elliott Bay, and Sinclair Inlet) considered of "highest concern" due to exceedances of the standards for several or all parameters (PSAT 2007). Bellingham Bay, Oakland Bay, Case Inlet, Discovery Bay, Strait of Georgia, Carr Inlet, Port Orchard, West Point, Skagit Bay, and Port Susan were rated of "high concern" due to exceedances of the standards for dissolved oxygen and fecal coliform bacteria (PSAT 2007).

The DOE developed the Marine Water Condition Index (MWCI) in 2011 as a way to detect changes in water quality over time. The MWCI uses 12 variables to describe water quality conditions, including temperature, salinity, nutrients, algae biomass, and dissolved oxygen, in relation to broader oceanic water quality and natural variability. MWCI trends show a continuing increase in nutrients, possibly due to the increase in population density since 2002, for the Puget Sound Central Basin, southern Hood Canal, Oakland Bay, and Admiralty Inlet. Increases in population, particularly along Puget Sound's urbanized corridor, correlate with increases in nutrient discharges from both point source and non-point sources (DOE 2012).

In 2009, the DOE completed Washington State's Water Quality Assessment for 2007/2008. The results of the assessment were submitted to the Environmental Protection Agency as an integrated report to satisfy the Clean Water Act requirements of sections 303(d) and 305(b). The assessment includes a list of waterbodies that are known to be polluted. The list is available on the DOE's website.

The report assesses 5 percent of the river and stream miles, and 3 percent of lakes and gridded marine waters in Washington. Of the 26,000 segments assessed, 30 percent met all the tested water quality parameters (temperature, pH, dissolved oxygen, fecal coliform, total nitrogen, total phosphorous, total suspended sediment, and turbidity), 16 percent were designated as waters of concern, and 14 percent were placed on the 303(d) list. The number of segments assessed as Category 5 (standards for one or more pollutants have been violated and there is no Total Maximum Daily Load) increased by 919 from 2005. Of the 2008 key parameter exceedances, 33 percent were due to temperature, 27 percent were due to fecal coliform bacteria, 24 percent were due to dissolved oxygen, 10 percent were due to pH, 2 percent were due to total phosphorous, and 4 percent were due to metals, toxics and "other" pollutants."

(pp. 1-45 thru 1-47) "Sediment quality plays an important role in the health and structure of epibenthic and benthic habitats, influencing food web dynamics, primary productivity, and species diversity and abundance. The DOE's Marine Sediment Monitoring Team and the National Oceanic and Atmospheric Administration cooperatively collected sediment samples for 300 Puget Sound sites between 1997 and 1999 (Long *et al.* 2004).

The Sediment Quality Triad Index summarizes the data by frequency of occurrence and basin/region (Long *et al.* 2004). Most samples assessed as degraded were collected in the Whidbey Basin (Everett Harbor), Central Sound (Elliot Bay and Commencement Bay), and South Sound (Budd Inlet). The station samples were also analyzed using five strata based on the major geographic features and degree of anthropogenic activity (harbors, urban embayments, passages, deep basins, and rural embayments). The largest percentage of samples with degraded sediment quality was associated with the harbor and urban embayment strata; the samples with the highest sediment quality were found in passages, deep basins, and rural embayments.

In 2005, the Puget Sound Ambient Monitoring Program (PSAMP) summarized 12 years of data from ten long-term monitoring stations to establish a record of sediment conditions for a variety of habitats and geographic locations throughout Puget Sound (Partridge *et al.* 2005). The data associated with grain size, total organic carbon content, and the composition and structure of benthic invertebrate communities were collected annually. Sediments were analyzed for more than 180 priority pollutant metal and organic contaminants: for example, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and pesticides (Partridge *et al.* 2005).

While many of these parameters were stable over time, changes associated directly with anthropogenic sources were found in urban embayments. Analysis of the chemical contaminant data set indicated that, in general, concentrations of metals in 2000 were lower than in 1989-1996 more often than they were higher, while the opposite was true of PAHs (Partridge *et al.* 2005). The decrease in concentrations of metals may reflect a decreased discharge of metals into Puget Sound; the increase in PAH concentrations is likely attributable to increased suburban runoff. Overall, Sinclair Inlet had the highest concentration of metals; PAH concentrations at the Thea Foss Waterway station was one to two orders of magnitude greater than at any other station (Partridge *et al.* 2005)."

(pp. 1-47 thru 1-51) "Submerged and emergent vegetation provides structure to shallow water benthic habitats and reduces wave energy, which stabilizes the sediment and shoreline, and slows erosion (Fonseca and Cahalan 1992; Van den Berg *et al.* 1998). Vegetation also removes nutrients from the water column – thereby reducing algal blooms and associated decreases in dissolved oxygen – and converts carbon dioxide into oxygen in both the water column and the sediment (Findlay *et al.* 2006; Hemminga and Duarte 2000; Hietala *et al.* 2004; Laskov *et al.* 2006; Van den Berg *et al.* 1998). Aquatic vegetation can also be a major source of food for birds, fishes, and invertebrates, which may consume the vegetation itself or consume species that shelter in the vegetation (such as zooplankton and larval and juvenile fish). Aquatic vegetation also serves as a food source indirectly by contributing detritus and dissolved organic matter to the system (Alvarez and Peckarsky 2005; Hilt 2006; Moore *et al.* 2004). Species may also use vegetation for egg attachment, nursery and rearing areas, and refuge from predation (Kendall and Mearns 1996; Munger *et al.* 1998; Shaffer 2004; Webb 1991).

Seagrasses are rooted flowering plants that live partially or completely submerged in marine and estuarine waters. Of the six seagrass species occurring in Washington, the two eelgrasses (the native *Zostera marina* and the non-native *Z. japonica*) are the most widespread seagrasses: they are documented to occur along approximately 1,135 kilometers (705 miles) of shoreline (Washington DNR 2002). North and central Puget Sound have the highest percentages of eelgrass; the southern end has the lowest percentage. Surfgrasses (*Phyllospadix* spp.) can also be found, but are generally less abundant than eelgrass and are restricted to the lower intertidal and shallow subtidal zone in high-energy (exposed), rocky, marine shorelines. Widgeon grass (*Ruppia maritima*) is even less common than the surfgrasses and inhabits the high intertidal in areas with brackish water.

Eelgrass meadows are a major source of carbon in the nearshore ecosystem and have one of the richest assemblages of animals among all aquatic habitats in the state. Eelgrass is used by a number of juvenile salmonids and other fish for foraging and refuge, by herring as a spawning substrate, and by a variety of crabs for feeding and refuge (Holsman *et al.* 2003; McMillan *et al.* 1995; Phillips 1984).

As part of the PSAMP, Washington DNR's Submerged Vegetation Monitoring Project (SVMP) has been collecting data on the abundance and distribution of native eelgrass in greater Puget Sound since 2000. The study area is divided into five regions: central Puget Sound, north Puget Sound, San Juan Archipelago, Strait of Juan de Fuca, and the Saratoga-Whidbey Basin. More than a quarter of the total amount of eelgrass in Puget Sound is found in Padilla and Samish bays in the Puget Trough ecoregion.

Gaeckle *et al.* (2009) provided recent data on eelgrass in Puget Sound, extending the overall data record to nine years (2000 to 2008). In Puget Sound overall, native eelgrass shows a pattern of slight decline; more sites display long-term decreases in eelgrass than increases; and more sites show one-year decreases in eelgrass than increases. However, this slight declining trend has not resulted in a decrease in the spatial extent of eelgrass across Puget Sound over the last nine years.

Sampling results from the Hood Canal region suggest that Hood Canal is showing the largest decline and is of highest concern for the decline in native eelgrass (*Z. marina*). The Strait of Juan de Fuca and central Puget Sound regions also show declining trends and are the second highest concern (Gaeckle *et al.* 2009). In particular, several shallow embayments in the San Juan Archipelago have shown a pattern of sharp decline in eelgrass abundance, including some areas used as herring spawning sites (Dowty *et al.* 2005). The Saratoga-Whidbey and north Puget Sound regions had the lowest frequency of change in eelgrass area – the number of decreasing sites matched the number of increasing sites – and this location is currently of low concern for native eelgrass decline (Gaeckle *et al.* 2009).

While not the primary focus of the SVMP work, data on non-native eelgrass (*Z. japonica*) were also gathered. This introduced species tends to have a shorter growth form and different sheath morphology than the native species. Little is known, however, about differences in the ecological services of the two species. The non-native species tends to colonize shallower areas in upper intertidal zones and can co-occur with *Z. marina* (Dowty *et al.* 2005). In 2009, *Z. japonica* was observed at 18 sites in all regions. Since 2000, non-native eelgrass has been observed at 68 different sites in Puget Sound (Gaeckle *et al.* 2009).

Seaweeds are macroscopic marine algae (macroalgae). These algae occur throughout the nearshore, in saline waters where light levels are great enough to support their growth. Although most seaweed species grow attached to consolidated substrates, some seaweeds, such as ulvoids (flat green seaweeds) can live unattached to the bottom. The vast expanses of rocky shores along the Strait of Juan de Fuca, and rocky outcrops on the outer coast of Washington support many of the 633 species that occur throughout the Pacific Northwest (Gabrielson *et al.* 2000). Central Puget Sound supports approximately 160 species; south Puget Sound supports only a few species (Thom *et al.* 1976).

Along many rocky shores in Washington, the upper intertidal band of seaweeds consists of low growing turf and crust-forming species. Below this is a band of the fucoid brown seaweed (*Fucus* spp.), usually followed by a diverse mix of red, green, and brown seaweeds. In the shallow subtidal zone, larger brown algae can dominate and form an assemblage comprised of an understory of smaller species associated with large dominant species. As the photic zone deepens, the brown algae will give way to the more low-light tolerant red algae.

One group of brown algae includes all of the order Laminariales, commonly known as kelp. Kelp attach to the substrate by root-like holdfasts and are categorized into floating and non-floating kelp. Bull kelp and giant kelp are floating kelp that can form extensive canopies at or near the surface of the ocean. These beds are most common in rocky, high-energy marine environments. In Washington state, floating kelp beds are found on approximately 11 percent of the shoreline, primarily on the northwest coast of the Olympic Peninsula (Washington DNR 2002). Washington DNR's Nearshore Habitat program has been monitoring the areal extent of kelp bed populations along the Strait of Juan de Fuca and the Olympic Peninsula coast annually since 1989 to evaluate natural variation and changes related to human impacts (Dowty *et al.* 2005). Annual variability is high; the overall extent of kelp fluctuated between a high of 11,832 acres in 2000, and a low of 4,722 acres in 1989.

Sargassum muticum is a non-native brown alga from Asia that has been established in Washington for decades. Sargassum occurs in lower intertidal and shallow subtidal rocky habitats and displaces native macroalgae. This species is found most often along the shorelines of Hood Canal, the San Juan Archipelago and the Strait of Georgia, and is least common along the outer coast. Data collected by the ShoreZone Inventory program (Washington DNR 2002) show that Sargassum is present along 18 percent of the state's shorelines.

Marine species of cordgrass (*Spartina* spp.), are aggressive weeds, severely disrupting estuarine ecosystems by outcompeting native vegetation. In some areas, these species have become well established and are rapidly raising tidal elevations, displacing eelgrass and native marsh plants, and reducing habitat for migratory waterfowl, invertebrates, and possibly fish.

In Washington, four different marine *Spartina* species grow in intertidal regions from high intertidal marshes to within 1 meter of MLLW. *Spartina patens* and *S. densiflora* are adapted to grow in upper marshes where they mix with native plants. *Spartina alterniflora* and *S. anglica* tend to invade bare mud in the lower tidal area. Spartina infestations occur throughout Puget Sound, in Willapa Bay, and in Grays Harbor (Washington State Department of Agriculture, 2005).

In all, there are presently 11 counties in western Washington with one or more infestations of marine Spartina species: Clallam, Grays Harbor, Island, Jefferson, King, Kitsap, Pacific, San Juan, Skagit, Snohomish, and Whatcom counties. *Spartina anglica* was identified for the first time in Whatcom County in 2005. The infestation was found by a shoreline resident in Birch Bay at the northern boundary of Whatcom County (Murphy 2005).

Aggressive, comprehensive treatment programs continue to be implemented and improved to address the control of Spartina species. Post-treatment evaluations indicate that most effective reductions occur in contiguous infested areas; reductions are more difficult to achieve in vegetative transition areas. Cooperative efforts include participation by the Washington State Department of Agriculture, WDFW, DNR, other state agencies, universities, the U.S. Fish and Wildlife Service, counties, tribes, private organizations, and private landowners (Murphy 2005).

Japanese eelgrass (*Zostera japonica*) was listed as a Class C noxious weed by the Washington State Noxious Weed Control Board in 2012. Japanese eelgrass was listed as a noxious weed because it is non-native, difficult to control, and negatively impacts the shellfish industry (WA State Noxious Weed Control Board 2012)."

Land Uses and Development

Unless cited to indicate otherwise, the following content is taken with minimal editing from the DNR's Aquatic Lands HCP planning document (DNR 2014a, pp. 1-51 through 1-54):

(pp. 1-51 thru 1-54) "Washington's population has almost doubled since 1970, with most of the growth occurring in the urban areas of western Washington. The Washington Office of Financial Management (OFM) has released its first population forecast since the 2010 Federal Census. The state's population is currently estimated at 6,668,200. Nearly 70 percent of the population is concentrated in the counties surrounding Puget Sound (OFM 2011). Over the 30-year forecast period, Washington State's population is expected to grow by just over 2 million, reaching 8,791,000 in 2040 (OFM 2011).

The state's population is expected to increase almost 40 percent in the next 20 years; the largest growth is projected to occur in Franklin County (southeast Washington), Stevens County (northeast Washington), and the less-developed regions surrounding Puget Sound (OFM 2011). As the state's population grows, the demand for access to the water for recreation, commerce, and food production will increase. Development pressures will also increase the amount of impervious surface in the state, generating more stormwater and non-point source pollution.

Aquatic lands are used for a variety of recreational and commercial purposes. Human use of aquatic land is also associated with modifications of the aquatic landscape through the introduction of exotic species; alteration of flowing waters for hydropower, flood control, or irrigation; dredging to create and maintain navigational channels; shoreline armoring; filling aquatic land to create terrestrial land; and placement of structures in nearshore and littoral areas. The resulting changes in the landscape include the loss of wetlands and deltas; the channelization of waterways; altered river flows and flow patterns; changes in land cover; interruption of small drainages; increased runoff; altered shoreline structure and function; and disruption or elimination of sediment transport and nutrient processes (Redman *et al.* 2005; Williams and Thom 2001).

Human alteration of the nearshore ecosystem generally occurs through changes in key controlling factors such as light, wave energy, riparian vegetation, and both sediment transport and delivery (Nightingale and Simenstad 2001). Specific modifications include:

- Overwater Structures: Structures can decrease available light, affecting the ability of vegetation to grow, and causing behavioral changes in fish migrating along the shoreline. The structures also change wave energy and currents, which alters sediment transport mechanisms and associated habitat-forming processes.

- Shoreline Armoring: The installation of bulkheads, breakwaters, and similar structures can greatly change the functional capacity of the nearshore ecosystem by altering wave energy patterns. There are approximately 1,476 kilometers (917 miles) of shoreline armoring in the nearshore of Washington State, excluding the Columbia River (Washington DNR 2002).

- Fill and Dikes: Filling has occurred historically in the urbanized areas of Puget Sound and the Strait of Juan de Fuca because these areas were developed to meet the needs of port facilities and other economic activities on the waterfront. In parts of Puget Sound, over 95 percent of tidal wetlands have been lost or isolated from the adjacent estuaries by dikes (Frenkel and Morlan 1991; Gregory and Bisson 1997). In some cases tidal wetlands have been completely or partly filled to accommodate a variety of land uses, including agriculture, recreation, residential development, and industry. These modifications may also affect nearshore flushing rates by altering or eliminating freshwater input (Alberti and Bidwell 2005; National Ocean Service 2004).

- Dredging: Maintenance dredging of working ports and federal navigation channels is a necessary activity to maintain the usability and economic viability of these resources. In addition, dredging is an important option for the complete removal of contaminated sediments in aquatic cleanup sites. Dredging occurs primarily in the Columbia River [and Grays Harbor] navigation channels and in some urban areas where large port facilities are located. There have been several dredging projects greater than 100,000 cubic yards within Puget Sound, including two in Seattle and two in Tacoma. The largest of these is the Blair Inner Reach Cutback and Turning Basin Expansion, which removed 2.6 million cubic yards of material (Science Applications International Corporation 2005)."

Dumbauld and McCoy (2015) evaluated the effect of oyster aquaculture on eelgrass at the estuarine landscape scale in Willapa Bay:

- "Recent research suggests that oyster aquaculture has direct impacts on native seagrass … at small spatial and short temporal scales in U.S. west coast estuaries … We quantified impacts of oyster aquaculture … at the estuarine landscape scale … A model of *Z. marina* cover outside of aquaculture was created using distance to estuary mouth, distance to nearest channel, salinity, elevation, and cumulative wave stress as factors, and was then used to predict … distribution within oyster aquaculture beds … The amount of *Z. marina* cover observed within oyster aquaculture beds was less than predicted, but represented <1.5 percent of the total predicted … cover in Willapa Bay in any year … The majority of beds had 65-145 percent of the model-predicted … cover and exhibited relatively low variability between years, suggesting that *Z. marina* … is resilient to oyster aquaculture as a disturbance and does not result in persistent effects at the landscape scale in this estuary." (p. 29)

- "Seagrasses … [are] sensitive to a wide variety of pulse disturbances with parallels to mechanical implements used to harvest shellfish (e.g. boat propellors, anchors, and moorage chains: Dawes *et al.* 1997, Thom *et al.* 1998; dredge and fill operations and simple trampling: Erftemeijer and Lewis 2006) … Shellfish harvest practices have been less studied, but mechanical harvest implements directly removed plants and generally caused more disturbance than hand harvest or off-bottom longline oyster culture … (Wisehart *et al.* 2007, Tallis *et al.* 2009)." (p. 30)

- "We … use [several] factors to predict *Z. marina* distribution for each aquaculture bed, and compare the model-predicted, interpolated, and actual quantities … [We] determine whether any impacts of oyster aquaculture … were chronic or transitory by analyzing data from 3 separate years." (p. 31)

- "Active on-ground oyster aquaculture beds were overlain on the actual, interpolated, and model-predicted *Z. marina* layers for each year, and the sum of the pixel values were extracted for each aquaculture bed—giving the total quantity of *Z. marina* actually observed, interpolated, and model-predicted for each bed for each year." (p. 34)

- "To calculate the total effect of oyster aquaculture on *Z. marina*, we took the sum of the actual, predicted, and interpolated probabilities for all of the oyster beds for 2005, 2006, and 2009 … Subtracting the actual amount of cover from the predicted and interpolated amounts gives an estimate of the total amount of eelgrass cover missing due to oyster aquaculture." (p. 34)

- "We predicted that mechanically harvested beds would either exhibit chronically low proportions of *Z. marina*, if the effects of dredging are long-lived, or high variability, due to a rapid removal (mechanical harvest) and recovery (regrowth), relative to more stable hand-picked beds." (p. 34)

- "Models exploring individual predictors suggest that distance to estuary mouth and tidal elevation explained most of the variation in *Z. marina* cover … [However,] The best performing models only describe approximately half of the variation … in each year." (p. 35)

- "The total area of *Z. marina* estimated to be missing using a model prediction in 2005 and 2006 was only 22 and 8 ha, respectively … In 2009, there were 0.4 ha, more *Z. marina* present than predicted by the model … The total area … estimated to be missing using the interpolation prediction was higher for all years, at 80, 84, and 60 ha, respectively … Although large in aggregate, even the highest estimate is <1.5 percent of the total amount of *Z. marina* cover found in Willapa Bay in these 3 years." (p. 35)

- "Mechanical harvested beds on average had 100 percent and 92 percent of the model and interpolation-predicted Z. *marina*, respectively, hand-harvested beds had 120 percent and 127 percent of the predicted and interpolation-predicted *Z. marina*, and mixed harvest beds had 117 percent and 97 percent, respectively … Trends for some individual oyster culture beds were quite evident in aerial photographs." (p. 36)

- "The majority of beds exhibited expected levels of *Z. marina* with low variation across years … [However,] All of the beds with <65 percent of the mean expected amount of … cover (n = 24) were mechanically harvested beds and demonstrated a chronically low level of *Z. marina* cover … across years." (p. 36)

- "Our results demonstrate a negative effect of oyster aquaculture on the native seagrass … at the landscape scale in Willapa Bay … but also show that this impact is small compared to the overall signature of both *Z. marina* and oyster aquaculture in this estuary." (p. 37)

- "While the total area of *Z. marina* declined slightly over time in our study, <1.5 percent of either the total predicted or interpolated amount … was missing (maximum of 80 ha) and could thus potentially be attributed to aquaculture in any single year … This lack of substantial overall impact is similar to the few studies conducted at the estuarine landscape scale elsewhere." (p. 38)

- "We suspect that on balance, the effect of bottom-cultured oysters on eelgrass in Willapa Bay was variable enough at smaller spatial scales to eliminate any significant effect at the larger landscape scale in our study." (p. 39)

- "Oyster aquaculture beds that were harvested with a mechanical dredge had significantly lower *Z. marina* than those harvested by hand or those reported to us as mixed harvest beds … Nonetheless, a mean of 99.9 perecent of the model-predicted and 91.6 percent of the interpolation-predicted *Z. marina* were observed on mechanically harvested beds." (p. 40)

- "Our results suggest that the majority of oyster aquaculture impacts are not persistent at the landscape scale ... Our results suggest that current oyster aquaculture practices do not substantially reduce and may even enhance the presence of *Z. marina* at the estuarine landscape scale." (p. 41)

- "Eelgrass ... appears to be resilient over both short and longer temporal periods and resistant to oyster aquaculture as a disturbance in this ecosystem ... Our research in Willapa Bay suggests that oyster aquaculture as disturbance is generally within the scope of existing 'natural' disturbances to the system (e.g. winter storms), and eelgrass is inherently adapted to this scale of disturbance ... Bivalve aquaculture has not been implicated in shifts to alternate states or reduced adaptive capacity of the larger ecological system." (Dumbauld and McCoy 2015, p. 42)

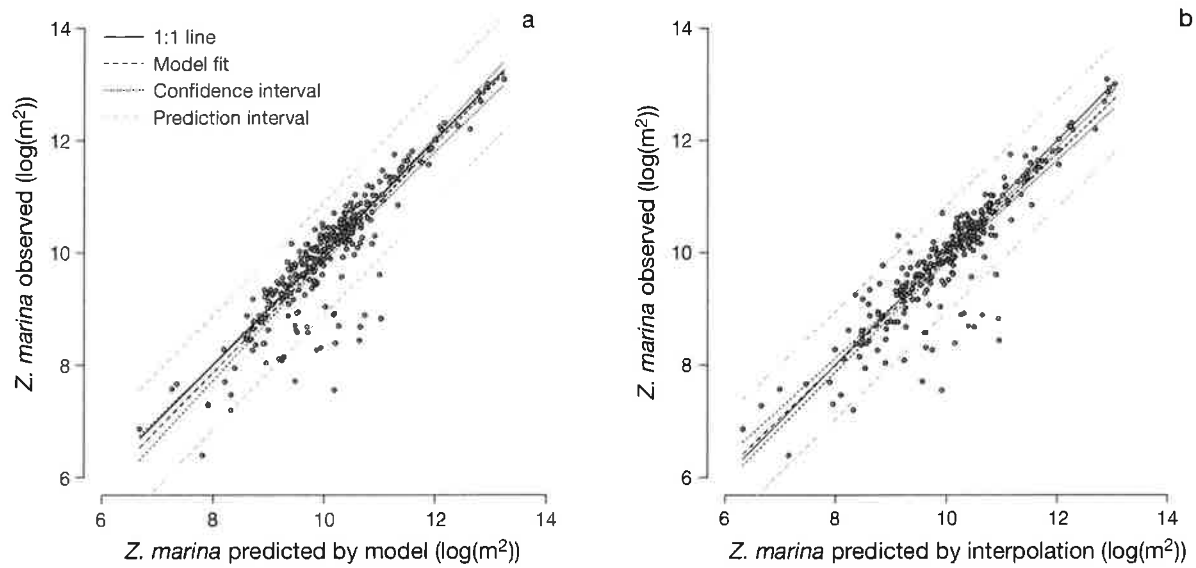


Figure A. Relationships between predicted and observed eelgrass cover in all aquaculture beds (Willapa Bay, WA; 2005)(Dumbauld and McCoy 2015, p. 37).

Entranco, Inc. and Hamer Environmental (2005) have reported outcomes from a program of intentional hazing implemented in conjunction with marine construction at the Hood Canal Bridge:

- Environmental consultants/contractors to the Washington State Department of Transportation were asked to "Identify marbled murrelet presence in the vicinity of pile driving activities ... actively encourage their dispersal from the area to reduce chances of underwater injury from pressure waves associated with pile driving ... [and] track incidental take exempted ... in the Biological Opinion" (p. 1).

- "Biologists conducted the hazing from an inflatable boat … [in an] attempt to move [marbled] murrelets out of the monitoring area without … considerable stress … hazing attempts … [were] abandoned should this activity trigger two dive responses by an individual bird." "If a murrelet was swimming away from the pile driving site in response to a hazing attempt, the crew maintained the boat's speed, keeping the minimum distance of 25 m between the boat and the murrelet, until the bird was out of the monitoring area. When a murrelet flew out of the monitoring area during a hazing event, the hazing event was ended." (pp. 4, 8, 9)

- "During the 5-month project, the boat crew conducted 150 pre-pile driving sweeps searching for [marbled] murrelets. During this period, we hazed 181 individuals or groups of birds … Forage dives were discriminated from disturbance dives by the behavior of the bird. Birds observed forage diving were generally 25 m or more from the boat and showed no behavioral changes to the boat's presence. Disturbance dives were dives where the bird began responding to the boat's presence by quick head glances back at the boat and side-to-side, rapid swimming away from the boat, and then a quick dive … More than 80 percent of the time, hazers were able to move the bird farther away from pile driving activity during partial-hazing attempts. Marbled murrelets that tended to stay in the same spot or move closer to pile driving activity were actively feeding and appeared to be more interested in following prey than in avoiding the hazers." (pp. 13, 14)

- "The majority of behaviors recorded during hazing were birds forage diving (88 percent) … We found that the main activity … was to forage, as most birds were observed to repeatedly and constantly dive, even when the boat was >100 m away. It was not unusual to see [marbled] murrelets diving into small schools of herring and catching fish within the monitoring area … birds would continue to forage dive as a hazing attempt began … We only recorded disturbance dives 8 percent of the time and these occurred when birds would surface near the boat (<25 m) and quickly dive without any rest … We only observed birds to fly in response to a hazing attempt three times (1 percent) … [possibly] due to the slow speeds at which the boat approached the birds." (Entranco, Inc. and Hamer Environmental 2005, p. 20)

Environ International Corporation (2011) has cited several studies that suggest geoduck harvest has only a modest impact on benthic invertebrates:

- "Intertidal habitat structure and composition is largely driven by physical processes, such as tides, storm-generated waves, interannual variation in climate, and nearshore sediment transport (Hall *et al.* 1994) … Ecological theory suggests that many species typical of wave-exposed sandy environments … exhibit behaviors that enable them to survive daily tidal scouring events (Gorselany and Nelson 1987 as cited in Dernie *et al.* 2003) … It is generally assumed that benthos found in more dynamic sandy habitats will recover more quickly following physical disturbance than those found in less energetic muddy habitats, based on the adaptive strategies of the respective assemblages found in these environments (Kaiser *et al.* 1998, Ferns *et al.* 2000) … Microcosm studies appear to support this hypothesis (Dernie *et al.* 2003)." (p. 50)

- "Pearce *et al.* (2007, unpublished) … observed that recovery rates of benthic invertebrates varied in response to timing (season), magnitude, and location of the disturbance in relation to the species involved and level of mobility of those organisms … Kaiser *et al.* (2006) commented that recovery may take longer in cases where recolonization through larval recruitment is the dominant mechanism." (p. 51)

- "Spencer *et al.* (1997 as cited in Straus *et al.* 2008) found that the netting used to reduce Manila clam predation led to an increase in surface deposit-feeding worms compared to a community dominated by subsurface deposit-feeding worms in non-netted plots … The authors suggested that competition from surface deposit-feeding worms on the netted plots may have excluded the sub-surface deposit-feeding worms." (p. 51)

- "Powers *et al.* (2007) documented that the macroalgal growth on protective netting placed over hard clam (*Mercenaria mercenaria*) aquaculture sites supported elevated densities of mobile invertebrates and juvenile fishes, similar to natural seagrass … habitats." (p. 52)

- "Fleece *et al.* (2004, unpublished) completed a dive study at three locations in Case Inlet that compared epibenthic fauna between geoduck beds with individually netted tubes, adjacent eelgrass beds, and control sites … The authors observed a higher density of epibenthic fauna in geoduck beds in relation to control sites, and similar densities in relation to adjacent eelgrass beds … The structure created by tubes most likely provides additional habitat structure for many epibenthic invertebrate species." (p. 53)

- "It is … notable that in all of these studies, the underlying physical habitat into which the aquaculture gear was placed was a sand/mud … Even though an increase in colonization [is] likely … these structures … are still ephemeral (i.e., they last as long as the gear is present)." (Environ International Corporation 2011, p. 53)

Ferraro and Cole (2012) investigated recurring empirical relationships between operationally-defined biotic communities and habitat types in Willapa Bay, Grays Harbor, and Tillamook Bay, Oregon:

- "Bathymetry, sediment type, and the presence of ecosystem engineering (Jones *et al.* 1994) or niche constructing (Boogert *et al.* 2006) species are habitat characters that operationally define estuarine habitats with different benthic macrofaunal communities in the US Pacific Northwest (Posey 1986; Ferraro and Cole 2004, 2007, 2011; Berkenbusch and Rowden 2007) … Ecosystem engineers in the bioregion include [but are not limited to] eelgrass …, dwarf eelgrass …, Atlantic cordgrass (*Spartina alterniflora*), burrowing mud shrimp [and] ghost shrimp …, and oysters … *Z. marina*, *Z. japonica*, *S. alterniflora* and oysters are autogenic ecosystem engineers, as they create habitat by their own physical structure." (p. 2)

- "The surface area of both Willapa Bay and Grays Harbor is >7x that of Tillamook Bay … Except for the size difference and the prevalence of coarse ocean beach sand in Tillamook Bay, the three estuaries are geomorphologically similar." (p. 3)

- "The Bray-Curtis coefficient on … transformed abundance data was used to measure sample similarity in benthic macrofaunal species composition and abundance (Clarke and Warwick 2001) … Benthic macrofaunal community measures determined for each sample were: (1) number of species or identifiable taxon (S), (2) total abundance (A), (3) total biomass (g, wet wt.) (B), (4) abundance of deposit feeders (AD), (5) abundance of suspension feeders (AS), (6) abundance of facultative (deposit and suspension) feeders (AF), (7) Swartz's dominance index (SI) … (Swartz *et al.* 1985), and (8) Brillouin's (1962) diversity index (H; base e)." (p. 4)

- "There were a total of 107 benthic macrofauna taxa … Twenty-three … species were collected in one and only one habitat type … [but] unique species accounted for <1 percent of the benthic macrofaunal abundance in the habitat in which they were found." (p. 5)

- "Even though many of the more common benthic macrofaunal taxa occurred in multiple habitats … and few benthic macrofaunal species were unique to a single habitat … benthic macrofaunal Bray-Curtis similarity was significantly different among the habitats … Mean benthic macrofaunal S varied among habitats by as much as 3.4x, A by as much as 45x, B by as much as 11x, AD by as much as 56x, AS by as much as 12x, AF by as much as 913x, SI by as much as 2.1x, and H by as much as 2.6x." (pp. 5, 6)

- "In two-way ANOVAs with all six habitat types common to Tillamook Bay-1999 and Willapa Bay-1998, habitat was significant on mean benthic macrofaunal S, A, B, AD, AS, AF, SI and H, indicative of habitat effects … In two-way ANOVAs with all seven habitat types common to Tillamook Bay-1999 and Grays Harbor-2001, habitat was significant on mean benthic macrofaunal S, A, B, AD, AS, AF, SI and H, indicative of habitat effects." (p. 6)

- "In the Tillamook Bay/Willapa Bay/Grays Harbor ecological periodic table there are two habitat boxes for … *Zostera marina* habitat … They distinguish two variants of *Z. marina* habitat: one whose benthic macrofaunal community differs from that in oyster habitat … and the other whose benthic macrofaunal community was indistinguishable from that in oyster habitat … Habitat variant boxes for … *Z. marina* habitat … signify that an important factor or factors are missing from [the] operational definition … Whatever the factor(s), it/they measurably affect the benthic macrofaunal community's … composition and structure in *Z. marina* habitat … The needed changes or additions to our definitions of *Zostera marina* … habitat require further study." (pp. 8, 9, 11)

- "The benthic macrofaunal habitat usage patterns … surpass in detail common generalizations, such as that benthic macrofaunal species richness, abundance, and diversity are typically greater in more structurally complex habitats (Hemminga and Duarte, 2000)." (p. 10)

- "The benthic macrofaunal habitat usage patterns in Tillamook Bay were, in most respects, similar to those in Willapa Bay and Grays Harbor … patterns on the relative abundances of the feeding guilds were also similar … There was, for example, a consistently higher proportional abundance of deposit feeders in *Z. japonica* and oyster habitat, suspension feeders in *Z. marina* and oyster habitat, and facultative feeders in *Z. japonica* habitat than in the other habitat types …With a few exceptions … our habitat types expressed essentially the same quantitative patterns of benthic macrofaunal community composition, structure, feeding guild densities, dominance, and diversity in all three estuaries." (p. 11)

- "Ecological periodic tables for different biotic communities will reveal patterns of patterns and permit pattern-to-pattern comparisons … It seems highly improbable that the differential use of intertidal estuarine habitats by benthic macrofauna (Ferraro and Cole 2007, 2011, this study), nekton (Ferraro and Cole 2010) and birds (Lamberson *et al.* 2011) is coincidental … Examinations of patterns of habitat usage by different biotic communities, especially those with strong trophic linkages, are likely to shed new light on important ecological relationships." (Ferraro and Cole 2012, p. 12)

Ferriss *et al.* (2015, pp. 15-33 *In* Washington Sea Grant 2015) used a trophic model incorporating mediation functions to examine potential food web implications associated with a future growth in central Puget Sound geoduck production:

- "Expansion of the shellfish aquaculture industry may affect the structure and dynamics of coastal estuarine food webs … To better understand potential food web tradeoffs, trophic and non-trophic interactions (e.g., habitat facilitation, predator refuge) were incorporated into a food web model of central Puget Sound to predict the potential effects of an increase in geoduck (*Panopea generosa*) aquaculture." (p. 15)

- "The nontrophic effects of increased geoduck aquaculture, related to the influence of anti-predator structure, had a stronger influence on the food web than the trophic role of cultured geoducks as filter feeders and prey to other species … Increased geoduck culture caused substantial increases in biomass densities of surf perches, nearshore demersal fishes, and small crabs, and decreases in seabirds, flatfishes, and certain invertebrates (e.g., predatory gastropods and small crustaceans) … This study identifies species that should be a priority for additional empirical research and monitoring related to bivalve aquaculture interactions." (p. 15)

- "Bivalve aquaculture may alter the composition of benthic communities (Cheney *et al.* 2012, Dubois *et al.* 2007, Dumbauld *et al.* 2009, Simenstad and Fresh 1995) and influence the abundance and distribution of higher trophic level animals such as seabirds (Connolly and Colwell 2005, Faulkner 2013, Zydelis *et al.* 2009)." (p. 15)

- "Bivalve aquaculture may have important non-trophic effects … Changes in pelagic-benthic coupling, competition for space, prey concentration, predator refuge, and altered habitat structure (either biogenic structure or gear structure) may change the behavior of species and influence interspecific interactions (see review by Dumbauld *et al.* 2009; NRC 2010)." (p. 15)

- "In Puget Sound, Washington, McDonald *et al.* (2015) and VanBlaricom *et al.* (2015) showed that anti-predator structure and disturbance resulting from harvest of cultured geoducks, respectively, can suppress some benthic species while promoting others … thus, culture practices likely have important mediation effects." (p. 16)

- "Ecosim mediation functions can simulate the influence of a functional group or species on the strength of predator-prey interactions between a different pair of species … The geoduck aquaculture mediation functions are primarily based on observed numerical responses of benthic invertebrates to anti-predator structure (partially buried tubes with net covers) placed on plots with outplanted geoducks over their first two years." (p. 17)

- "McDonald *et al.* (2015) found anti-predatory structure on geoduck plots to have an exclusionary effect on flatfishes and predatory gastropods (moon snail), and an attraction effect on demersal fishes (e.g., gunnels, shiner perch), small crabs, sea stars, and red rock crabs." (p. 20)

- "The first phase entailed estimating the ecological carrying capacity for cultured geoducks in central Puget Sound and assessing the presence of ecological thresholds related to increasing geoduck aquaculture … The second phase involved identifying trophic and non-trophic effects of geoduck culture on individual functional groups." (p. 20)

- "To perturb the food web, cultured geoduck biomass and associated landings were increased by 120 percent in 50 years … A 120 percent increase represented a realistic level of increase in geoduck aquaculture and was a large enough perturbation to allow examination of changes across multiple trophic levels, habitats, and life histories (e.g., birds, pelagic and demersal fishes, and invertebrates) … Functional group biomass predictions from the base model (low cultured geoduck biomass) were compared with those from the model with 120 percent cultured geoduck biomass and no geoduck mediation effects (trophic effects only), as well as the model with 120 percent cultured geoduck biomass with geoduck mediation functions (trophic and non-trophic effects) to determine the possible ecological impacts of expanding geoduck aquaculture." (p. 21)

- "A 120 percent increase in cultured geoduck biomass had a limited impact on phytoplankton biomass and measures of ecological resilience … The addition of cultured geoducks into the central Puget Sound food web without any mediation functions had very little impact on the simulated biomasses of other food web members." (p. 21)

- "In contrast, the addition of cultured geoduck mediation functions had a notable impact on the food web [Figure A] … The biomass of food web members that were linked to geoduck culture through mediation functions changed considerably, with the biomass densities of some members increasing and decreasing by more than 20 percent (e.g., surf perches, small crabs, predatory gastropods, and small mouth flatfishes) … In addition, changes in the biomass of food web members directly linked to geoduck culture propagated through the food web, contributing to additional changes in other members' biomass … In total, the biomasses of 9 of the 10 functional groups with cultured geoduck mediation functions changed substantially." (pp. 21, 22)

- "Geoduck mediation functions linked to demersal fishes and small crustaceans had substantial effects on the food web … For example, the cultured geoduck-demersal fish mediation function resulted in decreases in herons (-23 percent) and resident birds (-17 percent), and increases in Pacific cod (+7 percent) and harbor seals (+7 percent) ... The cultured geoduck–small crustacean mediation functions resulted in reductions in the biomasses of juvenile wild salmon (-7 percent) and juvenile hatchery salmon (-4 percent)." (p. 22)

- "Habitat modification and facilitation are the predominant ecological effects of geoduck aquaculture in a highly productive system such as central Puget Sound … The trophic impacts of cultured geoducks as both grazers and prey were not influential at the system level … Cultured geoducks did not substantially reduce the availability of phytoplankton for other species." (p. 22)

- "Geoduck predators (moon snails, starfish, flatfishes, red rock crab, and sea birds) are all generalists to varying degrees and showed limited change in biomass in response to increased geoduck aquaculture … However, the impact of antipredator structure (tubes and nets) placed on geoduck plots had a larger influence on the surrounding food web by providing predation refuge or by changing foraging opportunities … In turn, these effects propagated throughout the food web." (p. 22)

- "This study suggests that efforts to understand the ecological effects of shellfish aquaculture in productive systems should go beyond modeling the direct trophic effects of bivalves and incorporate non-trophic information when possible." (p. 22)

- "The demersal fish and small crustacean functional groups were sensitive to increased cultured geoduck biomass and subsequently influenced biomass changes throughout the food web … Demersal fishes benefit from predator refuge provided by the anti-predation structure on geoduck farms, allowing their population to increase while other predator populations (e.g., seabirds) decrease owing to lack of prey availability … Small crustaceans are one of the most important functional groups in the system, supporting the majority of bird groups, fish groups, and certain invertebrates (e.g., shrimps, octopuses, age 0+ Dungeness crabs, sea stars)(Harvey *et al.* 2012a)." (p. 24)

- "The substantial decrease of most bird groups in the model is important to note, as these are important ecologically, culturally, and socio-economically … [There was a] decrease in eagle populations … [and] the biomass of other bird groups decrease[d], implying bottom-up control … reduced access to key prey (e.g., demersal fishes and small crustaceans) because of the predator refuge provided by anti-predator nets on geoduck farms … Migratory shore birds (biomass increase) do not primarily prey upon demersal fishes and small crustaceans, and are likely benefiting from a release of eagle predation while not suffering prey depletion … Further empirical study is required to understand the relationship between shellfish aquaculture and birds." (Ferriss *et al.* 2015, p. 24 *In* Washington Sea Grant 2015)

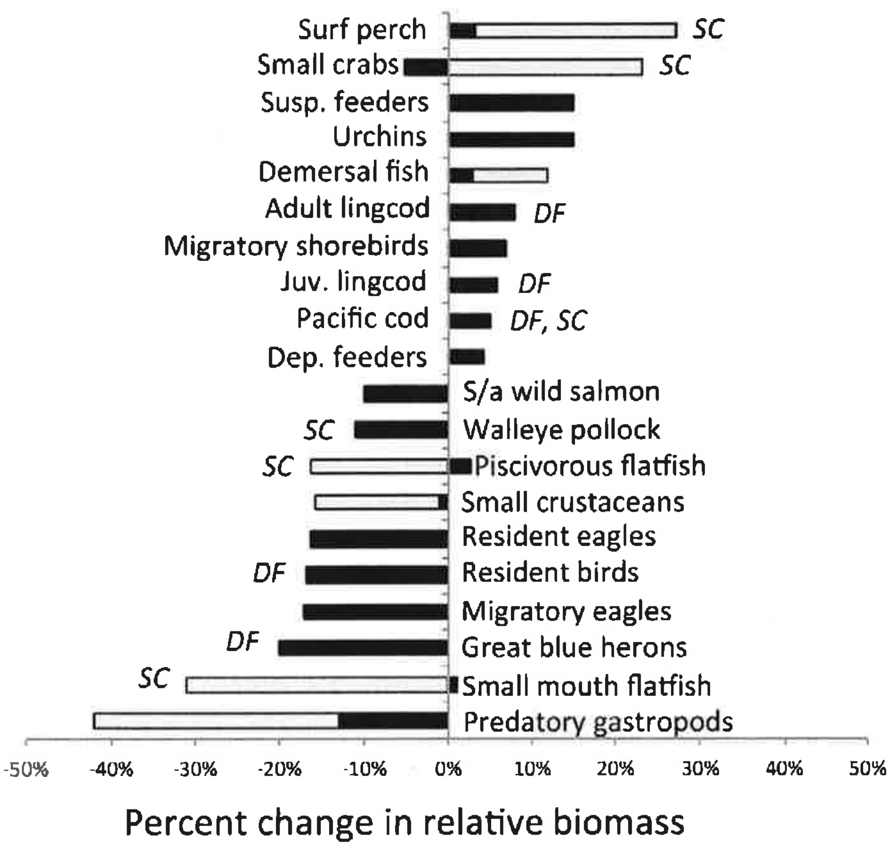


Figure A. Functional groups with the greatest change in relative biomass. (Ferriss *et al.* 2015, p. 22 *In* Washington Sea Grant 2015).

Forchino (2010) has described the diversity, and diversity of function, inherent to undisturbed benthic systems:

- "Benthic organisms [can] be separated into the fauna and flora, and then according to their preference for hard and soft substrata … [and] according to size … microfauna (<63 µm; ciliates, rotifers, sarcodines), meiofauna (63-500 µm; nematodes, oligochaetes, gastrotrichs), macrofauna (500 µm to 5 cm; polychaetes, amphipods, bivalves), and megafauna (>5 cm; echinoderms, decapods) … The ratios of the different dimensional categories depend on the sediment type, but normally in a typical intertidal beach the microfauna dominate numerically, but the macrofauna dominate in terms of biomass (Gray and Elliott 2010)." (pp. 16, 17)

- "The interactions of all physical factors will determine the composition and density of the infauna (Eleftheriou and McIntyre 1976) … Species … are somewhat protected against sedimentary instability and variability in temperature, salinity, exposure, and predation by burrowing (Eagle 1973) … Unstable sediments support fewer organisms than stable ones, and only those mobile species which can re-establish their position (Allen and

Moore 1987) … Survival rates of organisms, such as sedentary polychaetes … decrease when surface sediments are disturbed daily, although it is possible that small ones are simply relocated (Brown 1982) … Motile species … are adapted to life in unstable sediments and survive through rapid burrowing (McDermott 1983) … Species diversity … [and] community structure [are] influenced by habitat stability and sediment type … Coarse sediments, which are unstable and difficult to burrow into, are dominated by epifauna, while fine sediments are increasingly dominated by infauna … Many species are found in or on a range of sediment types, but others have a more restricted distribution (Wolff 1973)." (pp. 19, 20)

- "One of the most important characteristics … is the granulometry … [or] grain size … Coarse intertidal sediments … are inhabited … by those species able to tolerate such mobile sediments, such polychaetes (e.g. *Syllidae* sp.) and fast burrowing venerid bivalves (Pastor de Ward 2000) … At the other extreme, very fine sediments … may preclude the presence of a meiofauna inhabiting the pore spaces between grains (Pastor de Ward 2000; Gray and Elliott 2010) … They [also] have poor water circulation … There is only a small exchange of overlying oxygenated water … oxygen that diffuses into the sediments is rapidly used up … increasing the oxygen demand … (La Rosa *et al.* 2001; Yoza *et al.* 2007)." (pp. 13, 14)

- "The hydrophysical regime is variable … Changes in the hydrophysical regime and thus substratum will change the faunal composition of the biotope complex … [and] Seasonal changes do occur in subtidal community structure (Boesch 1973)." (pp. 23, 24)

- "Light is a key factor … sediments have an abundance of benthic microalgae … that grow within the top few millimeters of illuminated sediments (McIntyre et al. 1996) … beneath this layer … [a] "dark-blue-green layer" of filamentous cyanobacteria (*Phormidium* and *Oscillatoria*) binds the sand grains together … The top few millimeters constitute a zone of intense microbial and geochemical activity … Below … the sediment is black and anaerobic … methanogenic fermenters and sulfate reducers dominate and under certain conditions methane and hydrogen sulfide [can] be released (Gray and Elliott 2010)." (Forchino 2010, pp. 15, 16)

Forrest *et al.* (2009, pp. 1-15) have compiled and synthesized a large body of literature discussing the environmental and ecological impacts of oyster cultivation:

- "Biodeposits are heavier than their constituent particles, and readily settle on the seabed beneath culture areas (Haven and Morales-Alamo 1966; Kusuki 1981; Mitchell 2006) … Since biodeposits are organic-rich and consist of a substantial proportion of fine particles (i.e. silt and clay), seabed sediments beneath oyster cultures can become organically enriched and fine-textured relative to surrounding areas … (Forrest and Creese 2006)." (p. 3)

- "Extreme enrichment effects as a result of oyster farming have been described historically only for suspended culture systems in Japan, and been attributed to repeated culturing and overstocking (Ito and Imai 1955; Kusuki 1981) … Hence, it is apparent that the magnitude of benthic enrichment from elevated intertidal culture is generally relatively minor by comparison with suspended subtidal culture of fish (e.g. Brown *et al.* 1987; Karakassis *et al.* 2000; Forrest *et al.* 2007a) … The magnitude of effects from enrichment will depend primarily on stocking density and biomass in relation to the flushing characteristics of the environment (Pearson and Black 2001) … Additionally, the level of biodeposition for a given stocking density, and the assimilative capacity of the environment, may vary seasonally (Kusuki 1981; Souchu *et al.* 2001; Mitchell 2006) … The capacity of the environment to assimilate and disperse farm wastes will mainly depend on water current velocity and wave action (Souchu *et al.* 2001), as these factors control the size and concentration of the depositional 'footprint' … Generally, well-flushed aquaculture sites can be expected to have depositional footprints that are less intense but more widely dispersed than shallow or poorly flushed sites (Pearson and Black 2001)." (p. 3)

- "Hard surfaces on the seabed such as live and dead oysters, calcareous debris (e.g. bivalve shells, polychaete tubes), and farm materials potentially provide novel habitats for fouling organisms and associated mobile biota, which would otherwise not occur (or be at reduced densities) in the absence of oyster growing … Such effects have been widely documented in the case of on-ground shellfish culture (Dumbauld *et al.* 2001; Hosack *et al.* 2006; Powers *et al.* 2007; Ysebaert *et al.* 2009) and oyster reefs (Peterson *et al.* 2003; Escapa *et al.* 2004; Ruesink *et al.* 2005; Coen *et al.* 2007) … The structured habitat provided by oyster reefs can support a diversity of taxa … that may be absent or at reduced densities in adjacent unvegetated soft-sediment habitats (Ruesink *et al.* 2005 and references therein)." (pp. 3, 4)

- "Changes in seabed topography … have been described beneath oyster farms in several studies (Ottmann and Sornin 1982; Everett *et al.* 1995; Forrest and Creese 2006) … Such changes can result from the accumulation of shell and inorganic debris, and erosion or accretion of sediment beneath and between farm structures (Forrest and Creese 2006) … Sedimentation rates directly beneath cultures are generally elevated by comparison with non-culture areas (Mariojouls and Sornin 1986; Sornin *et al.* 1987; Nugues *et al.* 1996), being as much as three times greater directly beneath farm structures than at control sites (Forrest and Creese 2006)." (p. 4)

- "Excessive sediment build-up within Pacific oyster leases can occur at sites where cultivation structures are in high density or aligned perpendicular to tidal currents, resulting in the entrapment of suspended sediments (Kirby 1994; Handley and Bergquist 1997) … Redistribution of sediments either into (Kirby 1994) or out of (Mallet *et al.* 2009) culture sites may also occur in relation to events such as storms that lead to large scale sediment mobilization." (p. 4)

- "Studies of onground culture systems have … demonstrated physical effects during intermittent shellfish harvesting, and the recovery of soft-sediment communities in a matter of weeks to months in unvegetated habitats (McKindsey *et al.* 2006 and references therein) … By contrast, recovery from physical disturbance by eelgrass … may take several years (McKindsey *et al.* 2006; Dumbauld *et al.* 2009 and references therein)." (p. 4)

- "Oyster farm structures and farm related alterations … are likely to lead to effects on waves, currents, and flushing characteristics in the vicinity of farm sites (Gouleau *et al.* 1982; Nugues *et al.* 1996; Hewitt *et al.* 2006) … Literature for oyster reef habitats indicates that flow changes across the seabed may alter fluxes of materials (e.g. sediments) to adjacent habitats, and influence ecological processes such as patterns of dispersal and recruitment of invertebrates and fish (Breitburg *et al.* 1995; Ruesink *et al.* 2005) … Effects of this general nature are also conceivable in the case of elevated oyster culture, although specific differences can be expected given that the extent to which flows are modified … (e.g. because of differences in the 'porosity' of benthic reef versus elevated structures) … [the] attributes of the cultivation structures (e.g. height, density) and the extent to which cultivation physically alters the seabed (e.g. by shell accumulation)." (p. 5)

- "The potential for adverse water quality-related effects … is low, which is perhaps not surprising considering that intertidal farm sites are substantially or completely flushed on every tidal cycle … Any water quality effects associated with … culture can … be minimized by appropriate site selection and farm design (e.g. ensuring … minimal retardation of flushing processes)." (p. 5)

- "There has been considerable research into food depletion and modelling of carrying capacity for oyster culture (e.g. Ball *et al.* 1997; Bacher *et al.* 1998; Ferreira *et al.* 1998) as well as for other bivalves and polyculture systems (e.g. Carver and Mallet 1990; Prins *et al.* 1998; Smaal *et al.* 1998; Gibbs *et al.* 2002; Nunes *et al.* 2003) … Typically, this work has focused on phytoplankton depletion and maximum production capacity within growing regions … The literature in this field primarily addresses the role of natural or cultivated bivalve populations, whereas the filter-feeding activities of fouling organisms and other biota associated with shellfish cultures can also be functionally important (e.g. Mazouni *et al.* 2001; Mazouni 2004; Decottignies *et al.* 2007)." (p. 6)

- "Influences from oyster aquaculture on estuarine carrying capacity are inextricably linked to the issues of nutrient cycling, [solid particulate matter (SPM)] depletion, and coupling between the seabed and water column … There is compelling evidence that bivalve aquaculture can affect nutrient cycling and the quantity and quality of SPM across a range of spatial scales (Prins *et al.* 1998; Cerco and Noel 2007; Coen *et al.* 2007; Lin *et al.* 2009) … Empirically, phytoplankton depletion is certainly evident at local scales in the vicinity of oyster cultures (Dumbauld *et al.* 2009) or intensive culture zones (Lin *et al.* 2009), and serial depletion among multiple adjacent farms at larger spatial scales has been described for other types of suspended bivalve culture (Gibbs 2007; Grant *et al.* 2007)." (p. 6)

- "The potential for wider effects on ecological carrying capacity as a result of SPM depletion … is invariably situation specific and scale-dependent … (Anderson *et al.*, 2006) … Carrying capacity is also … temporally variable, as the amount of phytoplankton and other SPM in estuaries is likely to be influenced by factors operating from tidal time scales to longer term climatic events … (Dame and Prins 1998; Prins *et al.* 1998; Zeldis *et al.* 2000)." (p. 6)

- "Marine farm structures and artificial structures in general, provide a three-dimensional reef habitat for colonisation by fouling organisms and associated biota (Costa-Pierce and Bridger 2002) … In a manner similar to … the accumulation of oysters and debris, elevated shellfish aquaculture structures provide a novel habitat that can support a considerably greater biomass, richness, and density of organisms than adjacent habitats (e.g. *C. virginica* cages, Dealteris *et al.* 2004; *M. edulis* ropes, Murray *et al.* 2007)." (p. 6)

- "[However] It is also well-recognized that the biota fouling artificial structures can be quite different [from] that in adjacent areas (Glasby 1999; Connell 2000)." (p. 6)

- "The role of elevated oyster culture in the spread of pest organisms … [is] particularly significant … Inadvertent pest introduction is one of the more significant issues associated with aquaculture in estuaries (DeFur and Rader 1995) … The reason is that, by comparison with all other issues, the spread of pest organisms … can occur at regional scales (e.g. as a result of seed-stock transfer) potentially leading to ecologically significant and irreversible changes to coastal ecosystems (Elliot 2003) … Although management approaches may be developed to minimize any pest risks that are considered unacceptable (e.g. treatment of seed-stock before regional transfer), there are few examples where such strategies have been completely effective (Piola *et al.* 2009)." (Forrest *et al.* 2009, p. 10)

Godet *et al.* (2009) considered the effects of intensive clam cultivation on *Lanice conchilega* [sand mason worm] beds and found that beds were both degraded and less attractive to foraging oystercatchers:

- "Manila clam *Ruditapes philippinarum* cultivation is an original shellfish farming activity strongly mechanized … In the Chausey archipelago (France) this activity settles on the *Lanice conchilega* [sand mason worm] beds, habitat known to host a rich and diversified benthic macrofauna and which is an attractive feeding ground for birds … A first study highlighted that this activity had strong negative effects on the *L. conchilega* beds and their associated benthic macrofauna … Here we assess the impacts … on the Eurasian Oystercatcher *Haematopus ostralegus* for which Chausey is one of the most important national breeding sites … We found that Oystercatchers significantly selected the *L. conchilega* beds to feed and that their spatial distribution was significantly modified after the creation of new clam concessions." (Abstract)

- "[Most] studies dealing with impacts on fauna concern the macrobenthic compartment (Pearson and Rosenberg, 1978; Tenore *et al.*, 1982; Mattsson and Linden, 1983; Kaspar *et al.*, 1985; Jaramillo *et al.*, 1992; Grant *et al.*, 1995; Simenstad and Fresh, 1995; Nughes *et al.*, 1996) … The potential effects of aquaculture on birds are less studied and the few existing studies are recent … They concern fish farming (Kelly *et al.*, 1996; Buschmann *et al.*, 2006), mussel culture (Caldow *et al.*, 2003; Roycroft *et al.*, 2004) and oyster culture (Hilgerloh *et al.*, 1999, 2001) … The effects can be positive, by increasing the abundances of some bird species (Hilgerloh *et al.*, 2001; Caldow *et al.*, 2003; Roycroft *et al.*, 2004; Buschmann *et al.*, 2006) but may be also negative for others species (Kelly *et al.*, 1996) … It is difficult to draw general conclusions and case-by-case studies are therefore still required" (p. 589)

- "Here, we focus on the impacts of the Manila clam *Ruditapes philippinarum* (Adams and Reeves, 1850) cultivation on an original benthic habitat: the *L. conchilega* (Pallas, 1766) beds … In 2005, we studied the impacts of Manila clam cultivation on the Chausey's *L. conchilega* beds focusing on the macrobenthic compartment (Toupoint *et al.*, 2008) … This study mainly revealed that clam cultivation induced a decrease of both the *L. conchilega* densities and of the abundance and the diversity of the associated macrofauna … In this paper, we aimed at assessing the impacts of the degradation of Chausey's *L. conchilega* beds by this activity on the spatial distribution of a secondary consumer: the Eurasian Oystercatcher *Haematopus ostralegus*." (p. 590)

- "The Manila clam has been cultivated in the Chausey archipelago (Normandy, France) since the 1980s, and this activity takes place on the *L. conchilega* beds of the site … The clam production cycle is performed in three years … After spat seeding … juveniles are immediately covered with plastic nets (5 mm mesh size) to avoid crab and bird predations." (p. 590)

- "Before the creation of the new clam concessions, *L. conchilega* beds were significantly selected by Oystercatchers as a major feeding ground … By comparing our data with the Wetland International winter counts on this site (unpublished data from the Groupe Ornithologique Normand), we found that approximately 2/3 of the wintering Oystercatchers of Chausey fed on our study area … with a majority feeding on *L. conchilega* beds … We highlighted (Godet *et al.*, 2008) the important abundances of large bivalves especially the Cockle (*Cerastoderma edule*) … known to be an important prey for the Oystercatcher (Cramp and Simmons, 1983)." (pp. 591-593)

- "The previous study of Toupoint *et al.* (2008) revealed that the decrease of *L. conchilega* densities was coupled with a decrease of the abundance, species richness, and species diversity of the associated macrofauna … These results agree with those of Zuhlke (2001) who emphasized that the positive effects of this engineer species were ephemeral and disappeared instantaneously with the disappearance of the worm aggregations …The present study revealed that the positive effects of the *L. conchilega* beds for birds are also ephemeral … the regression or the disappearance of *L. conchilega* beds involved directly a loss of attractiveness for the feeding Oystercatchers." (p. 593)

- "The variation in the extent of *L. conchilega* beds may be explained both by the setting of new concessions, which altered the initial *L. conchilega* beds, but also by other environmental natural factors ... Such factors have been studied by several authors but low-temperature during severe winters is known to have strong negative effects on the *L. conchilega* beds (Buhr and Winter, 1976; Strasser and Pieloth, 2001; Zuhlke, 2001)." (p. 593)

- "We know that these habitats are very dynamic, but surprisingly the most abundant areas remained stable during the last two decades and historical reports revealed that such beds have been present in the Chausey archipelago since 1828 (Audouin and Milne-Edwards, 1828) ... [But] Manila clam cultivation has strong short-term mechanical effects based on a three years cycle (Toupoint *et al*., 2008)." (p. 593)

- "Before conducting this study ... we hypothesized that the introduction of clams should represent a new food resource for the Oystercatchers ... Quite surprisingly, we found that Oystercatchers did not select the clam concessions for feeding." (p. 593)

- "During the first year of the production cycle, clam concessions are not attractive for Oystercatchers because: (1) during six months nets prevent any predation, (2) during the following months, clam are hardly large enough to be profitable for the birds, and (3) the associated benthic macrofauna is less abundant in one-year concessions ... Clam concessions are potentially the most attractive during the second year of the production cycle until the beginning of the third year, before harvesting ... Nevertheless, we did not find any differences between the different concessions of one, two, or three years for the attractiveness of the birds." (p. 593)

- "We can consider that *L. conchilega* beds are an attractive habitat for the Oystercatchers of the Chausey archipelago ... The alteration of this habitat via clam cultivation induces a significant loss of attractiveness for the feeding Oystercatchers ... Natural variations of benthic habitats may drastically affect the birds ... Nevertheless, the rapid ... [growth] of shellfish farming activities along the world's coasts may have irreversible and increasing negative impacts on secondary consumers which have only just begun to be explored by the scientific community." (Godet *et al.* 2009, p. 594)

Good *et al.* (2010) has reported on the progress made removing derelict gear in Puget Sound and the Northwest Straits, and the pattern of remaining threats:

- "Since 2002, hundreds of derelict nets containing over 32,000 marine animals have been recovered from Washington's inland waters ... invertebrates (76 species) ... fishes (22 species) ... birds (16 species) ... 93 percent of fish, and 100 percent of birds and mammals were dead when recovered ... Mortality from derelict fishing gear is underestimated at recovery." (p. 39)

- "Synthetic fishing gear is functionally resistant to degradation in the water, and, once discarded or lost, this gear may remain in the marine environment for decades (USOAP, 2004) … One consequence of derelict fishing gear in the marine environment is the entanglement and killing of target and non-target fishery species long after the gear has been lost or abandoned, a process also known as 'ghost-fishing' (Breen, 1990)." (p. 39)

- "Since 2002, the Northwest Straits Commission, working with Natural Resources Consultants, Inc., the Washington Department of Fish and Wildlife, and National Oceanic and Atmospheric Administration (NOAA) Fisheries, has documented and removed over 94 tons of derelict nets, pots and traps from the inland marine waters in Washington (NWSC, 2008)." (p. 40)

- "Of the 902 derelict fishing nets recovered from Puget Sound and the Northwest Straits as of June 2008, 876 were gillnets. The remaining nets were purse seines (n = 23), trawl nets (n = 2), and aquaculture nets (n = 1) … 25 percent were derelict for somewhere between 5 and 24 years." Most of the recovered and removed gillnets were located in the San Juan island archipelago and north Puget Sound; very few were found in the Strait of Juan de Fuca, south Puget Sound, or Hood Canal. (pp. 42, 43)

- "All of the marine birds (n = 509) and mammals (n = 23) documented were dead. Derelict gillnets entangled and/or killed at least 106 species of marine fauna – at least 65 species of marine invertebrates, 22 species of marine fishes, 15 species of marine birds and 4 species of marine mammals … Most of the derelict gillnets contained evidence of entanglement and death." (p. 44)

- "In general, nets in flat featureless sandy or muddy habitats tend to ball up and pose less risk … (Matsuoka *et al.* 2005) … However … One derelict gillnet in a muddy habitat in the Port Susan area of central Puget Sound entangled some large, heavy commercial crab pots and woody debris, stretching the gillnet open over six meters off the seabed … In this one net, we documented 50 fish, 142 marine birds (64 freshly killed), and one marine mammal; the piles of bones beneath it were testimony to the larger numbers it likely killed. Given constant rates of recruitment and degradation over the 23 weeks it was derelict in the environment, it may have killed upwards of 1800 marine birds (J. June, unpublished data)." (p. 45)

- "Nets hung up on rocky reefs and underwater obstructions tend to remain stretched open more so than those in open sandy habitats (Akiyama *et al.* 2007)." (p. 48)

- "Derelict gillnets in Puget Sound seem to act as magnets to predators and scavengers, maintaining the potential for mortality over time … Many invertebrate scavengers (crabs, sunflower stars) are numerous in recovered gillnets and are likely drawn to the nets as they accumulate dead animals, and some scavengers, in turn, become entangled (Kaiser *et al.* 1996)." (p. 48)

- "Gillnets are especially lethal for marine fish, as nets are designed specifically for catching and killing them … [But] Gillnets are also deadly for marine birds and mammals, which must periodically surface to breathe air. Diving birds and marine mammals appear to fall prey to nets while pursuing fish underwater; some of the forage fish and smaller fish species aggregate in and under the relative safety of the netting, which results in entanglement of their predators. For marine birds, marine debris-related mortality increased substantially at the end of the 20th century (Tasker *et al.* 2000)." (pp. 48, 49)

- "Expanding from the absolute minimum mortality documented in this study … upwards of 450,000 marine invertebrates, 12,000 fish, 12,000 marine birds, and 400 marine mammals may have been killed by the 870 nets recovered as part of this study. These estimates do not include the estimated 3000+ nets still out in the marine environment of Puget Sound and the Northwest Straits … The largest challenge is finding and removing the legacy gear – lost nets accumulated over the past 50+ years" (Good *et al.* 2010, p. 49)

Gorenzel, Conte, and Salmon (1994) have prepared guidance for the control of bird damage at aquaculture facilities. In addition to auditory and visual hazing and deterrent techniques, they consider a potential role for trapping and shooting (i.e., hunting):

- "Except for some blackbirds, trapping is not allowed without a permit from the U.S. Fish and Wildlife Service and upon recommendation by the [U.S. Department of Agriculture, Animal and Plant Health Inspection Service] (USDA-APHIS-Animal Damage Control). Permits are issued to compliment ongoing nonlethal methods. Check county or state permit requirements." (p. E-5)

- "Shooting … Same as for trapping, except that some blackbirds may be shot. Ducks may be hunted during waterfowl hunting seasons." (p. E-5)

- "Resolution of bird depredation problems is complicated. All fish-eating birds that frequent aquaculture facilities are classified legally as migratory and thus are protected by federal, and in most cases, state laws." (p. E-10)

- "Because of the economic loss caused by birds, a grower's first reaction often includes lethal action. Lethal control, however, is not allowed without a permit. Permits to use limited lethal action against depredating birds may be granted, but only after nonlethal techniques have been used correctly, and after qualified USDA-APHIS personnel verify that these methods need to be reinforced by use of lethal methods." (p. E-10)

- "A permit is not needed to physically or mechanically exclude any fish-eating bird … Except for threatened or endangered species such as the bald eagle [(*Haliaeetus leucocephalus*)], a permit is not required to harass or scare fish-eating birds." (p. E-10)

- "If lethal reinforcement of existing hazing devices is required, [USDA-APHIS] wildlife damage control biologists may make recommendations on the damage report for lethal control of the species and the maximum number of birds that may be killed. This report will be attached to a completed U.S. Fish and Wildlife Service Federal Fish and Wildlife License/Permit Application or Depredation Permit (Form 3-200), and mailed to the Special Agent in Charge in the appropriate USFWS Regional Office … Exceptions to this procedure involve … specific species that may have special protection in your area." (p. E-10)

- "Recommendations include familiarization with federal and state laws related to bird depredation, knowledge of bird identification, and good communication with involved agencies. Actions that may be taken against a depredating bird species to protect a crop may vary from state to state and region to region. In recent years more incidences of aquaculture-related bird depredation cases have been reported, and increased legal action has been directed against growers charged with wildlife violations. Because of the severe legal consequences, it is highly recommended that a grower have knowledge of all these factors and proceed through the proper permit process before taking action against depredating species." (p. E-10)

- "Waterfowl (mallards, mergansers, and other ducks) may be legally hunted during the hunting season. A hunting license and federal duck stamp are required." (Gorenzel, Conte, and Salmon 1994, p. E-17)

Gorenzel and Salmon (2008) have reviewed available techniques and strategies for hazing and dispersing birds:

- "Where birds go when hazed is an important consideration … It is generally easier to move birds from a particular site if other sites are equally attractive." (p. 2)

- "The species present in the area will in part determine the types of hazing equipment that can be used. Certain hazing techniques are very effective in deterring certain species, but could be completely ineffective and sometimes counterproductive with other species. Waterfowl, and hunted species in general, can be dispersed from an area with propane cannons and pyrotechnics. However, diving birds such as grebes [(*Podiceps* sp.; *Aechmophorus* sp.)] or loons [(*Gavia* sp.)] will dive … surface, and dive again … This behavior can make it difficult to herd the birds away." (p. 2)

- "Biosonics … [recorded] distress or alarm calls are available for only a limited number of species and are usually species-specific." (p. 2)

- "The phenological status of birds may affect hazing success … Migrants in general are easier to disperse from most sites than are breeding birds … [but] shorebirds may be difficult to disperse from a traditional migratory stopover … Molting is also a factor, as some birds … cannot fly at certain stages in their molt." (p. 3).

- "Most deterrent techniques have been developed to prevent damage to a crop or structure … auditory or sound-making devices, visual scaring devices [such a mylar tape and lasers], exclusion, habitat modification, chemical repellants, removal (trapping), and [hunting or] killing … Techniques that incorporate both visual and auditory aspects, such as firing pyrotechnics while patrolling on an ATV, are even more effective." (p. 9)

- "The key elements in any strategy to haze birds are timing, organization, variation, and persistence … Variation, the use of a variety of hazing techniques, whether in combination or in rotation … helps prevent or delay the onset of habituation … To be successful, the hazing operation must be diligently applied [and] dynamic." (p. 10)

- "Auditory Techniques. Pyrotechnics … fired from a starter pistol … shotgun … or hand-held flare gun … Propane cannons … for shore-based hazing … Biosonics … [recorded] distress and alarm calls … the Phoenix Wailer Mk III can broadcast up to 94 electronically produced noises … [including] sixteen natural bird calls (alarm calls, distress calls, and predator calls) … the Breco Bird Scarer … [is] very similar to the Marine Phoenix Wailer … the Canadian Wildlife Service recommends this device … [it represents] the only unmanned hazing device available for offshore and open-water use … Visual Techniques. Mylar tape … Scarecrows … Flags … Balloons … Lasers … and Lights." (pp. 12-41)

- "Boats … can be effective in dispersing water birds … Typically the appearance and fast approach of a motorboat causes ducks and geese to flush immediately … However, the flushing distance depends on the degree of habituation to boats … Birds in areas frequented by boats … allow a closer approach before reacting … Boats are less effective for certain diving birds, such as grebes or loons, that are likely to dive repeatedly and not take wing." (p. 46)

- "Bird Profiles. Diving Birds. Loons [(*Gavia* sp.)] … do not respond well to hazing … their primary response is to repeatedly dive … herding from a boat can be attempted, but most likely will prove futile … Grebes [(*Podiceps* sp.; *Aechmophorus* sp.)] typically dive in reaction … it may be possible to slowly herd grebes … Diving ducks … dive underwater to feed on fish, crustaceans, mollusks, invertebrates, or vegetation … surf scoter (*M. perspicillata*), black scoter (*M. nigra*), [and] white-winged scoter (*M. fusca*) … are almost exclusively found on saltwater … [diving] ducks are hunted birds and respond well to pyrotechnics and propane cannons … Shorebirds … little is known about hazing shorebirds … they do not damage crops or cause significant problems, thus there has been little reason to haze them … shorebirds take flight in response to pyrotechnics but may not leave the immediate vicinity, instead [they may] circle and land nearby … Marine Birds. Alcids … [including] common murre (*Uria aalge*) … marbled murrelet … [and] rhinoceros auklet (*Cerorhinca monocerata*) … little is known about hazing alcids … there has been little reason to haze them." (Gorenzel and Salmon 2008, pp. 59-80)

Goss-Custard and Verboven (1993) report bird counts and the observed effects of human disturbance on shorebird feeding and other behaviors:

- "Activities include dog-walking, casual and commercial shell-fishing, birdwatching, and walking … most of the direct observations have been made while watching oystercatchers *Haematopus ostralegus* on mussel beds." (p. 59)

- "Few people use the mudflats in the upper half of the estuary where the majority of most of the shorebirds obtain their food at low water … small numbers of shell-fishermen maintain pots and slates … Since the small numbers of people involved walk slowly and are well dispersed over the flats, the disturbance seems to be minor … birds normally fly only a short distance and quickly resume feeding … Unless new sports or commercial fisheries arise that attract a much great[er] number of people to mudflats, levels of disturbance in many of the birds' most important feeding areas may not generally be very significant." However, "Two of the smallest mussel beds on the Exe are seldom used by birds in daylight because people occur there almost continuously." (p. 62)

- "Studies … have identified some of the effects that people have on foraging oystercatchers … When disturbed, most oystercatchers fly to another part of [the] bed … where many then rest … More birds stop feeding as the number of people on the bed increases … Oystercatchers steal mussels from each other with increasing frequency as the density of foraging birds, and thus opportunity to steal from subordinate individuals, increases (Ens and Goss-Custard 1984) … [Feeding or] intake rate decreases as bird density rises … [especially for] juveniles, which are amongst the least dominant of oystercatchers … The conclusion therefore, is that as the number of people increase on the mussel bed, most birds spend less time feeding and do so at a lower rate." (p. 63)

- "When disturbance does occur, birds compensate by moving elsewhere or by feeding at a greater rate during undisturbed periods of the day … birds move from adjacent bed … to bed … when large numbers of people occur there." (p. 64)

- "The birds feed … all the time … on receding and advancing spring tides in daylight, throughout daylight neap tides, and throughout both neap and spring tides at night … Over the winter as a whole, at least two-thirds of their feeding is done at times when people seldom occur on the beds." (p. 65)

- "In terms of its effects on the overall feeding opportunities for oystercatchers, disturbance may occur for over half the effective time that the birds feed during the winter … This would be serious if this meant that the birds were actually prevented from feeding for over half the time ... But this is not so … oystercatchers can adapt to minimize the effects of disturbance." (p. 65)

- "They can … habituate to people … though this depends critically on the extent to which the people move about … Anglers and the local … mussel pickers usually move rather little … having found a suitable place, they remain there for much of the tidal cycle … After the initial disturbance, the oystercatchers settle down and even feed nearby … Severe disturbance … usually arises if … pickers … give the birds little chance to settle down … The effects on most birds might be insignificant because they can adapt their foraging behavior." (p. 65)

- "The most convincing demonstration would be that disturbance reduced the birds' fitness … their chances of surviving the winter, or to acquire energy reserves to migrate successfully or to maintain a good enough body condition to breed well in summer … If increasing disturbance has significantly affected oystercatchers over the last 15 years, it should be reflected in changes in their numbers." However, "When different mussel beds are compared, there is no clear association between changes in oystercatcher numbers and disturbance levels … The counts suggest no clear link between the increase in disturbance over the years … its present level, and the changes in bird numbers on the various mussel beds of the Exe." "There is, in fact, no evidence from counts … that the total numbers of oystercatchers have been affected by the increased levels of disturbance over the last decade … Bird numbers … have increased roughly in line with the rise in the British wintering population … There may only have been some local redistribution within the estuary … The mere presence of people on the feeding grounds is clearly not sufficient reason in itself for believing the disturbance is deleteriously affecting the birds." (pp. 63-65)

- "Being amongst the least efficient foragers and poorest competitors on the mussel beds, young birds may suffer disproportionately from disturbance … This difficulty would be greatest in cold weather when energy requirements are high yet the opportunities to feed … are least." "This could be significant, because modelling shows that the overall population size can be much affected by the winter mortality rates of young birds (Goss-Custard and Durell 1990). However, the counts provide no evidence that disturbance of young birds has actually reached the point at which the population size is being affected, despite the marked increase in human activities that has taken place over the same period." "Many of the points made … [regarding] oystercatchers apply to other species of waders … There is no evidence that current levels of human disturbance significantly affect the feeding, and thus numbers, of overwintering shorebirds on this apparently rather typical estuary." (Goss-Custard and Verboven 1993, pp. 65, 66)

Greene *et al.* (2012) published a report evaluating the status of the Puget Sound's nearshore pelagic foodweb, a multi-trophic level assessment in six oceanographic basins:

- "We measured over 20 potential indicators of nearshore pelagic ecosystem health at 79 sites … These metrics included measurements of abiotic conditions and nutrient availability, and abundance and diversity of phytoplankton, bacteria, zooplankton, jellyfish, and pelagic fish species." (p. 4)

- "South Sound and Hood Canal had the most reduced dissolved oxygen and pH, highest relative abundance of jellyfish, and lowest abundance of forage fish and fish species richness. In contrast, the Rosario … and Whidbey Basins were characterized by relatively few abiotic or nutrient problems, few deviations in the abundance of different groups of microbes and phytoplankton, relatively high densities of non-gelatinous zooplankton (i.e., not jellyfish), high fish species richness, and relatively high forage fish abundance. Admiralty Inlet and the Central Basin scored in between this range, although they too exhibited high jellyfish abundance and reduced forage fish abundance." (p. 4)

- "Land use rarely explained more than 5 percent of the variation in observed data, indicating a dominant marine influence and the potential for resilience of the Puget Sound's pelagic waters to anthropogenic influence. The strong spatial structure observed in our results indicates that different pelagic food webs exist across the system." (p. 4)

- "Taxonomic composition of both vertical and surface plankton samples varied by basin … Some of the spatial differences correspond to major environmental gradients … the presence of the more oceanic copepod species *Acartia longiremis* in the Admiralty and Rosario Basins, and the high relative abundance of the estuarine species *Acartia hudsonica* in the more river-dominated Whidbey basin." (p. 24)

- "Preliminary results suggest pelagic trophic dynamics differ spatially within Puget Sound and that land use may be an influential factor … Isotopes appear to show a strong signal of shoreline land use." (p. 37)

- "The overall pattern of metrics suggests that the 'healthiest' basins may be the Rosario and Whidbey Basins. These were characterized by relatively few abiotic or nutrient extremes, few deviations in the abundance of different groups of microbes and phytoplankton, relatively high densities of non-gelatinous zooplankton, high fish species richness, and relatively high forage fish abundance. Rosario Basin had just a few metrics at medium levels and no metrics in 'poor' condition, while the Whidbey Basin had a few abiotic/nutrient metrics at medium levels and just one metric in 'poor' condition … The catchments supplying water to these basins are the centers of agriculture for Puget Sound, and efforts to reduce agricultural-related impacts (e.g., nutrient loading) and improve estuarine and nearshore habitats (e.g., reduced diking and shoreline hardening) will likely have the biggest benefits to these basins." (p. 41)

- "In contrast, Hood Canal and South Sound were rated the lowest [or least 'healthy'] in our system. Hood Canal is the most different from the other five basins … [Observed] features suggest that Hood Canal experiences a late-season rise in primary production from phytoplankton and cyanobacteria … As has been summarized recently by EPA and the Department of Ecology, Hood Canal is naturally challenged by its unique geography and oceanography, and a recent report determined that it is premature to assign all these problems to anthropogenic activities (Kope and Roberts 2012)." (p. 43)

- "South Sound also rated relatively poorly, and was distinguished by several unique features. Water temperatures were most frequently highest at South Sound sites, and exhibited the largest variance among all of the basins. Ammonium and silicic acid concentrations were also most frequently highest at South Sound sites … [Observed] features suggest that South Sound sites experience elevated primary and heterotrophic production, possibly fueled by ammonium and enhanced by warmer temperatures. In turn, relative abundances of jellyfish were the highest found in Puget Sound, and fish species richness was dominated by hatchery salmon. Forage fish were also relatively low in abundance." (Greene *et al.* 2012, p. 43)

Gutierrez *et al.* (2003, pp. 79-90) have described the ecological role of molluscan shell production in aquatic habitats:

- "Mollusk shells are abundant, persistent, ubiquitous physical structures in aquatic habitats … [they are] substrata for attachment of epibionts, provide refuges from predation, physical, or physiological stress, and control transport of solutes and particles in the benthic environment … Shell producers should not be neglected as targets for conservation, restoration, and habitat management." (p. 79)

- "Here we review the ecosystem engineering roles of an important, widespread group – aquatic mollusks. These organisms have community and ecosystem-level impacts via several mechanisms." (p. 80)

- "Shells and shell aggregations introduce complexity and heterogeneity into benthic environments and are important elements of habitat structure affecting population-, community-, and ecosystem-level processes." (p. 80)

- "The shell itself is a substratum for boring and sessile epibenthic organisms that cannot settle on the soft bottom … Shell production is known to control (1) the availability of substrata for settling by fouling organisms, (2) the availability of enemy- and stress-free space, and (3) the transport of particles and solutes in the benthic environment." (p. 81)

- "Mussels in soft-bottomed environments provide substrata for the attachment of invertebrates and algae that are usually unable to attach to bare mud (Albrecht and Reise 1994, Buschbaum 2000) … on rocky shores [they] allow colonization by infaunal organisms … [between] interstices among shells … organisms which otherwise cannot live in rocky habitats (Tokeshi and Romero 1995)." (p. 85)

- "In shell habitats dominated by living mollusks, recruitment and mortality are often influenced by the structural complexity conferred by conspecific neighbors. Adult mussels create substrata for the attachment of settling conspecifics (Bayne 1964, Petersen 1984, Bertness and Grosholz 1985)." (Gutierrez *et al.* 2003, p. 86)

Gutierrez *et al.* (2011) has described how physical 'ecosystem engineers' (seagrasses, kelps, reef-forming bivalves, burrowing crustaceans, and infauna) participate in and contribute to the functioning of estuaries and coastal ecosytems:

- "We focus on the impacts of physical ecosystem engineers on … key functional attributes of estuaries and coasts – [including] sedimentary processes … and the creation and modification of habitat for other organisms." (p. 5)

- "Consideration of physical ecosystem engineering as a process and a consequence reveals four general components (engineer, structure, abiotic, biotic) linked by three cause/effect relationships … (1) Engineer causes structural change; (2) Structural change causes abiotic change; and (3) Abiotic change causes biotic change. The first two relationships are processes, while the third is a consequence." (p. 8)

- "Macroalgae, grasses, epibenthic bivalves, tube-building polychaetes, reef-forming corals, and mobile invertebrates that create habitat are all autogenic engineers." (p. 8)

- "Engineered structures deteriorate and disappear unless maintained. Their persistence – and hence persistence of their abiotic effects – is a function of the intrinsic durability of the structural materials and the intensity of structurally destructive forces (Jones *et al.* 1997), and ranges from the ephemeral … to the highly persistent." (p. 9)

- "Abiotic variables relevant to habitat creation and modification for other organisms are … diverse and include changes in accretion/erosion … changes in light availability, temperature, moisture, oxygen availability, water flow exposure, attachment substrates, [and] enemy- or stress-free space … The overall abiotic impact of an engineered structure will also depend on the baseline abiotic state." (pp. 9-11)

- "While mussels have little influence on the availability of hard substrates on rocky shores, they have a very large effect in soft-sediment systems (Gutierrez *et al.* 2003) … Initial establishment of mussels in areas dominated by soft-substrates increases the availability of hard substrate (i.e., abiotic change) with a positive feedback effect on subsequent mussel recruitment (Bayne 1964)." (pp. 11, 12)

- "Seagrass meadows rival tropical forests and efficient crops as the most productive ecosystems on Earth (Duarte and Chiscano 1999), and are a source of important ecosystem services to humans, such as support for biodiversity, carbon sequestration, and sediment stabilization and coastal protection (Duarte 2000, Hemminga and Duarte 2000, Barbier *et al.* in press)." (p. 25)

- "The dampening of waves and currents by seagrass canopies leads to increased sediment deposition (Gacia and Duarte 2001, Gacia *et al.* 1999, Hendriks *et al.* 2008) and decreased resuspension (Lopez and Garcia 1998) … seagrass[es] can also directly intercept suspended sediment particles with their canopies … However, sediment accumulation can be seasonal." (p. 26)

- "Seagrass[es] … affect the seafloor topography through the accretion of rhizomes and roots in the sediments, thus exerting additional engineering influences on flow and sedimentation patterns … [and] can also modify environments via the export of litter and its accumulation in adjacent ecosystems … litter often accumulates [on] beaches." (p. 27)

- "The role of seagrass meadows in maintaining high biodiversity is supported by their capacity to expand and diversify the habitat available for other organisms … Seagrass meadows and patches also serve as refuge to a range of epibenthic … and infaunal species that … [benefit from] decreased risk of predation within the dense matrix of seagrass roots and rhizomes (Hemminga and Duarte 2000, Heck and Orth 2006)." (p. 28)

- "The physical influences of seagrass structure (leaves, roots, rhizomes) on biotic variables (predation risk, food availability, larval retention; Orth *et al.* 1984, Judge *et al.* 1993, Irlandi 1994, 1996) can lead to increased organismal abundance and/or species richness in seagrass meadows relative to adjacent unvegetated habitats (Heck 1977, Heck and Thoman 1984, Edgar *et al.* 1994, Jenkins *et al.* 1997) … seagrass habitats are often considered … 'nursery habitats' because of their … roles in sustaining … enhanced growth and survival of juveniles of commercially important species (Heck and Thoman 1984, Beck *et al.* 2001)." (p. 29)

- "Kelp and other … marine macroalgae … create habitats very distinct from adjacent waters … surface and subsurface kelp canopies diminish light (Pearse and Hines 1979, Reed and Foster 1984) … [and] canopy shade may positively affect sessile invertebrates by providing refuge from competition (Eckman and Duggins 1991, Arkema *et al.* 2009) … Because understory algae and sessile invertebrates have different light requirements, giant kelp allows for temporal and spatial coexistence of these competitors by creating alternative niches for them to occupy (Arkema *et al.* 2009)." (pp. 29-31)

- "The production of large kelps creates three-dimensional complexity in coastal environments, providing habitat for numerous species of plants and animals. Fish and invertebrates take refuge within kelp holdfasts and among stipes and canopy blades. Often, the population size of kelp forest animals depends upon the density and structural complexity of the kelp (Holbrook *et al.* 1990)." (p. 32)

- "Reef-building bivalves create spatially and topographically complex habitats that foster unique assemblages of organisms … The best-known examples of reef-building bivalves are intertidal and shallow subtidal mussels and oysters … These suspension feeders create persistent, extensive, dense populations that are attached to each other and the substrate." (p. 35)

- "Mussel beds and oyster reefs can show a high degree of temporal variation in persistence at small spatial scales, but over large spatial scales bivalves and shell material can persist for hundreds and even thousands of years in the same general location (Gutierrez and Iribarne 1999, Commito and Dankers 2001, Hertweck and Leibezeit 2002, Smith *et al.* 2003, Stone *et al.* 2005) … The patchy nature of reef and bed structure contributes to a spatially heterogeneous variety of autogenic and allogenic effects, both positive and negative, on the environment, other species, and the reef-builders themselves, across scales from individual shells to large spatial aggregations." (p. 36)

- "Where wave action and tidal currents are moderate, increased deposition over beds and reefs causes sediment to build up to form banks higher than the ambient substrate (Meadows et al. 1998) … Autogenic and allogenic banks create vertical relief. Intertidally, the upper portions of banks have reduced immersion time. Banks also act like dams to hold pools of water and increase immersion time." (p. 37)

- "Within the array of habitats and physico-chemical parameters resulting from reef and bed complexity, benthic and demersal animals, macrophytes, and microorganisms vary greatly. Organisms respond to individual shell traits and shell spatial arrangements, including the provision of attachment substrate; refuges from predation, competition, thermal stress, desiccation, and hypoxia; transport of materials and solutes; and delivery of larvae and postlarval juveniles and adults, including recruitment of mussels and oysters themselves (Gutierrez *et al.* 2003; Commito *et al.* 2005, 2008, Coen *et al.* 2007). Other physical ecosystem engineers such as kelps, seagrasses, and marsh grasses (e.g., Altieri *et al.* 2007) also interact with these bivalves." (p. 38)

- "Epifauna in hard- and soft-bottom habitats respond favorably to the provision of rugose, hard substrate by mussels and oysters. Rocky shore systems generally show enhanced species richness within bivalve assemblages (Tsuchiya 2002, Thiel and Ullrich 2002). This pattern generally does not occur in soft-bottom systems, primarily because some infauna have lower abundances and diversity within beds and reefs (Commito *et al.* 2005, 2008, Buchsbaum *et al.* 2009, Ysebaert *et al.* 2009), while oligochaetes, nemerteans, and opportunistic species may be enhanced … Epifauna and infauna abundance and diversity are strongly linked to spatial variation in live mussels and their shell material (Commito *et al.* 2008), demonstrating that reef-building bivalves are an important autogenic determinant of benthic community structure … [However,] the effects on macrofauna are quite variable, depending on bivalve species, geographic location, and local environmental conditions (Thiel and Ullrich 2002, Commito *et al.* 2005, 2008, Coen *et al.* 2007, Buchsbaum *et al.* 2009, Kochmann *et al.* 2009, Ysebaert *et al.* 2009)." (p. 38)

- "Burrowing crustaceans … create semi-permanent burrows, ranging from small, shallow structures to complex systems greatly extended laterally and to sediment depths > 1m (Swinbanks and Murray 1981) … burrows and bioturbation activities have a profound impact on physical and biogeochemical properties and processes, with knock-on effects for associated biota." (p. 39)

- "Physical habitat modifications by burrowing crustaceans occur in all sedimentary habitats, including sandflats … The creation of burrows extends the sediment-water interface to considerable depth … [and] active burrow irrigation accelerates the exchange of burrow/interstitial water with overlying water with concomitant oxygenation of the sediment column (Ziebis *et al.* 1996) … Burrowing and feeding activities also affect seabed stability by altering substrate particle size distribution, penetrability, and water content (Bertness 1985, Botto and Iribarne 2000)." (pp. 39, 40)

- "Species directly benefiting from the provision of habitat are burrow commensals, encompassing crustaceans, bivalves, polychaetes, and fish. The favorable microenvironment created within burrows also increases the abundance and diversity of infaunal species, including meiofauna (MacGinitie 1934, DePatra and Levin, 1989) … Bioturbation substantially increases habitat suitability for species dependent on uncompacted sediment (Tamaki *et al.* 1992) … [but] high levels of sediment disturbance and resuspension can be detrimental for susceptible species" (p. 41)

- "Infauna are invertebrates living within the matrix of aquatic sediments and include polychaetes, oligochaetes, bivalves, nemerteans, echiurans, sipunculids, as well as small crustacean such as burrowing amphipods and isopods … Despite their small size relative to other coastal and estuarine engineers, their abundance and activity levels dramatically impact the seascape." (p. 42)

- "Infaunal ecosystem engineers affect three-dimensional structure and thus the diversity of microhabitats in marine soft sediments … when infaunal organisms recruit into soft sediment habitats, they seek refuge by entering into the sediments and – in many cases – by producing shells, tubes, or burrows (Marinelli and Woodin 2002) … All these structures generate a remarkably more diverse environment within the sediment matrix relative to the originally smooth soft sediment … Their effects on abiotic factors such as porewater circulation and solute distribution have concomitant influence on microorganisms, meiofauna, and other infauna (Aller 1988)." (Gutierrez *et al.* 2011, p. 44)

Hayes *et al.* (2011) used acoustic transmitter tags, habitat class preferences, and compositional analysis of selection to describe bull trout movements, position, and marine habitat use in and around the Skagit River delta:

- "Bull trout populations that display an anadromous life history are unique to the distinct population segment of coastal Puget Sound … More information is needed to better understand the role of this life history type in the sustainability and adaptability of the species." (pp. 394, 395)

- "Recent studies in Washington State revealed anadromy in bull trout from Olympic Peninsula rivers (Brenkman and Corbett 2005) and in streams draining into Puget Sound (Goetz *et al.* 2004) … Moreover, bull trout from these populations are thought to be found in marine habitats at all times of the year (Beamer *et al.* 2004; Goetz *et al.* 2004)." (p. 395)

- "[In] Skagit Bay … depths as great as 50 m are found … [but] large intertidal areas, with maximum depths of less than 5 m are extensive." (p. 395)

- "We captured 35 bull trout … in the Swinomish Channel … Acoustic transmitters … were used to tag 20 fish captured near the confluence of the North and South forks from mid-March to early-April (river-tagged: RT) and 15 fish captured from the Swinomish Channel (channel-tagged: CT) from mid-May to mid-June 2006 … An additional nine transmitters from fish studied (saltwater-tagged: SWT) in 2004 or 2005 … were also detected during our study." (p. 395)

- "Fish positions were determined by using fixed receivers or by active relocation by boat … Additional position data were obtained from fixed receivers operated by the U.S. Army Corps of Engineers at several bay and upriver locations." (p. 397)

- "Summaries of fish positions and habitat descriptions were based on our best estimate of a fish's position during each 'event' … Detections separated by at least 2 hours were considered separate 'events'." (pp. 398, 399)

- "Habitat descriptions included shoreline, substrate, and vegetation classes (McBride *et al.* 2006) … These data were available for the majority of bay perimeter and shallow water habitat, but not for the Swinomish Channel … Substrate and vegetation data were available only within the intertidal zone." (p. 399)

- "We ranked habitat class preferences (Aebischer *et al.* 1993) by using a compositional analysis of selection (Leban 1999) to compare habitat use with habitat availability." (p. 399)

- "Subsequent detections indicated 12 of the 20 RT fish continued downstream and entered Skagit Bay … Six of seven SWT fish that were detected with the lower river receivers in 2006 were also detected in saltwater … Fourteen of the 21 fish were considered bay residents; the remaining 7 fish were detected only once or were found to be moving through the bay from other areas." (p. 399)

- "Bay residents were usually less than 0.4 km from the shoreline (83 percent of measurements) and 28 percent of detections were less than 100 m from shore." (p. 400)

- "Habitat class data and compositional analysis … suggested that bull trout use of habitats was not random … Coastal deposits, low bank, and sediment bluff accounted for nearly 76 percent (by length) of natural shoreline classes … Modified and unmodified shoreline classes were used in proportion to their availability … common modifications included concrete bulkhead and riprap … Green algae, eelgrass (*Zostera* sp.), and unvegetated were frequent vegetation classes; combined, they made up more than 70 percent of the area used by bull trout … Use of spit-berm, salt marsh habitats, and green algae vegetation classes was greater than expected, based on availability, while the unvegetated class ranked low." (p. 400)

- "Our data suggest that the marine habitats of Skagit Bay were used for extended periods of time (up to 133 d) by anadromous bull trout tagged in the lower Skagit River … These results agree with previous studies that showed marine residence from April [through] July … [But] the timing of marine residence could be more variable than indicated by our data … Some bull trout may be found in Skagit Bay during any month (Goetz *et al.* 2004)." (pp. 402, 403)

- "The bull trout we studied appeared to travel only modest distances from the Skagit River during their marine phase (<12 km) … [But] we did not extensively survey distant areas, and a few of our study fish were rarely or never contacted after tagging, so some fish may have migrated greater distances than we recorded." (p. 403)

- "One behavior that was common among bull trout in marine waters was the use of shallow, nearshore habitats … In general, fish positions were within 400 m of the shoreline and shallower than 4 m … Although some bull trout probably crossed sections of Skagit Bay with water depths greater than 10 m to reach the east shore of Whidbey Island, our detections never indicated that fish maintained positions in these deeper areas … The general pattern suggested that individual bull trout moved from the river to a discrete section of bay shoreline or the Swinomish Channel, stayed there for much of their marine residency, and then returned to the river … We found no evidence of consistently nomadic behavior for any fish." (pp. 403, 404)

- "Our descriptions of substrate, vegetation, and shoreline classes in bull trout habitats are the first of this type and thus are valuable despite incomplete mapping … However, habitat preference data should be considered preliminary because the number of detections of some fish was small, our fish location data were imprecise, and preference may be related to other factors … More detailed data are required to determine bull trout selection and intensity of use for specific habitats." (Hayes *et al.* 2011, p. 404)

Heck, Hays, and Orth (2003) used meta-analytic techniques to examine whether seagrass meadows function as effective nursey grounds:

- "We reviewed more than 200 papers that were relevant to the nursery role hypothesis … We used both vote counting and meta-analytic techniques to evaluate whether the body of previous studies that report seagrass meadows to be nursery grounds actually contain data that support this proposition … We also evaluated case histories of well-documented large scale seagrass losses on the nursery function." (p. 123)

- "Surprisingly, few significant differences existed in abundance, growth, or survival when seagrass meadows were compared to other structured habitats, such as oyster or cobble reefs, or macroalgal beds … Nor were there decreases in harvests of commercially important species that could clearly be attributed to significant seagrass declines in 3 well studied areas … One important implication of these results is that structure per se, rather than the type of structure, appears to be an important determinant of nursery value." (p. 123)

- "Valuable functions generally associated with seagrasses and cited frequently in the literature include … provision of optimal habitat for growth, survival, and reproduction of a diverse array of vertebrate and invertebrate taxa … its 'nursery function'." (p. 123)

- "The concept of a nursery must extend beyond simply the numbers of juveniles present, but also may entail higher survival, owing to protection from predators, and higher specific growth rates, due to the abundance of food resources within seagrass meadows, both of which are likely to result in more juveniles reaching the adult stage." (p. 124)

- "We sought to identify factors that create spatial variation in the nursery function of seagrass habitats, and to use well documented declines of seagrass to address whether loss of seagrass habitat has led to corresponding declines in species believed to use these habitats as nurseries." (p. 124)

- "Of the total 193 comparisons, 89 (46 percent) showed greater abundance in seagrass, 50 (26 percent) showed greater abundance in other habitats, and 54 (28 percent) showed no difference between seagrass and other habitats … Thus, for slightly more than half of the species studied, seagrass meadows did not support abundances that were significantly greater than those in surrounding habitats." (p. 126)

- "When seagrass meadows were either found not to differ significantly or to contain lower abundances than adjacent habitats, the adjacent habitats were often structurally complex … nursery habitats themselves." (p. 126)

- "There is stronger evidence of the importance of seagrass meadows in the northern hemisphere, where 58 of 77 comparisons (75 percent) showed significantly greater abundances in seagrass." (p. 127)

- "When all studies were considered together in the unlumped data set, seagrasses had a significantly positive effect on juvenile survival when compared to other habitats … [But] The effect of seagrass meadows on juvenile survival clearly varied across species … with no discernible patterns by taxonomy (fish vs decapod crustaceans) or geography (tropical vs temperate)." (pp. 127, 129)

- "When all studies were considered together, juvenile organisms had much greater growth rates in seagrass meadows than in other habitats … The magnitude of the difference … depended on the other habitat type being tested … In comparisons with unstructured and structured-unvegetated habitats … the effect size was extremely large … and statistically significant … However, as was the case with juvenile survival, there was no significant difference in juvenile growth rate … [between] seagrass meadows … [and] vegetated habitats such as macroalgal beds and salt marshes." (p. 130)

- "The enhanced survival of organisms in seagrass compared to that observed on unvegetated substrates seems to be due primarily to the simple effect of structure and not some intrinsic property of the seagrasses themselves … [Still] Over a period of more than 20 years, virtually all studies have found significantly greater survival in the presence than in the absence of seagrasses, whether in the laboratory (Nelson 1979, Coen *et al.* 1981, Main 1987, Mattila 1995) or in the field (Leber 1985, Heck and Wilson 1987, Heck and Valentine 1995)." (p. 131)

- "Growth was also significantly greater in seagrass than on unvegetated substrates, although there was little difference between growth in seagrass and other structured habitats … It may well be that greater growth in structured habitats occurs because structure provides more protection from predators and thereby allows more time for feeding, and thus significantly greater growth rates, than is possible in unstructured habitats … It is also true that structure provides more substrate for food resource to grow upon which can be an important factor influencing growth rates." (p. 132)

- "Case histories … [provided] neither a clear test nor a verification of the nursery hypothesis." (p. 132)

- "In aggregate, we believe that the evidence indicates that the factor most often limiting animal populations in shallow coastal water is the shelter from predators that structured habitats provide … But is important to note that almost no studies have yet measured the amount of successful movement from the purported seagrass nursery habitat to that of adults." (p. 133)

- "Not all seagrass meadows are likely to be equal in their nursery function … However, it is not necessary or prudent to wait for irrefutable evidence of any given habitat's nursery role before action is taken to conserve, manage or restore such habitats … Rather, we too believe that it is appropriate to err on the side of caution and to act on current knowledge of the suspected nursery value of different habitats (Beck *et al.* 2001)." (Heck, Hays, and Orth 2003, p. 133)

Hosack *et al.* (2006) compared the fish and invertebrate communities occupying intertidal mudflat, eelgrass, and oyster habitats in Willapa Bay:

- "The complexity of habitat structure created by aquatic vegetation is an important factor determining the diversity and composition of soft-sediment coastal communities … The introduction of estuarine organisms, such as oysters or other forms of aquaculture, that compete with existing forms of habitat structure, such as seagrass, may affect the availability of important habitat refugia and foraging resources for mobile estuarine fish and decapods." (p. 1150)

- "Understanding the relative importance of different intertidal habitats for estuarine species requires assessment of the comparative habitat value of SAV and other marine organisms that create complex structure in estuaries … Biotic assemblages present in oyster beds may differ from those in seagrass (Glancy *et al.* 2003) … For some organisms the habitat value of oyster may differ substantially from that provided by the fundamentally different architecture of seagrass." (pp., 1150, 1151)

- "We examined whether oyster aquaculture, seagrass, and mudflat habitats support comparable fish and invertebrate communities in … Willapa Bay, Washington … Habitat types were distinct since between-habitat dissimilarities ranged 82–88 percent, but within-habitat dissimilarities ranged 31–63 percent." (pp. 1151, 1153)

- "Epibenthic invertebrate densities were significantly higher in oyster and eelgrass than in mudflat, and composition was also significantly related to habitat [type]." (p. 1153)

- "Harpacticoid copepods comprised a large portion of total epibenthic invertebrates and showed a pattern of significantly higher densities in structured habitat … Habitat type explained a significant amount of variation in the composition of harpacticoid copepods." (p. 1154)

- "Benthic invertebrate densities were significantly higher in eelgrass compared to mudflat, but intermediate in oyster … Although total densities of benthic invertebrates were related to habitat type, their composition at the taxonomic level of class was not." (pp. 1154, 1155)

- "Species richness of fish and decapods was not related to habitat [type] … and abundance was [also] unrelated to habitat type." (p. 1155)

- "Results from this study … generally support those from previous studies elsewhere suggesting that complex habitat structure created by ecosystem engineers, such as seagrass and oysters, increases the abundance of associated sessile organisms (Orth *et al.* 1984; Summerson and Peterson 1984; Schmude *et al.* 1998; Jenkins *et al.* 2002; Heck *et al.* 2003) … Densities of epibenthic invertebrates, harpacticoid copepods, and benthic invertebrates varied significantly among habitat types and were generally higher in structured eelgrass and oyster habitats … The assemblage composition … differed between adjacent patches of low intertidal eelgrass, oyster, and unvegetated mudflat." (p. 1156)

- "Results for mobile fish and decapods were somewhat different than the generally accepted view of greater diversity and abundance in vegetated versus unvegetated habitats (Heck *et al.* 1989; Connolly 1994; Edgar and Shaw 1995) … While the composition of fish and decapods varied strongly across both time and space, habitat type explained little of the variation in composition, richness, or size of this component." (p. 1156)

- "Benthic invertebrate densities were significantly higher in eelgrass … The rhizome structure of eelgrass beds may support high densities of benthic invertebrates by increasing the circulation of oxygen and nutrients (Castel *et al.* 1989), and the root-rhizome structure of eelgrass may also provide refugia from predation for benthic invertebrates (Orth *et al.* 1984) … Reduced diversity and density of benthic infauna on open mudflats, particularly those adjacent to structured habitat, could be due to increased predation (Orth *et al.* 1984; Summerson and Peterson 1984)." (p. 1157)

- "The fish and decapod assemblage as a whole, which is highly mobile relative to epifauna and infauna, showed little habitat association in Willapa Bay, despite the habitat-specific associations of the invertebrate organisms that would be expected to serve as important prey resources … Fish and decapods frequently exhibit diel cycles in habitat use … Fish [and decapods] caught in this study were sufficiently mobile to forage over much larger spatial scales than the patches of habitat we selected for sampling." (Hosack *et al.* 2006, p. 1158)

Kraan *et al.* (2009) provide evidence that intensive, landscape-scale shellfish activities have caused or contributed to prey depletion, reductions in available foraging habitat, reduced survival, and reduced numbers of red knots (*Calidris canutus islandica*):

- "Whether intertidal areas are used to capacity by shorebirds can best be answered by large-scale manipulation of foraging areas … The recent overexploitation of benthic resources in the western Dutch Wadden Sea offers such an 'experimental' setting … We review the effects of declining food abundances on red knot *Calidris canutus islandica* numbers, based on a yearly large-scale benthic mapping effort, long-term colour-ringing, and regular bird-counts from 1996 to 2005 … We focus on the three-way relationships between suitable foraging area, the spatial predictability of food, and red knot survival …

Over the 10 years, when accounting for a threshold value to meet energetic demands, red knots lost 55 percent of their suitable foraging area … This ran parallel to a decrease in red knot numbers by 42 percent … Densities of red knots per unit suitable foraging area remained constant at 10 knots [per] ha between 1996 and 2005, which suggests that red knots have been using the Dutch Wadden Sea to full capacity." (p. 1259)

- "Whether habitats are used to capacity by their inhabitants, i.e. 'carrying capacity', is a question that has long occupied research agendas … in intertidal areas … Often, an area's carrying capacity is expressed as the maximum number of bird-days, or the maximum numbers to survive winter, given the total food stocks available (Goss-Custard 1985; Sutherland and Anderson 1993; Goss-Custard *et al.* 2002, 2003; Van Gils *et al.* 2004)." (pp. 1259, 1260)

- "Field studies experimenting with landscape-scale declines of food stocks are impractical and unethical (Courchamp *et al.* 1999) … However, in the Dutch Wadden Sea, as a result of intensive exploitation of natural resources in this protected nature reserve, such an 'experiment' has now been carried out (e.g. Piersma *et al.* 2001; Lotze *et al.* 2005; Van Gils *et al.* 2006a; Kraan *et al.* 2007; Swart and Van Andel 2008) … The mechanical harvesting of cockles *Cerastoderma edule*, allowed in three-quarters of the intertidal flats, has decreased both the quality (flesh-to-shell ratio) and the abundance of available cockles for red knots *Calidris canutus* (Van Gils *et al.* 2006a)." (p. 1260)

- "The focal species, red knots of the *islandica* subspecies, are long-distance migrants that socialize in large flocks outside the breeding season in the Wadden Sea (Piersma *et al.* 1993; Nebel *et al.* 2000; Piersma 2007) … An estimated one-third to half of the population visits the area at some stage during winter (Nebel *et al.* 2000; Van Gils *et al.* 2006a), whose total population number dropped by 25 percent between 1997 and 2003 … (Van Gils *et al.* 2006a) … As the diet of red knots consists of a number of prey species (e.g. Piersma *et al.* 1993; Van Gils *et al.* 2005a), we use a multiple prey species functional response model." (p. 1260)

- "There was a significant decrease of 55 percent in the area suitable for foraging … [and] the number of red knots decreased by 44 percent within a decade … When the suitable foraging area and the number of *islandica* knots between both periods were compared, it was shown that both declined by about the same amount." (pp. 1262, 1263)

- "Capitalizing on an 'experiment' resulting from … shellfish overexploitation in formally fully protected intertidal flats in the western Dutch Wadden Sea (Piersma *et al.* 2001; Lotze *et al.* 2005; Van Gils *et al.* 2006a; Kraan *et al.* 2007; Swart and Van Andel 2008), we examined changes in the three-way relationships between suitable foraging area, spatial predictability of food, and red knot survival." (p. 1264)

- "Knots, visiting the area in winter … [over] the period 1996-2005 … were faced with a decline in the extent of suitable foraging area, especially from 2002 onwards … For a benthivorous predator, which also has to deal with tidal cycles (Van Gils *et al.* 2005b, 2006b, 2007), interference competition (Van Gils and Piersma 2004; Vahl *et al.* 2005), and predation by raptors (Piersma *et al.* 1993; Van den Hout, Spaans and Piersma 2008), these landscape-scale changes have population-level impacts." (p. 1265)

- "The decline of suitable foraging area and the decline of *islandica* knots ran parallel … and the mean density of birds remained stable … This not only strongly indicates that the available suitable foraging area regulates red knot numbers in the western Dutch Wadden Sea, but also that the intertidal areas are used to full capacity by red knots (Goss-Custard 1977, 1985)." (p. 1265)

- "Loss of spatial predictability of food … means that food might be more difficult to find (Mangel and Adler 1994) … An increasing amount of time has to be devoted to the actual searching of cryptic prey, reducing the daily energy intake further … In addition, longer foraging periods lead to higher risks (e.g. predation risk), as described elsewhere (Van Gils *et al.* 2006b, 2007)." (p. 1266)

- "Following the … decline of suitable foraging area … survival of *islandica* knots decreased from 89 percent to 82 percent … Reduced survival (with constant recruitment) only explained … 42 percent of the loss in numbers: more red knots 'disappeared' from the Dutch Wadden Sea than could be explained by the increased mortality (e.g. Van Gils *et al.* 2006a) … Apparently, many surviving red knots emigrated permanently out of this marine protected area … and reduced food abundance may have indirectly lead to reduced breeding success (Ebbinge and Spaans 1995; Baker *et al.* 2004; Morrison, Davidson and Wilson 2007) … In any case, the reduced annual survival clearly supports the suggestion that the Wadden Sea was filled to capacity in the decade during which this study took place (Goss-Custard 1985; Goss-Custard *et al.* 2002)." (Kraan *et al.* 2009, p. 1266)

Laist (1997) compiled a comprehensive list of species with marine debris entanglement and ingestion records:

- "Problems Associated with Collecting and Analyzing Entanglement Data. Entangling debris is scattered over broad areas, making interactions possible almost anywhere … Animals that become entangled and die may quickly sink or be consumed by predators at sea … Those that die and float … are often concealed within a mass of debris … These factors frustrate systematic attempts to detect entangled animals. As a result, most data on entangled animals are opportunistic anecdotal records … Most entanglement records have been gathered by land-based observers examining animals that strand on beaches or congregate seasonally on shorelines to nest, breed, molt, etc." (p. 100)

- "Land-based surveys offer no measure of the number of animals that die in … debris at sea … dead entangled animals that strand on shore represent an unknown proportion of entangled animals that die … at sea." (p. 101)

- "Overall, the lists of affected species indicate that marine debris is a broad-scale [problem] … affecting a significant percentage of the world's marine species." (p. 102)

- "Coastal and Marine Birds. Reports of entangling debris were found for 56 species of marine and coastal birds … including 16 percent (51 of 312) of the world's seabird species listed by Harrison (1983), and 5 other coastal species … The records suggest that seabirds become entangled accidentally when seeking natural prey items associated with entangling debris … By far, the debris items most frequently reported in seabird entanglement records are monofilament line and fishing net. Other entangling items reported commonly, particularly for some species, are fishing hooks, six-pack yokes, wire, and string." (p. 103)

- "Factors Influencing Entanglement Rates … [The] amount and distribution of debris have been related to probable sources (e.g., urban centers, commercial fishing areas, and shipping corridors) and to surface currents and wind patterns … Foraging strategies and feeding behavior may also be related to entanglement rates among seabirds … seabirds that feed by scavenging (e.g., herring and black-headed gulls) and plunging (e.g., pelicans and gannets) are among the species with the highest entanglement rates … entanglement records are usually least common among species that feed by pursuit diving, surface seizing, and dipping." (pp. 105, 106)

- "Most fish and crustacean entanglements occur in lost or discarded fishing gear specifically designed to exploit the normal behavior patterns of such species … It seems likely that virtually all target and nontarget species taken in commercial fisheries are also killed in lost or discarded gear … As animals become trapped in lost gear, they can lure other animals that in turn become trapped in a self-perpetuating cycle (Kruse and Kimker 1993)." (p. 107)

- "The effect of entangling debris is essentially the same for all species and is primarily mechanical (Laist 1987). Animals that become entangled may exhaust themselves and drown, have their mobility impaired to a point where they can no longer catch food or avoid predators, become hung up on rocks or other fixed objects by trailing rope or line, or incur wounds and infections from the abrasion or constriction of attached debris … [However] In many cases, animals that interact with entangling debris do not become entangled or become entangled only briefly with little or no apparent harm … [But] Debris imposes added energy requirements while at the same time impairing foraging efficiency, leading to eventual starvation and death … While gradual starvation may be the fate of animals entangled in relatively small pieces of debris, those that become entangled in larger items probably die quickly … from injury or predation … Fish and crustaceans caught in lost traps or immobilized in lost gillnets may die from cannibalism, predation, starvation, and suffocation as gear is buried by sand (Muir *et al.* 1984; Kruse and Kimker 1993; Paul *et al.* 1993) … Entangled animals that die for reasons other than predation may be detectable for only short periods of time because of scavenging and decomposition, or be concealed in ways that frustrate detection (e.g., resting on the sea floor or floating at sea just below the sea surface)" (pp. 107-109)

- "Because of the predominance of fishing related debris in entanglement incidents, source-reduction efforts should focus on incorporating new management measures into fishery management programs to avoid losses and to increase recovery of such items … [Programs should] require fishermen to report when, where, and the circumstances under which nets or traps are lost … [and] clean up lost fishing gear." (Laist 1997, p. 118)

McDonald *et al.* (2013 *In* Washington Sea Grant 2013, Appendix II) looked at the effects of geoduck aquaculture gear on resident and transient macrofaunal communities:

- "Resident macroinvertebrates (infauna and epifauna) were sampled monthly (in most cases) using coring methods at low tide … SCUBA and shoreline transect surveys were used to examine habitat use by transient fish and macroinvertebrates." (p. 50)

- "Here 'resident' describes macrofauna species that occupy intertidal beaches throughout their entire benthic life history … whereas 'transient' macrofauna make frequent (often daily, linked to tidal fluctuations in water level) migrations between intertidal and subtidal habitats." (p. 51)

- "The Shannon index was utilized to compare differences in diversity between plots … This measure is commonly used in ecological studies and combines aspects of species richness and relative abundance … (Shannon 1948, Shannon and Weaver 1949) … A higher index value indicates higher diversity." (p. 54)

- "At all three sites, the community of resident macrofauna consisted primarily of polychaete worms (Annelida), small crustaceans (Arthropoda), and small bivalves (Mollusca) … In some locations echinoids (Echinodermata), larger bivalves, burrowing sea anemones (Cnidaria) and sea cucumbers (Echinodermata) were important community components … All sites were characterized by substantial seasonal variation." (p. 54)

- "We collected and identified 68 taxa … [Our] analyses illustrate differences in community structure across months …, plot types, and phases at each site … Within each site … community data from the pre-gear phase were similar at culture and reference plots … Similarly, there were no significant differences … for culture and reference plots at any site when aquaculture structures were in place (gear-present) … During the post-gear phase, values … were lower (relative to the previous phase)." (p. 54)

- "Abundance of individual [resident] taxa showed marked differences across months, plot type, [and] phases … [But,] Taxa showed no consistent response to geoduck aquaculture … Only two taxa experienced persistent negative effects: the polychaete Families Spionidae … and Orbiniidae." (pp. 54, 55)

- Transect surveys for transient fish and macroinvertebrates found "…No significant differences between culture plots and reference areas … when PVC tubes and nets were absent, either pre-gear or post-gear … However, a significant difference was detected between culture plots and reference areas when aquaculture gear was present … While communities associated with culture plots were represented by a variety of functional groups when nets and tubes were in place (gear-present), flatfish were conspicuously underrepresented … At the same time, reference areas were characterized by flatfish and hermit crab, and less so by true crab and sea star … Of the significant functional groups, true crab and other nearshore fish show strongest associations with culture plots during the gear-present phase, when PVC tubes and nets were in place." (p. 55)

- "[Transient] Species diversity … was unaffected by geoduck aquaculture operations … There was no significant difference in diversity between culture plots and reference areas … Total numbers of organisms … were similar prior to gear deployment … and after gear removal … However, there was an overall increase in total abundance while aquaculture gear was present, and macrofauna counts were more than two times higher at culture plots compared to the reference areas." (p. 55)

- "Resident invertebrate communities were characterized by strong seasonal patterns of abundance and site-specific differences in composition … Some individual taxa responded negatively to the presence of geoducks and aquaculture gear (e.g., polychaete Families Spionidae and Orbiniidae), while others responded positively (e.g., polychaete Family Goniadidae and anemone Family Edwardsiidae), and still others were unaffected (e.g., bivalve genus Rochefortia and polychaete Family Capitellidae) … Several infaunal taxa recovered to pre-gear abundance, or increased in abundance, once aquaculture gear was removed … Effects on resident … infauna and epifauna may be site-specific … Elucidating potential mechanisms responsible for differences in the response of infauna will require additional study." (p. 56)

- "Unlike resident macrofauna, the transient fish and macroinvertebrate community was clearly affected by aquaculture activities … Presence of PVC tubes and nets significantly altered abundance and composition, but not diversity, of transient macrofauna … Over two times more organisms were observed during surveys at the culture plots than at reference areas during the structured phase of geoduck aquaculture, indicating that geoduck aquaculture gear created favorable habitat for some types of Puget Sound macrofauna." (p. 56)

- "Effects of aquaculture on transient macrofauna did not persist once PVC tubes and nets were removed … When PVC tubes and nets were removed, the transient macrofauna community was no different from the pre-gear condition … These data suggest transient macrofauna communities associated with these intertidal beaches begin to recover … within a few months of removal of the PVC tubes and nets." (p. 57)

- "Aquaculture practices did not affect diversity of macrofauna … No consistent differences in diversity of resident macrofauna were observed in the present study … The similar pattern observed in both culture plots and reference areas may be attributed at least in part to annual [or seasonal] variation in species abundance and composition." (p. 57)

- "Taken together, these results indicate that changes in habitat complexity associated with geoduck aquaculture produce short-term effects … [However] we caution that … Additional impacts might be demonstrated by considering different metrics, including growth … [and] It is not possible to extrapolate results to consider the cumulative effects of multiple culture cycles in a single location … or the landscape effects of a mosaic of adjacent aquaculture areas interspersed with other habitat ... [Furthermore,] Our sampling was not adequate to assess rare or patchy species, particularly salmonids." (McDonald *et al.* 2013 *In* Washington Sea Grant 2013, Appendix II, pp. 57, 58)

Meseck *et al.* (2012, pp. 65-79) investigated the influence of a commercial FLUPSY on water quality and sediment chemistry in a small temperate embayment:

- "The output from the FLUPSY was compared to estuarine transects in the bay to determine if any outputs from the FLUPSY could be detected within the embayment … Dissolved nutrient concentrations in the FLUPSY output were no higher than in the rest of the embayment … the FLUPSY had minimal effects on the chemical ecology of the embayment." (p. 65)

- "Despite similar energy balances as in commonly accepted agriculture practices, concerns remain that the environmental effects of bivalve aquaculture are not fully understood … Environmental models constructed by Meeuwig *et al.* (1998) … suggest that intense bivalve culturing can alter material and energy cycles in some coastal systems, leading to concerns that bivalves could overgraze a system for other consumers (i.e. zooplankton, fish) … Bivalve grazing, however, may reduce the effects of eutrophication by sequestering nutrients assimilated by the bivalves, and also stimulate primary production" (p. 66)

- "Few studies have examined potential effects on nutrient cycling, fluxes, and retention at the coastal ecosystem scale (Newell 2004, Nizzoli *et al.* 2006, 2011, Cranford *et al.* 2007)." (p. 66)

- "To determine if outputs from a nursery-culture system growing *C. virginica* oyster seed could be detected within the magnitude of temporal variability in the environment, a commercial nursery site employing a … [FLUPSY] was studied … Because the FLUPSY takes water from the embayment (input) and has a known discharge pipe, we can use the fixed-station, estuarine-transect approach commonly used in estuaries to determine anthropogenic point and non-point sources in a watershed (Cutter and San Diego-McGlone 1990, Maie *et al.* 2006, Wu *et al.* 2012)." (p. 66)

- "This study quantified the: (1) water column nutrient concentrations, (2) surface water [chlorophyll] a concentrations, and (3) sediment characteristics for the entire embayment and around the commercial nursery. By comparing the embayment's seasonal variability to the output of the commercial nursery, we assessed if impacts from the oyster nursery upon the embayment can be detected within the natural temporal and spatial variability of the embayment." (p. 67)

- "Using the area of the embayment … we calculated the amount of total ammonia fluxing from the sediments, and compared it to fluxes from the FLUPSY and the salt marsh." (p. 69)

- "There was no difference in salinity … water temperature … phosphate … or silica … between the inflow and outflow of the FLUPSY … There were, however, differences in [total suspended material], [chlorophyll] a, total ammonia, and nitrate+nitrite … From June until November, there was net removal of [total suspended material] … and [chlorophyll] a … The FLUPSY was a source of total ammonia … and nitrate+nitrite … throughout the season … [However,] the output of total ammonia from the FLUPSY was within the concentration range observed in the embayment … The FLUPSY was a very minor source of total ammonia when compared to the salt marsh and sediments." (pp. 70, 71, 75)

- "Our results clearly show that the net effects of the FLUPSY … on the chemistry of the water column and the sediments were minimal compared to the temporal variability of the system … Overall, the chemical ecology … was little affected by the oyster nursery … Waste byproducts from the FLUPSY remain[ed] very localized, and intense recycling of nitrogen [nitrate+nitrite] may have helped sustain primary production in the immediate vicinity of the FLUPSY." (Meseck *et al.* 2012, pp. 77, 78)

Mumford (2007) described the ecology of *Kelp and Eelgrass in Puget Sound*:

- "Kelp and eelgrass are … marine organisms of sufficient importance in Washington's waters to be afforded some protection by statute …These organisms need fairly high light levels to grow and reproduce, so they are found only in shallow waters … Hence, they are totally dependent on the nearshore environment." (p. v)

- "Both are highly productive, annually producing large amounts of carbon that fuel nearshore food webs, principally through detritus pathways … Both also provide critical three-dimensional structure in otherwise two-dimensional environments, and many other marine organisms use this structure [as habitat]." (p. v)

- "Carbon fixed by kelp is critical in supporting nearshore food webs; in at least some areas, it is a far more important source of carbon than is phytoplankton … A variety of commercially important organisms … including sea cucumbers, crabs and other shellfish, may thus depend directly or indirectly on the carbon produced by kelp." (p. 1)

- “Eelgrass … is an important primary producer, fixing carbon that then enters nearshore food webs (Thom 1990a) … Relatively few organisms directly consume eelgrass; the major exceptions are brant (Wilson and Atkinson 1995; Baldwin and Lovvorn 1994) and a few invertebrates … Most eelgrass biomass enters the food web through detritus, as the ends of blades slough off and whole plants break or are uprooted.” (p. 1)

- “Eelgrass beds … slow water currents and dampen waves, thereby trapping sediments [and] detritus … The roots of eelgrass stabilize the sediment via the matting effects of their dense, interlocking rhizomes … In addition, the rhizomes strongly influence geochemical conditions in the sediments (Kendrick *et al.* 2005) … The blades, and to some degree the rhizomes, also act as substrate for various organisms that otherwise would not be found on soft sediments; for example microalgae and invertebrates such as copepods, amphipods and snails … During parts of the year, the blades are so overgrown that they appear ragged or dirty.” (p. 2)

- “Eelgrass is an important spawning substrate for Pacific herring (Penttila 2007) … The extensive relationship between eelgrass beds and salmonids is described in Fresh (2006) and others (Shreffler *et al.* 1992; Shreffler and Thom 1993; Thom 1987; Boström *et al.* 2006) … Other species, including shrimp, flatfishes, and at least some stage in the life histories of most important Puget Sound fishery species, use eelgrass beds for feeding, refuge from predators, and [as] nursery areas.” (p. 2)

- “The habitat requirements for kelp include not only those conditions needed for the large kelp plant, but also for the tiny and cryptic gametophytes, for induction of reproduction, and for fertilization (Foster and Schiel 1985; Dayton 1985; Druehl and Wheeler 1986).” (p. 4)

- “[Eelgrass] grows in several bed configurations or patterns (Bell *et al.* 2006) … In areas where conditions are thought to be most suitable, beds are solid or continuous … In other areas there may be persistent patchy beds, often at the ends or edges of solid beds … Continuous beds are often found in extensive tideflats, and more fragmented beds in areas fringing linear shorelines (Berry *et al.* 2003) … Little is known about interannual variation in bed area, but it appears to be less than 10 percent (Berry *et al.* 2003; Dowty *et al.* 2005).” (pp. 10, 11)

- “[Eelgrass] shows … interesting landscape distribution attributes … First, the lack of beds in southern Puget Sound … At the point where tidal amplitude is enough to cause the lower limit to be the same as the upper limit, eelgrass will not grow … The problem is exacerbated by the fact that the timing of extreme low tides in southern Puget Sound is in midday, when temperatures are the highest … in northern Puget Sound and in Hood Canal, the most luxuriant, dense and continuous beds are distributed along the cusp at the margins of river deltas, not along the delta face itself, nor along stretches of beach far away from river mouths.” (p. 11)

- "Competitors of kelp … include any shallow … space-occupying organism … The tiny gametophytes and small sporophytes can be out-competed for space or light by a variety of algae and sessile invertebrates … Once grown out of these small stages, however, kelps can outcompete most other seaweeds and sessile invertebrates because of their rapid elongation (10 cm per day in *Nereocystis*) and large adult size … Even the smaller, non-floating kelps can overtop and shade other algae." (p. 12)
- "Direct stressors to eelgrass include harrowing or roto-tilling for on-ground oyster culture and damage from propellers … Similarly, [for] kelp, if … [cut] below the meristem, or growing region, [this] will result in the death of the entire plant." (Mumford 2007, p. 14)

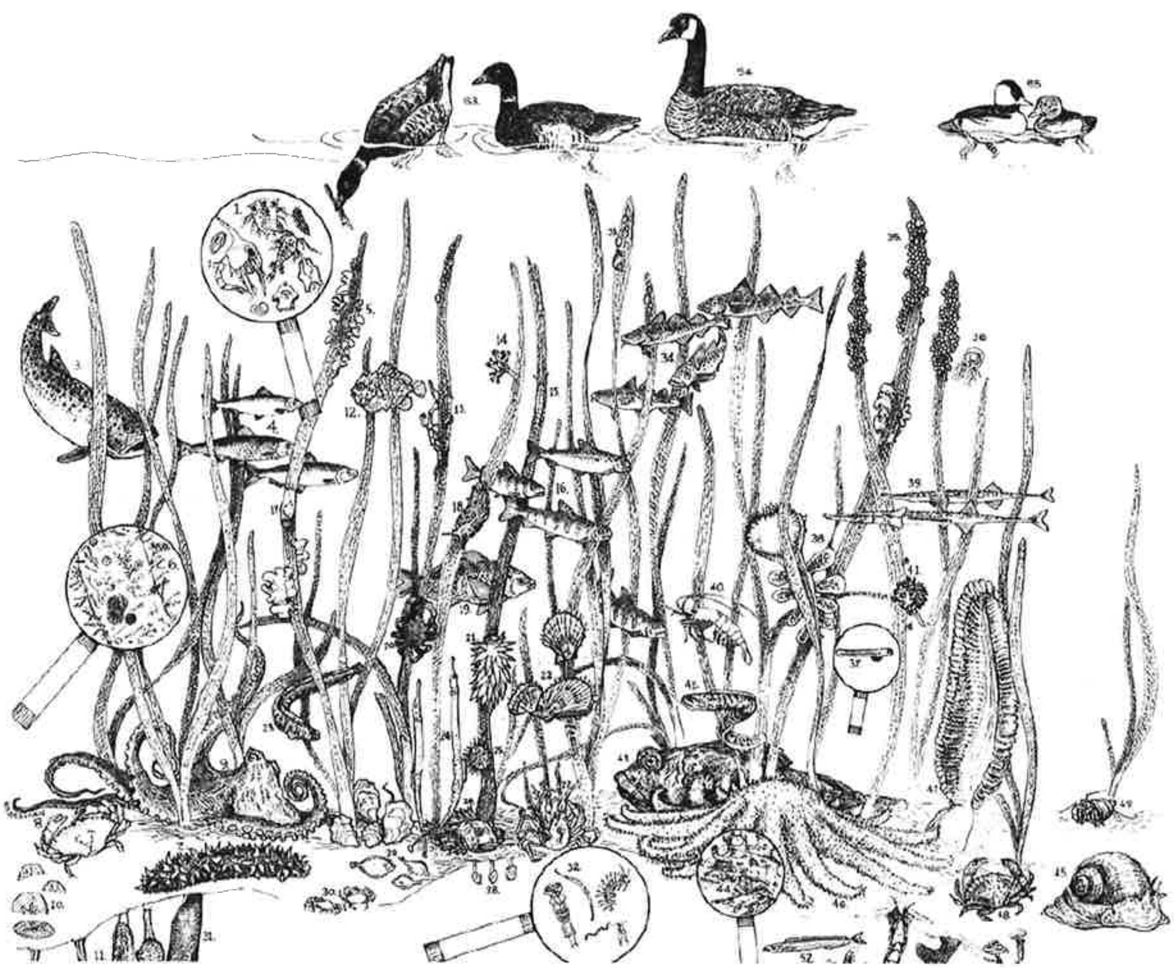


Figure A. The eelgrass meadow; a world of microhabitats (Mumford 2007, p. 3)

Neckles *et al.* (2005) described disturbance of eelgrass by commercial mussel harvesting and subsequent recovery:

- "Significant injury to roots, rhizomes, and meristems is lethal to seagrass shoots." (p. 58).

- "The effect of physical disturbance on plant communities depends on the size, frequency, and intensity of disruption, and on ecological, physiological, and life history characteristics affecting ecosystem recovery (Pickett and White 1985)." (p. 58)

- "The rate of seagrass recovery following disturbance … depends on the capacity for seedling colonization, successful establishment of new patches, and lateral patch expansion (Duarte and Sand-Jensen 1990, Olesen and Sand-Jensen 1994a) … Flowering intensity and seed production are highly variable within and among seagrass species (Marba and Walker 1999, Walker *et al.* 2001), but regardless of reproductive effort, reported rates of new patch recruitment into disturbed areas are generally low (Duarte and Sand-Jensen 1990, Vidondo *et al.* 1997, Bell *et al.* 1999, Ramage and Schiel 1999) … Factors contributing to low patch formation rates include limited seed dispersal capabilities (Orth *et al.* 1994, Luckenbach and Orth 1999), low germination rates (Orth *et al.* 2003), and high seedling mortality (Duarte and Sand-Jensen 1990, Olesen and Sand-Jensen 1994a, Ramage and Schiel 1999) … Consequently, recovery of disturbed areas may be strongly dependent on the lateral vegetative growth of established patches (Duarte 1995, Marba and Duarte 1995)." (p. 58)

- "Dramatic differences in the habitat characteristics of disturbed and reference sites were seen in the areas of the most recent [mussel] dragging activity … Detailed examination of the … dragged area … one year after disturbance, revealed remnant patches of mature plants (i.e. eelgrass patches that remained following [mussel] dragging) throughout the scar … [and] new patches, consisting entirely of first-year seedlings or of seedlings plus lateral shoots, were distributed fairly uniformly throughout the dragged area." (pp. 63, 64)

- "The broadly overlapping zones of statistical similarity in measured plant characteristics … suggest considerable variability in the actual length of time that would be required for newly vegetated substrate to achieve reference conditions." (p. 66)

- "Fishing gear has been shown repeatedly to reduce the structural complexity of benthic habitats by smoothing sedimentary bedforms and physically removing biota that produce habitat structure (Auster and Langton 1999, National Research Council 2002) … Mobile gear has been found to affect seagrass beds similarly through removal of the vegetation (Fonseca *et al.* 1984, Peterson *et al.* 1987, Orth *et al.* 2002; but see Meyer *et al.* 1999) … Mussel dragging … had a comparably severe impact on localized habitat structure by eliminating large amounts of vegetation." (pp. 67-68)

- "The measured effect of disturbance … depended on the scale of observation and the apparent intensity of [mussel] dragging effort … Presumably, the number, sizes, and distribution of remnant patches of eelgrass following dragging are a function of the dragging intensity, with patches occurring on substrate that was missed by the dredge … This difference in dragging intensity most likely reflects the pattern of mussel distribution rather than any difference in gear efficiency." (p. 68)

- "Although stable environmental conditions would … moderate fluctuations in new patch formation and edge expansion over time … Given the potential for wide variability in these controlling factors, some level of annual variation in patch dynamics would be expected." (p. 69)

- "Our model of within-bed eelgrass recovery emphasized the importance of initial dragging intensity." (Neckles *et al.* 2005, p. 69)

New Fields Northwest (2008) evaluated a new, large floating mussel raft facility on north Totten Inlet and potential direct and indirect effects to currents, dissolved oxygen, nutrients, phytoplankton abundance, biomass, primary productivity, and carbon-flow:

- "Current velocities around the rafts … generate a large amount of horizontal and vertical mixing … [and] create a large down current eddy that mixes ambient water with raft-influenced water." (p. vi)

- "During periods of low ambient DO (generally late August to September), DO concentrations below 5.0 mg/L would … persist some distance downstream from the raft edge." (p. vi)

- Data collected at Taylor Resources, Inc.'s existing Deepwater Point raft facility and model predictions for the proposed, new facility both indicate an approach to the "…WDOE criteria for high concentrations of ammonium (>5 μM) … However, once the water passes 70 m (230 ft) beyond the raft system, the ammonium signal was no longer detectable." (p. vii)

- "Approximately 3,400 kg N [per year] would be removed with mussel harvest and 1,083 kg N [per year] would be removed with the associated fouling community … Nitrogen removal … would represent approximately 17 to 40 percent of the estimated anthropogenic nitrogen introduced to Totten Inlet [annually]." (p. vii)

- "For the purposes of food web modeling, a fall/winter and spring/summer profile was used for phytoplankton standing stock … Primary production by phytoplankton in Totten Inlet was estimated to be 40,614,000 kg C/year during the spring/summer period … Of this total production, [just] 7.4 percent is consumed by primary consumers … The proposed mussel raft was predicted to consume <1 percent of the production during the spring/summer period … Primary production by phytoplankton in Totten Inlet was estimated to be 3,066,000 kg C/year during the fall/winter period … Of this total production, [just] 15.7 percent is consumed by primary consumers … The proposed mussel raft was predicted to consume <1 percent of the production during the fall/winter period … No changes to carbon flow in the water-column food web were predicted to occur as a result of the consumption associated with the proposed mussel rafts during the spring/summer or fall/winter period." (pp. vii, viii)

- "DO concentrations were generally reduced 0 to 30 percent, with 70 percent as a maximum, as water passes through the mussel rafts … While DO may be significantly reduced within the raft, it will generally remain above the biological stress concentration of 5.0 mg/L … [Even during] periods of low ambient DO (late August and early September), concentrations … will likely recover to ambient DO concentration within 70 to 200 m, due to dilution from the entrainment of surrounding waters and from turbulence." (p. 23)

- "In order to evaluate variability about the production and consumption estimates, monthly estimates were calculated for both seasons … For the spring/summer period, consumption of primary production by cultivated mussels was lowest in April and July, with phytoplankton consumption rates of approximately 55,000 kg C/year … Consumption in May, June, August, September, and October ranged from 115,000 to 132,000 kg C/year … Based on the mean and UCI consumption estimates, the proposed mussel rafts [were] predicted to remove 0.1 to 0.4 percent of the primary production for Totten Inlet during the spring/summer period." (p. 79)

- "Phytoplankton consumption was more variable during the fall/winter season, ranging from 3,371 to 19,796 kg C/year … Based on the mean and UCI consumption estimates, the proposed mussel rafts [were predicted] to remove 0.1 to 0.7 percent of the primary production for Totten Inlet during the fall/winter period." (p. 79)

- "Because the removal of phytoplankton production by the proposed rafts occurs over a relatively small area within Totten Inlet, the consumption of plankton was compared to production calculated for smaller portions of the inlet … This comparison assumes a linear relationship between Totten Inlet production and local farm scale production … Average consumption for the spring/summer and fall/winter periods were compared to primary production for a range of areas, from 100 percent of the inlet to 1 percent of the inlet [Figure A]." (pp. 79, 80)

- "Relative to 10 percent of the area of Totten Inlet, the [proposed] rafts [are] predicted to remove 1.1 to 7.3 percent of the seasonal [phytoplankton] production … These comparisons were made with the upper confidence interval values and can be considered a conservative estimate." (New Fields Northwest 2008, pp. 83, 86)

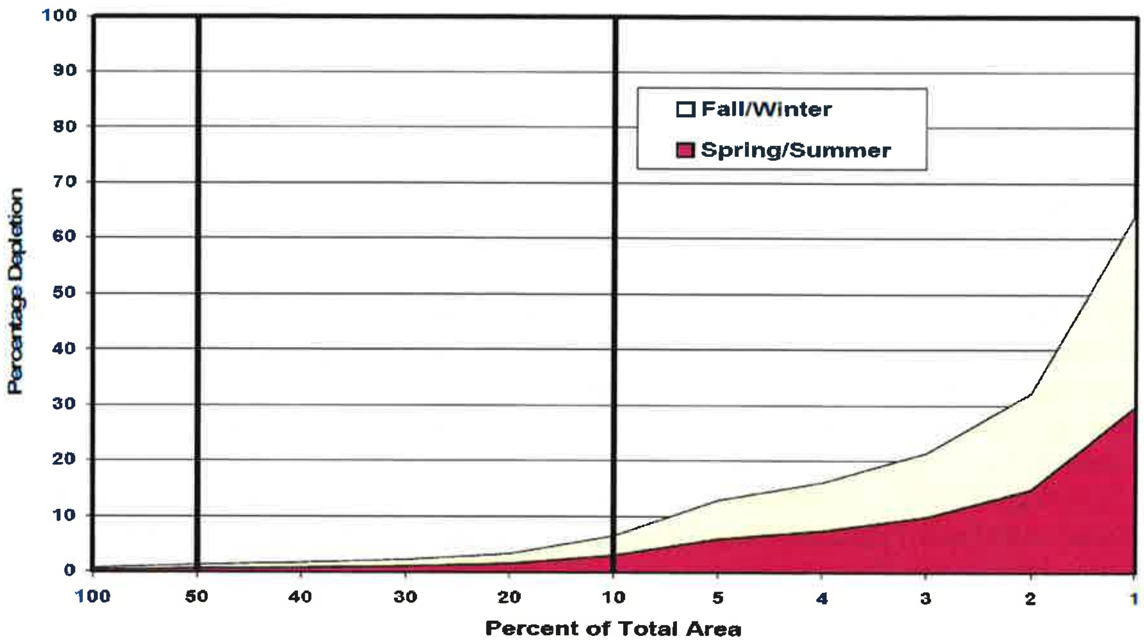


Figure A. Incremental increase in phytoplankton depletion predicted for the proposed north Totten Inlet mussel rafts (New Fields Northwest 2008, p. 81).

Norris, Bannister, and Walker (1998) reported evidence of prey depletion, its relationship to fishery exploitation, and the numbers of oystercatchers remaining on overwintering grounds during the spring:

- "The Burry Inlet estuary in South Wales supports internationally important numbers of oystercatchers *Haematopus ostralegus* during the winter where they feed predominantly on cockles *Cerastoderma edule* … The cockle population has been fished commercially for over a century." (p. 75)

- "The aim of our study was to investigate the relationship between oystercatcher numbers, the biomass of cockles present at the start of the winter, and the biomass of cockles landed by the fishery during the winter … Our analyses are based on data from 11 winters, covering the period 1982/83–1992/93." (p. 75)

- "The abundance of oystercatchers during spring (measured as total bird-days during March and April) was positively correlated with the biomass of cockles at the start of the winter, and negatively correlated with the biomass landed by the fishery over the winter … The most likely explanation for this is that birds disperse from the Burry Inlet earlier in spring when the biomass of cockles at the start of the winter is small and/or the biomass landed by the fishery is large" (p. 75)

- "The most likely causal explanation for this dispersal is that overwinter cockle losses due to predation, fishing, and other sources of mortality cause increased prey depletion when the biomass of cockles at the start of the winter is small … An increase in fishery landings during winter could therefore cause a reduction in oystercatcher abundance during spring." (p. 75)

- "The Burry Inlet cockle fishery is a low intensity fishery, removing < 25 percent of the available stock, and using traditional fishing methods such as hand gathering … Even at these low levels of fishing effort oystercatcher abundance was reduced during spring … The introduction of more efficient modern fishing methods, such as tractor or suction dredging, could therefore cause a decline in the abundance of oystercatchers within the estuary, if the level of exploitation increased as a result." (p. 75)

- "The removal of shellfish by fisheries, and disturbance to feeding birds is … seen as a potential source of conflict between fishery and nature conservation interests … [but] no studies have documented the effect of changes in food supply on bird numbers and how fishing influences this." (p. 76)

- "The autumn food supply and its depletion by exploitation could affect oystercatcher abundance either by influencing the number of birds which settle on the estuary at the beginning of winter, or the rate at which they depart between February and April, or both … Depletion by the fishery over the winter was calculated as the sum landed each month from October to April." (p. 79)

- "The number of oystercatchers wintering in the UK has increased over the 20 years … (Prys-Jones, Underhill, and Waters 1994) … Winter bird-days on the Burry Inlet have increased as the UK population has increased during the mid-1970s to early 1980s, but not subsequently … Winter landings by the fishery have increased significantly over the time series." (pp. 79, 80)

- "Multiple regression analysis provided no evidence that winter bird-days varied significantly in relation to either cockle biomass or winter landings … In contrast, there was evidence that spring bird-days varied in relation to both cockle biomass and winter landings … Although the number of birds arriving on the estuary during winter is independent of cockle biomass and fishery landings, the number remaining during spring does appear to be related to these variables." (pp. 80, 81)

- "Both autumn cockle biomass and winter cockle landings do seem to affect the number of birds left in March and April at the end of the winter … Thus, spring bird-days were positively related to autumn cockle biomass and negatively related to winter cockle landings … Results suggest that the declining trend in spring oystercatcher abundance has resulted from a decline in the biomass of cockles and an increase in the biomass landed by the fishery during the winter." (p. 82)

- "Our results suggest that when cockle biomass the preceding autumn is small and/or when the biomass landed by the fishery over the winter is large, adults returning to their breeding grounds disperse from the Burry Inlet earlier during the February to April migration period … The most likely causal explanation for this link is prey depletion." (p. 83)

- "Even at these low levels of exploitation, fishing reduced oystercatcher abundance during spring … Therefore, it seems likely that the introduction of more efficient modern fishing methods … would cause a decline in the abundance of oystercatchers within [this] estuary in spring … There is clearly a need to consider carefully levels of fishing effort permitted within the Burry Inlet in the future." (Norris, Bannister, and Walker 1998, pp. 83, 84)

Cury *et al.* (2011) considered global trends in seabird response to forage fish depletion:

- "Substantial long-term data sets on seabird breeding success have been compiled for many taxa in several marine ecosystems around the world … We used data from seabird species that have strong dietary dependencies on forage fish prey and where the time series for both the predator and the prey have high spatial and temporal congruence." (p. 1704)

- "Seabird breeding success showed a nonlinear response to changes in prey abundance … The threshold at which breeding success began to decline from the asymptote was not significantly different from the long-term mean of prey abundance … The threshold was 34.6 percent (95% confidence interval 31 to 39%), or approximately one-third of the maximum observed prey abundance." (p. 1704)

- "The asymptotic form of the relationship between seabird breeding success and forage fish abundance has been reported previously … but the common scaling across species and ecosystems, and the consistency of threshold values, are new observations. The global pattern shows a threshold below which the numerical response declines strongly as food abundance decreases, and above which it reaches a plateau and does not change even as food abundance increases." (p. 1704)

- "Periods of consistently high or low breeding success, or occasional complete breeding failures, are normal in seabirds … However, chronic food scarcity, as potentially defined by prey abundance below the threshold described here for seabirds, will compromise long-term breeding success, and this may affect the trajectory of their populations." (p. 1704)

- "The threshold defined by our study suggests that if management objectives include balancing predator-prey interactions to sustain healthy [upper trophic level] predator populations and ecosystem functions, a practical indicator would be to maintain forage fish biomass above one-third of the maximum observed long-term biomass." (Cury *et al.* 2011, p. 1706)

Phillips (1984) described the *Ecology of Eelgrass Meadows in the Pacific Northwest*:

- "The largest meadows of eelgrass in the Pacific Northwest occur in protected estuarine areas away from the open coast … [e.g.,] Padilla and Willapa Bays in Washington State." (p. xii)

- "Eelgrass rhizomes are buried … up to 20 cm (8.0 inches) deep in sediment, depending on the sediment consistency … In firmer substrates, rhizomes may be only half as deep as in soft muddy substrates." (p. 9)

- "Setchell (1929) noted that eelgrass growth was seasonal … While eelgrass activity in the Pacific Northwest does not fit neatly into … intervals, it does appear that eelgrass shows distinct seasonal patterns of activity, particularly in the case of vegetative growth and reproductive cycles." (p. 10)

- "Under most conditions eelgrass forms perennial stands. Under certain conditions of stress, eelgrass may act as an annual plant with a very heavy production of seeds (Felger and McRoy 1975, Mexico; Keddy and Patriquin 1978, Nova Scotia, Canada; Bayer 1979a, Oregon; Jacobs 1982, Europe; Phillips *et al.* 1983b, Washington) … There appears to be a direct relationship between the amount of physical disturbance (high or low water temperatures, intertidal conditions) and a dependence on sexual reproduction (degree of flower and seed production and survival of seedlings) to maintain an eelgrass meadow in the intertidal zone … In the subtidal zone there is a dependence on vegetative growth to maintain the meadows (Philliips 1972; Phillips *et al.* 1983b)." (pp. 11, 13)

- "Seagrasses affect the mean grain size, sorting, skewness, and shape of sediment particles, parameters that influence the redox potential of the sediments and mineral cycling processes (Swinchatt 1965; Fenchel and Riedl 1970; Burrell and Schubel 1977; Kenworthy *et al.* 1982) … Not only do the rooted plants extract and entrap fine particles … and retain particles produced [within] the grass bed … [they also] bind and stabilize the substrate (Burrell and Schubel 1977) … The sediment-microbial-nutrient seagrass complex … develops as a system, and physical disturbances have serious effects on the substrate as a suitable site for seagrass growth … Gross effects of eelgrass on sediment stabilization have been observed. Sand banks, formerly covered by eelgrass, were lowered by 30 cm (12 inches) almost overnight in Salcombe Harbor, Great Britain, after the plants disappeared in 1931 (Wilson 1949) … Many species of filter-feeding invertebrates, mollusks, and several flat fishes also disappeared … Up to 29 cm (8 inches) of sediment eroded from unvegetated sand banks following a single storm in Chesapeake Bay, while little, if any, sediment disappeared from within a nearby eelgrass meadow (Orth 1977a)." (p. 15, 16)

- "Several studies … (Ginsburg and Lowenstam 1958; Fonseca 1981; Fonseca *et al.* 1982a) documented the effect of seagrass leaf canopies on reducing current flow velocity and turbulence … Seagrass stabilizes sediments in two ways: a. leaves slow and retard current flow, reducing water velocity near the sediment-water interface, which promotes sedimentation of particles and inhibits resuspension of organic and inorganic material; and b. rhizomes and roots form an interlocking matrix, which bonds sediment and retards erosion." (pp. 16, 20)

- "Representative densities are reported, but density can vary seasonally, with depth, and with substrate nutrients and texture … As with density values, biomass also varies widely … It appears that the pattern first noted by Ostenfeld (1908) of decreased density on firm sand and increased density on softer substrates maybe the only correlation possible … Most of the biomass of eelgrass is in the sediments … Several factors are directly correlated with eelgrass productivity: light, temperature, carbon supply, nutrient supply, and plant density … Thus, there are hourly, daily, and seasonal differences at local sites as well as over a geographic gradient." (p. 21)

- "Until recently it was difficult to understand how nitrification could occur in the reduced root zone, but Iizumi *et al.* (1980) demonstrated that eelgrass roots excrete O_2 into the anoxic sediments … This creates oxygenated microzones around the roots, resulting in the nitrification of ammonia (which can be readily assimilated by eelgrass roots, rhizomes, and leaves) to nitrate for uptake by roots." (p. 28)

- "Epiphyte biomass at times equals the biomass of the leaves (Marsh 1973; Harlin 1975; McRoy and McMillan 1977) … The epiphytic plants, bacteria, and diatoms … form a brownish felt … This felt shelters and feeds members of the epifauna, as well as many grassbed predators (amphipods and at least four species of ducks and some shorebirds) … Studies [have] identified the specific animals in the epifauna and found that they were the dominant food of fish in the seagrass systems … It is obvious that the role of eelgrass as a substrate for … diatoms, bacteria, detritus, and other algae is of fundamental importance in providing a nursery for juvenile and adult forms of recreationally and commercially important animals … The sessile portion of the community must adapt its life span to the longevity of the blade upon which it grows … The entire food web associated with the blade … is dependent on the development of the microphytic coating … which attach to the blade … Without the initial layer and its ability to colonize and complete a life cycle in a very short time, it appears that much of the nursery and trophic functions of an eelgrass meadow would never develop." (pp. 36-38)

- "For commercially valuable inshore and offshore fish species, the eelgrass meadow is most important in the juvenile stage … [as] a nursery for their development … Orth and Heck (1980) reported a different fish community in eelgrass of the Chesapeake Bay (48 species), but noted similarities in seasonal abundances … They noted that the number of fish species associated with eelgrass was dramatically higher than nearby unvegetated substrates." (p. 48)

- "In the Pacific Northwest, Thayer and Phillips (1977) stated that most of the nekton … conduct diurnal and seasonal movements into and out of the eelgrass … [but] open-water fishes such as Pacific herring and young salmon … are found in eelgrass throughout the year … Habitat complexity, i.e., eelgrass density, its leaf canopy and rhizome-root penetration into the substrate, and epiphyte complex … [is] related to fish abundance and species richness (Brown 1982) … In northern Puget Sound, Miller *et al.* (1975) reported 64 fish species in eelgrass … three spine stickleback, staghorn sculpin, shiner perch, Pacific herring, Chinook salmon, and surf smelt were dominant … They concluded that the eelgrass fish fauna was the richest, most abundant pelagic fish fauna of any sampled … The eelgrass system provides resident fish with superior shelter, food, and protection … These fish probably spend a relatively small proportion of their energy coping with environmental extremes, searching for food, and escaping from predators, and can use a relatively large part of their consumed energy for growth." (Phillips 1984, pp. 49, 50, 53)

Rhoads and Germano (1986) have described infaunal succession and disturbance, and the influence of infaunal assemblages on biotic and abiotic conditions and processes:

- "Organism-sediment relationships which accompany benthic disturbances have predictable features … Infaunal succession in shallow nearshore clastic sediments commonly takes between 1 and 10 years … (McCall and Tevesz 1983) … [There is a] progressive development of the infaunal community over time [(Figure A.)] … [with] different taxa participating in various stages of infaunalization … This primary succession is … the predictable appearance of macrobenthic invertebrates belonging to specific functional types." (pp. 293, 294)

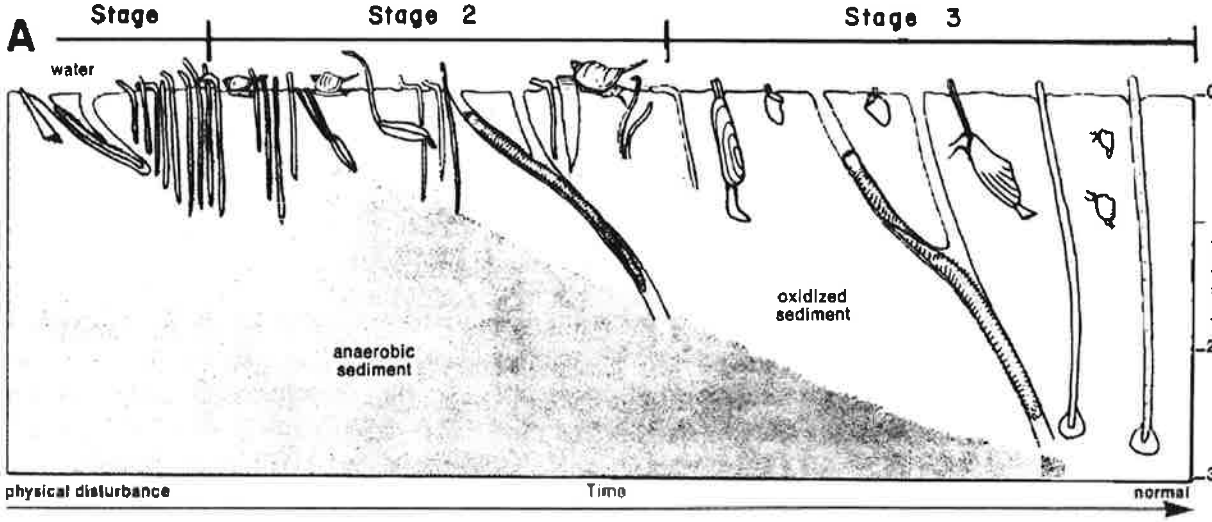


Figure A. Development of organism-sediment relationships over time following disturbance (Rhoads and Germano 1986, p. 294).

- "[Disturbances that cause] long-term degradation … frequently involve the loss of equilibrium species … These high-order seres are replaced by pioneering seres … Changes in organism-sediment relations and population dynamics accompany this change … High-order seres … are deeply burrowing errant or tube-dwelling infauna … for example, maldanid, pectinid, and orbinid polychaetes, caudate holothurians, protobranch bivalves, infaunal ophiuroids, and irregular urchins … [while] early or low-order successional stages … [include] tubiculous polychaetes or oligochaetes … [which] feed at, or near, the sediment surface … A transitional stage [and sere] … [may include] a diverse assemblage of tubiculous amphipods, molluscs, and polychaetes." (p. 295)

- The functional groups that dominate at points along the course of succession influence important benthic ecosystem attributes, including secondary production, nutrient cycling, and hypoxia. "…Pioneering species have very high intrinsic rates of increase, and annual or subannual disturbances may enhance secondary production by stimulating repopulation of newly opened space (Odum 1969; Rhoads *et al.* 1978; McCall and Tevesz 1983) … Recent work has shown that bioturbation is a quantitatively important process for moving water and dissolved constituents into and out of sediments … [at] orders-of-magnitude greater than simple diffusion rates (Lee and Schartz 1980; Aller 1980, 1982) … Sediment irrigation … affects primary production by controlling the flux rate of nutrients … from the bottom back into the water column …[and] pore water chemistry … Burrows and tubes effectively increase the three-dimensional surface area of diffusion." (pp. 291, 298-301)

- "This geometry is best developed in [high-order] Stage III seres and can be quantitatively important for cycling nutrients back to primary producers … [High-order] Stage III seres may play an important role in preventing the build-up of labile organic matter … deep biogenic irrigation of the sediment column increases pore water oxygen … [which counteracts] the potential for developing hypoxic or anoxic conditions." (Rhoads and Germano 1986, pp. 291, 298-301)

Rumrill and Poulton (2004) evaluated eelgrass response on experimental oyster longline plots with variable spacing and density:

- "Progressive mariculture management measures undertaken over the past several years within Humboldt Bay include: (1) conversion of oyster aquaculture activities from bottom to off-bottom culture; (2) elimination of shell deposition as a method to stabilize soft-sediment growing areas; (3) elimination of depredation activities designed to reduce losses of oysters to bat rays; and (4) the phase-out of dredging as [a] method to harvest oysters (Chew, 2001)." (p. 2)

- "It is clear … that intensive commercial cultivation of oysters typically results in chronic and variable levels of disturbance to eelgrass beds and their associated communities (Simenstad and Fresh 1995; Griffin 1997; Dumbauld 1997), and that new best management practices are needed to minimize the adverse ecological consequences … [however,] empirical studies are needed to investigate the ecological impacts of oyster cultivation on long-lines suspended between stakes." (p. 3)

- "Twelve study sites were established in Arcata Bay: (a) 4 experimental Pacific oyster long-line plots (with variable spacings of 1.5 [ft], 2.5, 5, and 10 [ft] between the suspended lines), (b) an adjacent long-line control plot (no oyster lines), (c) an oyster ground culture plot, and (d) six eelgrass study plots (no recent history of oyster mariculture) that are broadly representative of eelgrass beds throughout Arcata Bay … We conducted additional field sampling … to compare eelgrass presence, size, and biomass in the experimental plots …[with] commercial long-line plots." (p. 6)

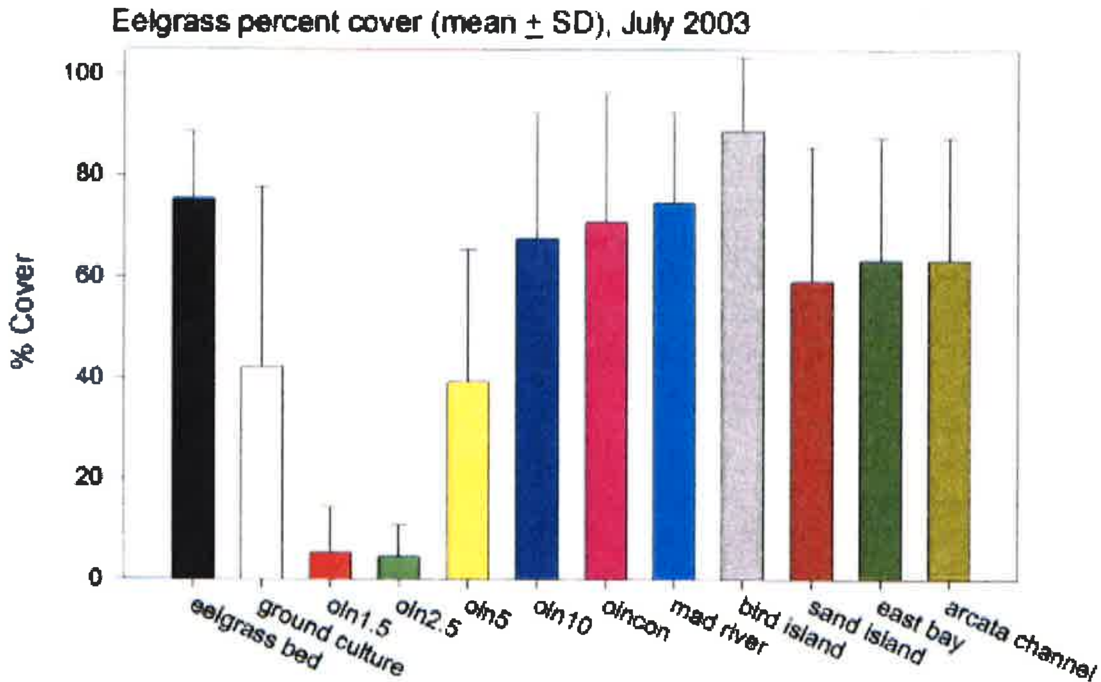
- "[There was] no significant differences in the initial starting conditions of eelgrass beds among the experimental oyster long-line study plots … [but] presence in the eelgrass reference site … was significantly higher than at the experimental oyster long-line spacing plots." (p. 10)

- "Lower eelgrass [percent] cover and density values were generally observed in the study plots in the winter … and higher eelgrass metrics were observed in the spring and summer sample periods … Spatial cover and plant density were … indicative of inherent variability among eelgrass beds." (pp. 10, 11)

- “Spatial cover and density of eelgrass plants exhibited a … response that was directly related to the density of oysters in the experimental long-line study plots … We observed a strong trend toward decreased spatial cover and density … with decreased distance between suspended oyster long-lines … Low eelgrass metrics were consistently observed within the narrow line spacing / high-density oyster plots [1.5 and 2.5 ft], where eelgrass cover was generally less than 15 percent … [However,] eelgrass beds in the ‘wide’ oyster long-line spacing plots [5 ft] were intermediate (35-45 percent cover) … and high spatial cover (55-65 percent cover) and density values … were observed in the ‘very wide’ oyster longline plot [10 ft spacing] … Eelgrass metrics in the wider oyster long-line plots tended to have slightly lower spatial cover values than the reference plots, but were within the range of variation exhibited by undisturbed eelgrass beds.” (p. 11)

- “The intensity of incident light was measured to assess the extent to which suspended oyster long-lines may shade the tideflat surface and impair growth … Light intensity was measured at the sediment surface and at an elevation of 60 cm above the sediment … within three experimental oyster long-line plots [2.5 and 5 ft spacing, control] … Results suggest that the shading effect of oyster long-lines … is probably negligible … [and] factors other than light availability are probably responsible for the reduced abundance of eelgrass in closely-spaced off-bottom oyster culture sites.” (pp. 2, 15, 16)

- “Changes in sediment deposition and erosion were clearly evident in the plots with high densities of oyster lines [1.5, 2.5, and 5 ft spacing] … The seasonal build-up of sediments was particularly evident … around the PVC stakes that support the oyster lines. Substantial and rapid sediment deposition was observed … [but] these soft and flocculent sediments were … [also] eroded away … Sediments were deposited more slowly over time within [the 10 ft spacing] oyster long-line plot.” (Rumrill and Poulton 2004, p. 15)



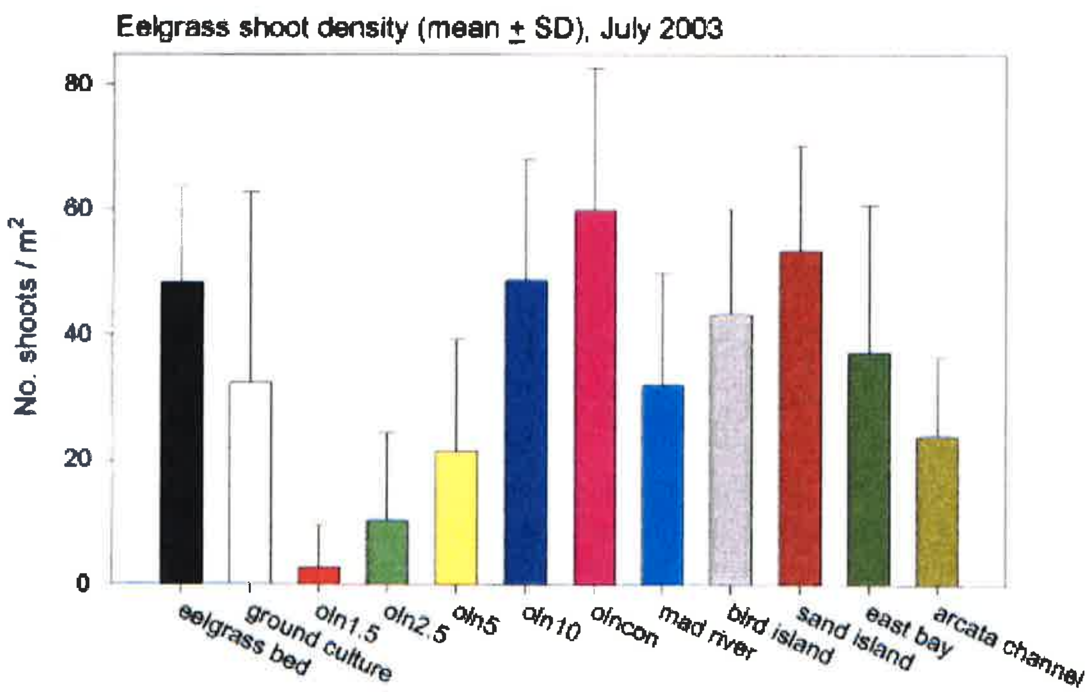


Figure A. Eelgrass metrics among oyster line plots and reference sites (Rumrill and Poulton 2004, p. 33).

Sousa, Gutierrez, and Aldridge (2009, pp. 2367-2385) have described non-indigenous, introduced bivalves as 'ecosystem engineers':

- "Given the usually high densities and broad spatial distributions of bivalves, their engineering activities can significantly alter ecosystem structure and functioning (e.g., changes in sediment chemistry, grain size, and organic matter content via bioturbation, increased light penetration into the water column due to filter feeding, changes in near bed flows and shear stress due to the presence of shells, provision of colonisable substrate and refuges by shells)." (p. 2367)

- "Epibenthic bivalves generally increase the complexity and heterogeneity of rocky and sedimentary substrates (e.g., Commito and Rusignuolo 2000). Accordingly, many epibenthic bivalves enhance organismal density, biomass, and/or diversity both in soft sediments and rocky bottoms of marine and freshwater ecosystems ... Increased bottom complexity and heterogeneity due to the presence of epibenthic bivalves usually, but not invariably, results in increased density, biomass, and richness of associated fauna." (p. 2368, 2369)

- "The fact that many [introduced] bivalve species have positive effects ... does not necessarily mean that they exclusively have beneficial effects on other species. Increases in total invertebrate density and richness after bivalve [introduction] are usually associated with decreases (and sometimes extirpation) of particular species." (p. 2369)

- "Most studies on increases in invertebrate density, biomass, and diversity associated with epibenthic bivalve [introductions] attribute them to increased surface area for recruitment and colonisation (Crooks and Khim 1999) ... [This] mechanism ... is expected to have larger effects in soft sediment systems, where they can provide substrata for the attachment of invertebrates and algae that are usually unable to attach to bare mud or sand (Gutierrez *et al.* 2003)." (p. 2369, 2370)

- "The introduction or addition of epibenthic bivalve shells can increase substrate complexity by creating a diversity of new microhabitats in the form of empty shell cavities and interstices between neighbouring shells (Gutierrez *et al.* 2003) ... bivalve reefs, beds, mats, and empty shell accumulations host a myriad of organisms in these microhabitats (Silver Botts *et al.* 1996; Thayer *et al.* 1997; Sylvester *et al.* 2007; Robinson *et al.* 2007; Werner and Rothhaupt 2007), largely via their roles as refuges from predators and sources of physical or physiological stress (see Stewart *et al.* 1998)." (pp. 2370, 2371)

- "Local increases in sedimentation are a common consequence of aggregations of invasive bivalves that can have important effects on other organisms. For example, reefs of introduced oysters, *C. gigas*, developing on rocky substrates ... trap sediments at higher rates than bare rocky platforms, increasing the habitat available for infaunal polychaetes (Escapa *et al.* 2004)." (p. 2371)

- "While filter feeding per se is not ecosystem engineering but predation, it has knock on consequences on the physical environment that can clearly be seen as ecosystem engineering. This is the case with increases in water clarity, and thus, light penetration into the water column … [which can result] in a shift in primary production away from the phytoplankton and towards the macrophyte community (Phelps 1994; MacIsaac 1996)." (p. 2372)

- "Introduction[s] of a particular species could have dramatically different consequences, depending on local environmental conditions and community composition … The currently broad geographic distribution of … *C. gigas* … provides an excellent opportunity for such spatial comparisons.' (p. 2373)

- "The impact of bivalve ecosystem engineering is not limited to its effects at the scale of colonised patches … it can also affect distant areas (Strayer *et al.* 2004b; Hastings *et al.* 2007) … It would be particularly useful to determine if the impact of some engineering processes that are spatially restricted to bivalve beds (e.g., provision of substrate for attachment, provision of refuges, sediment reworking) can have second- or higher-order, whole ecosystem consequences." (p. 2373)

- "While in some cases enhancement in fish stocks are likely the consequence of fish foraging on [introduced] bivalves … there are cases where fish density increases despite a low incidence of mussels in the fish diet. This suggests that fish enhancement might be occurring in response to increases in the density of other prey that uses the novel shell habitat as substrate or shelter." (Sousa, Gutierrez, and Aldridge 2009, p. 2374)

Speckman, Piatt, and Springer (2004) reported the following:

- "In general, marbled murrelets in Auke Bay and Fritz Cove appeared to be habituated to boat traffic, perhaps more so than murrelets in other parts of Alaska (Kuletz 1996; SGS, pers. obs.). Both motor and sailing vessels comprising a wide range of sizes frequently pass through Auke Bay and Fritz Cove, including 130-m ferries of the Alaska Marine Highway system, commercial fishing vessels, numerous sport fishing charter boats, transient pleasure boats, and hundreds of resident vessels. Of the hundreds of murrelets we encountered with the skiff each day, only a few birds reacted to the moving skiff by flying away; the vast majority merely paddled away, and a few dove briefly before surfacing to paddle away." (pp. 32, 33)

- "However … [marbled] murrelets that were holding fish for chicks appeared threatened by our skiff when we approached them during surveys. On 8 separate occasions … murrelets that were holding fish crosswise in their bills, presumably for chicks, swallowed those fish when approached closely by the skiff. Judging from their behavior, birds that swallowed fish did so because of the approaching skiff." (p. 33)

- "Such disturbance could be detrimental to [marbled] murrelets in areas where prey are relatively scarce, where birds must fly great distances inland to nesting sites, or where boat traffic is concentrated in waters immediately adjacent to nesting areas … The loss of prey … can represent a substantial energetic cost to adults if they have to repeat [the] foraging … to capture another fish … it may be too late to get another prey item for delivery to the chick, and presumably the cost to chicks is even greater than for adults. It is not known whether adult murrelets can make up for these losses. If not, boat disturbance could result in a decrease in food delivery to chicks." (Speckman, Piatt, and Springer 2004, p. 33)

Speich and Wahl (1995) described the marbled murrelet's habitat preferences and variability of occurrence in the inland marine waters of Washington State:

- "Marbled murrelets are found throughout the Puget Sound region, although their distribution varies spatially and temporally (Speich and others 1992; Wahl and others 1981; Wahl and Speich 1983, 1984) … [there is a] breeding population estimated at near 5,000 … [and] evidence of an influx of birds into … [the] Puget Sound during the winter." (p. 313)

- "There are only limited data from the Pacific Ocean coast of Washington … The best data are for the southern outer coast, the coast south of Point Grenville, including the Grays Harbor Channel and habitats in the shelf waters off the mouth of Grays Harbor channel to the continental shelf break (Wahl 1984), and the onshore area in the vicinity of Point Grenville (Speich and others 1987, 1992) … Along the north portion of the coast, the area north of Point Grenville, only limited data are available for the nearshore and offshore waters of the continental shelf (Speich and others 1992)." (p. 314)

- "Open Water Greater than 20 m Depth. In Sequim and Discovery bays, the large sheltered bays at the eastern end of the Strait of Juan de Fuca, marbled murrelets reach peak abundance during the fall period … No other habitat within this habitat group had as high a density, 2.5 birds/km^2." (p. 314)

- "Bays with Steep and Gradual Slopes … High densities of 4 and 5 birds/km^2, were found in habitats on steep slope and sand substrate within Whatcom and Skagit Counties (Chuckanut Bay) and within the San Juan Islands, during the winter period." (p. 314)

- "Areas of Tidal Activity. The occurrence of marbled murrelets in areas of tidal mixing is not unexpected, as these are generally thought of as productive areas where prey concentrate in nutrient and food-rich upwelled or mixed waters. Within Puget Sound, such areas are normally associated with narrow passages or points where currents, and mixing, are intensified." (pp. 314, 317)

- "Shorelines with Narrow Shelf. This group is represented by three specific habitat types, Kelp and Cobble, Cobble and Rock, and Sand and Mud. Within this general habitat group, there is considerable variation in densities … The highest density (19.98 birds/km2) determined for any habitat in Puget Sound occurred in the fall in the Kelp and Cobble substrate in the Whatcom County islands area … A relatively high density (5.05 birds/km2) was also determined for the fall period for Kelp and Cobble substrate in the San Juan Islands. Otherwise, with a couple of additional exceptions, densities of marbled murrelets in this habitat group were generally low." (p. 318)

- "Shorelines with Broad Shelf. This group is represented by four habitat types, Eelgrass and Sand, Kelp and Cobble, Cobble and Rock, and Sand and Mud. Here again the variation in densities of marbled murrelets between and within habitat types is apparent … The highest calculated densities occurred in Eelgrass and Sand substrate in Whatcom and Skagit Counties during the summer, Cobble and Rock substrate of "Assorted Areas" during the winter, and in the Sand and Mud substrate in the San Juan Islands during the fall. The last habitat type had overall the highest determined seasonal densities." (pp. 318, 319)

- "Grays Harbor Channel and Shelf Waters … The highest densities occurred in Grays Harbor Channel, followed by Grays Harbor Channel to 20 m depth, and 20 to 50 m depth. Only rarely were they recorded in deeper habitat areas. The highest densities occurred during the spring months and highest average density occurred in Grays Harbor Channel in March … Interestingly, over a period of 23 years, marbled murrelets were recorded on every census in Grays Harbor Channel in February, March, November, and December." (pp. 319, 320)

- "The overall pattern of abundance (density) and occurrence of marbled murrelets observed in the marine habitats of Puget Sound is one of variability. Our impression of marbled murrelets in Puget Sound before this limited analysis was of a species that moves about a great deal on several temporal scales … Not discounting our general impression of variability, we have noticed that they are often found in specific areas, while other areas are less likely to contain them." (p. 323)

- "Our field observations of marbled murrelets in Puget Sound, during the course of formal censuses and otherwise, suggest that the foraging distribution is closely linked to tidal patterns, in particular to specific locations when tidal flows are clearly evident." (p. 323)

- "As recognized previously, there are seasonal regional patterns in the distribution and abundance of [marbled] murrelets in Puget Sound. Of particular note, are the nearshore subregions along western portion of the Strait of Juan de Fuca where they are found less often during the winter … The densities … suggest a shift of birds from the Strait of Juan de Fuca during the spring and summer periods, to areas in the San Juan Islands and the eastern bays during the fall and winter periods. In addition, as demonstrated in Speich and others (1992), there is apparently an additional influx of marbled murrelets into the latter areas from the north, presumably British Columbia." (pp. 323, 325)

- "There may be several factors that could explain the observed apparent decrease in marbled murrelet abundance in the Grays Harbor study area … [and] continental shelf waters. Some may suggest that the population has been reduced by the accumulative removal of terrestrial nesting habitat areas … [However for] the time period presented (1971–1993), there are recent indications of changes in the marine carrying capacity of waters over the continental shelf and slope, off Grays Harbor and beyond. This is reflected in the recent record low abundances reported for several species of marine birds, birds representing several different foraging techniques and positions in marine food chains, and of various geographic affinity … Although the marbled murrelet is not … [a purely] oceanic species … the documented declines in abundance and local breeding success suggest that fundamental changes in marine systems have occurred, likely expressed by the reduced availability of prey." (p. 325)

- "The patterns of abundance and occurrence presented herein are descriptive in nature, and represent the 'what' … We need to address, as we have started to do here, 'why' marbled murrelets are found distributed as they are." (Speich and Wahl 1995, p. 325)

Stick, Lindquist, and Lowry (2014).

- "Studies indicate that it may be more meaningful to examine abundance trends of Puget Sound herring on a larger scale than the individual spawning stock level presented in this report. An evaluation of Puget Sound herring biomass trends … is presented … [later in] this report." (Executive Summary)

- "Individual stock status classifications since the 2009 status report have exhibited a decrease in the percentage classified as 'healthy' or 'moderately healthy' … while cumulative abundance of all stocks, excluding Cherry Point stock, remained relatively stable." (Executive Summary)

- "The overall abundance of south and central Puget Sound herring stocks since the previous stock status report has decreased, although the cumulative south/central stocks (excluding Squaxin Pass) are still classified as 'moderately healthy'." (Executive Summary)

- "The Cherry Point stock shows no signs of recovery from its critically low level of abundance. The cumulative north Puget Sound regional spawning biomass (excluding the Cherry Point stock) is classified as 'moderately healthy'; the Strait of Juan de Fuca regional spawning biomass continues to be at a low level of abundance (critical status)." (Executive Summary)

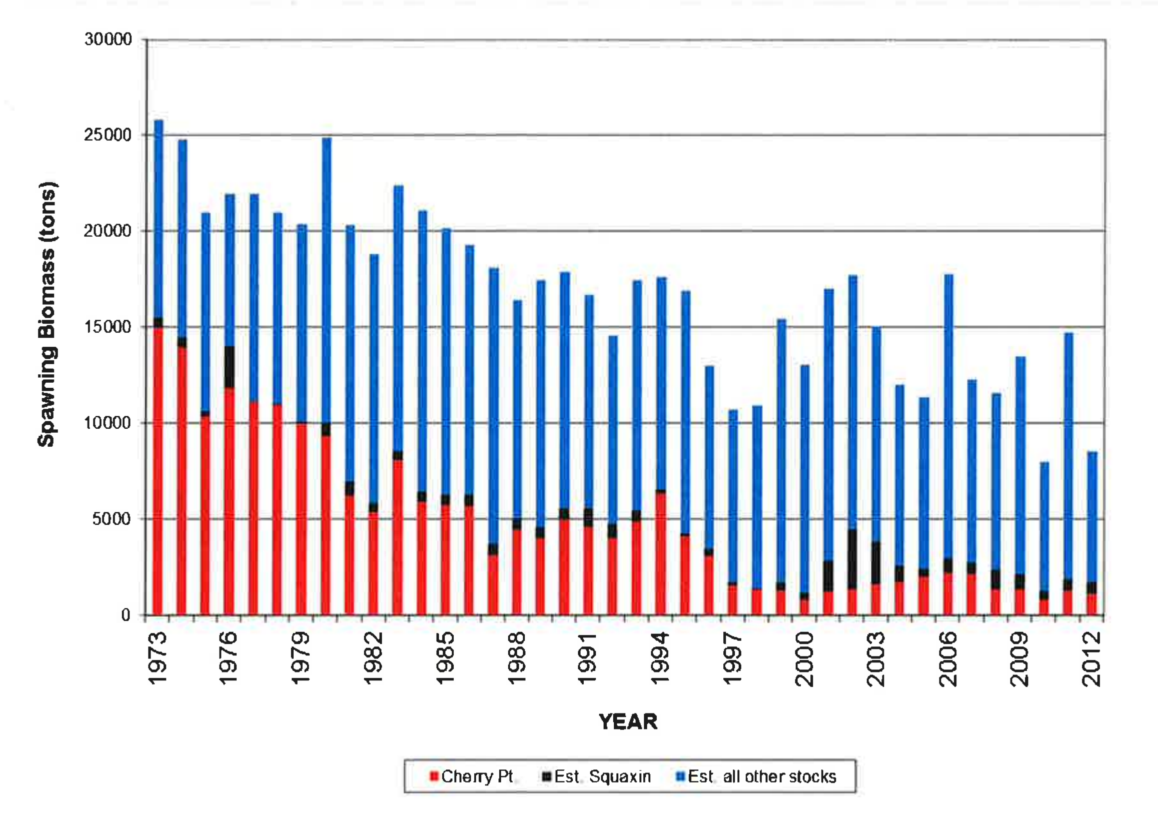


Figure A. Estimated Puget Sound Pacific herring cumulative spawning biomass estimates by genetic grouping, 1973-2012 (missing sample years estimated)(Executive Summary).

- "The stock assessment methodologies and criteria … in this report are generally similar to previous editions … [However,] due to budget reductions … [there was] termination of acoustic/trawl assessment surveys following the 2009 season, which had been conducted on selected Puget Sound herring stocks since the early 1970s. The current assessment is based solely on spawn deposition surveys." (p. 1)

- "Mitchell (2006) … [evaluated] microsatellite DNA loci … [and found] genetic differentiation was consistent … for the Cherry Point stock … [and] Squaxin Pass (Case Inlet) fish … [but] there was a lack of biologically meaningful genetic differentiation among the other area samples in this study." (p. 4)

- "The observed lack of genetic differentiation among other sampled herring stocks from Puget Sound (Quartermaster Harbor, Port Gamble, Kilisut Harbor, Skagit Bay, Fidalgo Bay, and Semiahmoo Bay) suggests sufficient gene flow between populations, particularly those with similar spawn timing … With the exception of Cherry Point, and possibly Squaxin Pass herring, Puget Sound herring stocks may be part of a metapopulation similar to the model assumed for B.C. herring … If Puget Sound herring stocks … interact as a metapopulation … observed 'disappearance' and/or dramatic decreases in abundance of individual stocks (e.g., N.W. San Juan Island, Kilisut Harbor, and Discovery Bay) may not be cause for major concern." (p. 6)

- "The dramatic one-year increase in spawning biomass observed for the Discovery Bay herring stock ... in 2006 may be an example of significant straying of adults to different spawning grounds ... If the majority of the 2006 spawning biomass documented for this area was strays from another stock the identity of this stock is unknown." (p. 4)

- "The Quilcene Bay herring stock is currently the largest in Puget Sound, with mean annual spawning biomass of almost 2,400 tons in the last ten years ... This stock was considered to be one of the largest herring stocks ... [from] the 1930s through the 1950s (Chapman et al. 1941, Williams 1959), followed by a significant decrease in abundance from that time to the mid-1990s ... An observed inverse abundance relationship with the Port Gamble herring stock may indicate spawning stock linkage, with intermixing and straying between spawning grounds probable." (p. 28)

- "Estimated spawning biomass for the Skagit Bay stock since 2009 (i.e., the last season an acoustic/trawl survey was conducted) has dropped by over 50 percent, to less than 500 tons." (p. 38)

- "Formerly considered to be a medium-sized north Puget Sound herring stock, the Fidalgo Bay stock has decreased substantially in recent years. Annual spawning biomass estimates have generally decreased each year since 2001, and dropped below 100 tons twice. Compared to the previous 25 year mean spawning biomass, the 2012 status is very depressed." (p. 42)

- "The ... [Samish/Portage Bay herring] stock has been considered 'moderately healthy' or 'healthy' since stock status classification began in 1994, and continues to be classified as 'healthy' today." (p. 44)

- "The Interior San Juan Islands herring stock is small ... Significant portions of eelgrass beds in Blind Bay previously used for spawning have disappeared." (p. 46)

- "The Northwest San Juan Island herring stock is a small ... A disappearance of extensive eelgrass beds for unknown reasons in Westcott and Garrison Bay ... first reported in 2001, has not shown significant improvement." (p. 48)

- "The Cherry Point herring stock ... Washington's largest herring stock from the 1970s until the mid-1990s ... has decreased dramatically and continues to be in critical condition, showing no signs of increased abundance ... A decrease in available spawning habitat has not been documented for this stock." (p. 52)

- "The Discovery Bay herring stock is traditionally the major Strait of Juan de Fuca stock. Its abundance has fluctuated dramatically since the early 1900s ... [even though] its spawning grounds are considered to be among the most pristine in Washington. Increased pinniped predation and/or movement to other spawning grounds with similar spawn timing are potential causes for biomass decline." (p. 56)

- "The Dungeness/Sequim Bay herring stock … [uses] the westernmost documented grounds for any Puget Sound herring stock. Despite the presence of abundant marine vegetation preferred for spawning in Sequim Bay, only one small spawning event has been documented there since 1994 … A decrease in available spawning substrate has been observed in parts of Dungeness Bay in recent years, but is not considered to be limiting abundance." (p. 58)

- "For the 2011-12 period, there was a continued drop in Puget Sound herring stocks classified as 'healthy' or 'moderately healthy' to 39 percent (7 of 18; 3 stocks with status considered to be 'unknown'). Two herring stocks, N.W. San Juan Island and Kilisut Harbor, have not had detectable spawning activity since 2008 and have a 'disappearance' classification. Sampling effort will continue in these areas to determine if/when a 'recolonization' of spawning herring, similar to that described in British Columbia areas (Ware and Tovey 2004), occurs in the future … The Cherry Point herring stock has shown no signs of improving from its critical status and the stock's smallest estimated spawning biomass to date was documented in 2010 … The other Puget Sound herring stock that appears to be genetically differentiated, Squaxin Pass, has been assessed as 'moderately healthy' at this time although it has exhibited a significant decrease in abundance in the last five years … The Strait of Juan de Fuca region's stock status has been primarily classified as 'critical' since 1994, with the exception of 2006." (pp. 60, 61)

- "Puget Sound Herring Spawning Biomass Estimates, 1973-2012. Pacific herring abundance, as well as that of other forage fishes, has a tendency to fluctuate greatly (Bargmann 1998), as reflected in large annual changes in spawning biomass estimates … As discussed in Stick and Lindquist (2009), it is likely that there is considerable gene flow among various Puget Sound herring stocks … Therefore, the most meaningful way to attempt to determine abundance trends and comparisons for the Puget Sound herring resource using spawning biomass estimates is to group stocks that have not demonstrated genetic divergence … Thus, the Cherry Point and Squaxin Pass stocks can be examined individually with all others stocks grouped together or by region." (p. 63)

- "The obvious decline of the Cherry Point herring stock has been well documented in previous herring stock status reports (Stick 2005, Stick and Lindquist 2009). Estimated spawning biomass for this stock has ranged from a high of almost 15,000 tons in 1973 to a low of less than 800 tons in 2008 … Using only sampled stocks, the cumulative spawning biomass of all other Puget Sound herring stocks combined has not exhibited a decrease similar to the Cherry Point stock, fluctuating between about 10,000 and 16,000 tons ([Figure B])… The south/central Puget Sound region's estimated cumulative spawning biomass has fluctuated between about 6,000 and 11,000 tons since 1973. The highest level for this region was in 2002 with a low estimated in 2010 … Several other of the south/central Puget Sound region's stocks are at record low levels since 2010 (e.g. Quartermaster Harbor, Port Orchard/Madison, and Port Susan)." (pp. 63, 64)

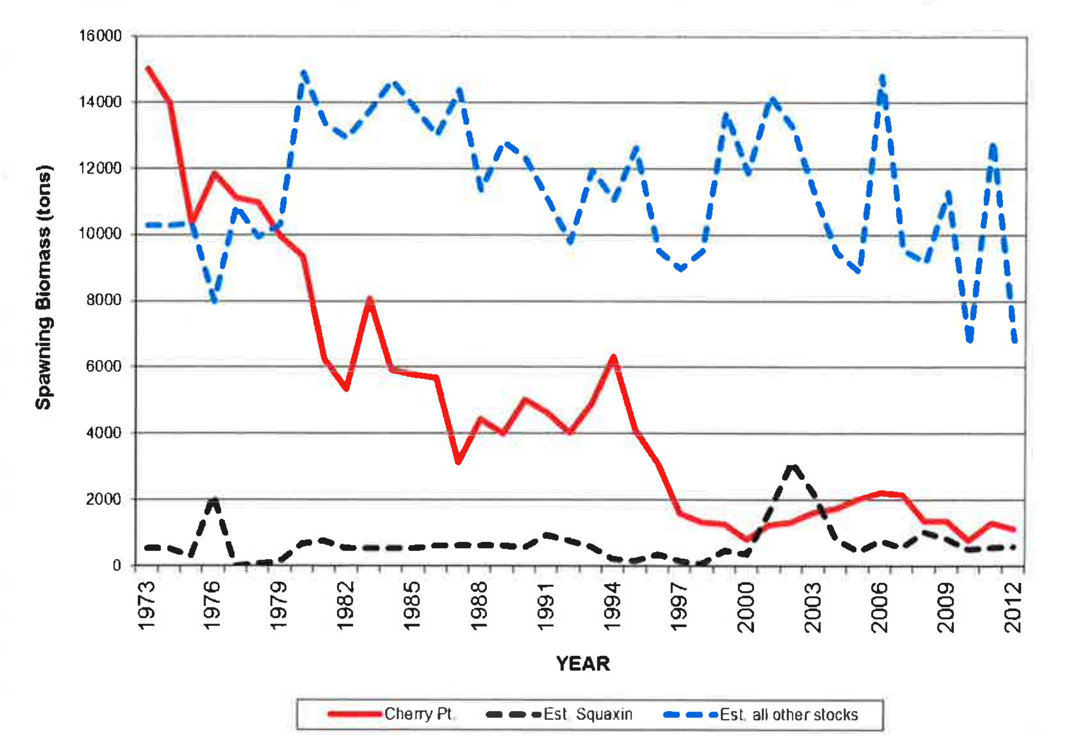


Figure B. Estimated Puget Sound herring cumulative spawning biomass estimates by genetic grouping, 1973-2012 (missing sample years estimated)(p. 66).

- "Recent spawning biomass abundance for the north Puget Sound region, excluding the Cherry Point stock, is lower than a cumulative peak observed in the 1990s … (Fidalgo Bay, Interior San Juan Islands, N.W. San Juan Islands) have been at low levels for a number of years … The cumulative estimated herring spawning biomass for the herring stocks in the Strait of Juan de Fuca region (Discovery Bay, Dungeness/Sequim Bay) continues to be very low compared to the peak period observed in the early 1980s. Extreme fluctuation in the estimated abundance of the Discovery Bay stock … has casted doubt on the amount of natal homing and fidelity for this stock … As previously mentioned, genetic studies have suggested that the Squaxin Pass herring stock is also genetically discrete from other populations. The estimated spawning biomass for the Squaxin Pass stock has fluctuated drastically but has generally been between 500-1,000 tons … The aggregate approach to evaluating herring stock status mentioned above has been used by the Puget Sound Partnership to develop one of their Dashboard Indicators of Puget Sound health (Puget Sound Partnership Vital Signs). The resultant three groups based on genetic sampling are: Cherry Point; Squaxin Pass; and all other stocks combined. Abundance trends for these groupings are essentially the same as described above with the inescapable decline of the Cherry Point stock, the same trend for Squaxin Pass, and a slight decline for all other stocks combined with low cumulative numbers in 2010 and 2012 ([Figure B])." (Stick, Lindquist, and Lowry 2014, p. 64)

Stillman *et al.* (2001) used a behaviour-based model to evaluate the impacts of current and alternative shellfishery regimes on oystercatcher health, mortality, and population size:

- "There has been considerable debate on the consequences of shellfishing for the survival of shorebirds … One long-running contentious issue has been how to manage mussel *Mytilus edulis* and cockle *Cerastoderma edule* shellfisheries in a way that has least effect on a co-dependent shorebird, the oystercatcher *Haematopus ostralegus*, which also consumes these shellfish … This study used a behaviour-based model to explore the effects that the present-day management regimes of a mussel (Exe estuary, UK) and a cockle (Burry inlet, UK) fishery have on the survival and numbers of overwintering oystercatchers … It also explored how alternative regimes might affect the birds." (p. 857)

- "The results suggest that, currently, neither shellfishery causes oystercatcher mortality to be higher than it would otherwise be in the absence of shellfishing; at present intensities, shellfishing does not significantly affect the birds … However, they also show that changes in management practices, such as increasing fishing effort, reducing the minimum size of shellfish collected, or increasing the daily quota, can greatly affect oystercatcher mortality and population size, and that the detrimental effect of shellfishing can be greatly increased by periods of cold weather or when prey are unusually scarce." (p. 857)

- "We built and field tested a behaviour-based model (Stillman *et al.* 2000a) … This can evaluate both current and alternative shellfishery regimes because it incorporates the main bird responses to shellfishing, which are behavioural (Goss-Custard *et al.* 2000) … By coupling the behaviour-based model for oystercatchers with a conventional demographic shellfish population model, the cumulative effects of policy over many years can also be explored for both birds and shellfish … The behaviour-based model predicts the changed intake rates … forced by shellfishing … (Goss-Custard *et al.* 2000)" (p. 858)

- "This study explored the impacts of the present-day management regime of the mussel fishery on the Exe estuary, south-west England … and of the cockle fishery on the Burry inlet, south Wales … on the survival and numbers of overwintering oystercatchers … It also explored the effect on birds of some possible alternative ways of managing these shellfisheries." (p. 858)

- "The model can simulate any type of shellfishing, but here we consider only those that are either currently used on the Exe estuary or Burry inlet, or could be employed were the shellfishery regime to change … Hand-picking and -raking are currently the main ways of fishing for intertidal mussels on the Exe, but dredging is frequently used elsewhere … Currently, only hand-picking occurs on the Burry inlet, but suction-dredging is widely employed elsewhere." (p. 860)

- "These fishing methods influence the shellfish and oystercatcher populations in different ways … Both hand-raking and dredging mussels remove all mussel sizes and so also reduce bed area … Although usually happening at a slower rate, hand-raking mussels can reduce bed area more than dredging … Continued dredging fragments a bed, making submerged mussels increasingly difficult to locate … In contrast, hand-raking can remove complete beds … Both the rate of shellfish depletion and the area of disturbance … increase as the number of fishing units increases." (p. 860)

- "Present-day methods and fishing effort did not affect the body condition of model oystercatchers on either the Exe or Burry … But with increased shellfishing, and the use of dredging, a point came when many oystercatchers could not compensate by feeding for longer or eating more smaller prey … Unsuccessful birds then drew on their energy reserves and so lost mass … The model predicted that increasing fishing effort substantially above current levels would reduce the average mass of surviving birds for all methods, except hand-raking cockles." (pp. 862, 863)

- "The simulations above the current fishing effort and using more intensive techniques, such as suction-dredging, showed that shellfishing can affect oystercatcher survival and numbers, but to different degrees … Mussel-fishing techniques that reduced bed area (hand-raking and dredging) both reduced the food available and forced birds to feed at higher densities, thus increasing both exploitation and interference competition." (p. 865)

- "Although the impact of fishing may often be small within a single year, subsequent fishing may have a greater effect if the oystercatchers or shellfish, or both, do not recover by the following year … The data required to run multiple-year simulations of cockle fishing were not available so long-term effects were explored for the Exe alone." (p. 863)

- "The simulations … showed that relatively small increases in mortality due to intensive shellfishing could indeed greatly reduce population size … Small increases in mortality caused by fishing should not be assumed to be of little importance." (p. 864)

- "Although within-year effects of shellfishing on oystercatcher mortality were sometimes small, their cumulative influence over a number of years could be much larger … In the case of hand-raking mussels, for example, continued fishing caused extremely high bird mortality because mussel populations were unable to recover between years." (p. 866)

- "Small changes in oystercatcher mortality caused larger changes in the long-term population size because the oystercatcher population did not recover from the effects of shellfishing between winters … The model predicted that the impact of shellfishing on oystercatchers depends not only on fishing effort but also on environmental factors such as the weather and overall food abundance." (p. 866)

- "The main new information needed to apply the model elsewhere is either readily available (weather), easily obtained with minimal fieldwork (shellfish bed exposure times), routinely surveyed anyway (shellfish abundance), or becoming much better known (mortality rate) … The model can be applied very rapidly to other systems to … [predict] the effect of a wide range of alternative shellfishery management options, and is currently being used in England, Wales, Northern Ireland, and France." (Stillman *et al.* 2001, p. 866)

Tallis *et al.* (2009) described measures of eelgrass growth, vigor, density, and production on mechanically harvested, hand harvested, and longline cultured oyster beds:

- "If eelgrass impact reduction, rather than avoidance, is identified as the management goal, the degree of tradeoff between eelgrass habitat and oyster production can be minimized by managing aquaculture methods or oyster planting densities, depending on the eelgrass measure of interest." (p. 251)

- "Both on-bottom aquaculture methods (hand picked and dredge) had lower eelgrass densities than uncultivated areas … Although site differences were important, uncultivated areas had three times more eelgrass than nearby dredged beds … Results were less clear for long line beds … Long line practices were associated with eelgrass densities higher than dredged areas, but indistinguishable from hand picked or uncultivated areas" (p. 254)

- "We found that long lines and hand-picking tend to have smaller effects on eelgrass density than dredging. There was no clear link between oysters, aquaculture structures, and eelgrass density in long line areas." (p. 254)

- "When all bed types were considered, our measures of eelgrass growth (2004) all varied with site and aquaculture method … with the interaction between these predictors being important, but weak … Surprisingly, eelgrass relative growth rates were faster in dredged and hand picked beds than in uncultivated areas … [However,] In contrast, all aquaculture areas had smaller plants (above-ground biomass) and lower production than uncultivated areas." (p. 254)

- "Oysters use space in direct competition with eelgrass … Eelgrass shoots cannot grow in areas occupied by shell, so direct … competition [should] lower eelgrass density." (p. 256)

- "Three years of surveys in actively managed oyster aquaculture areas in Willapa Bay … revealed that oysters … and aquaculture methods had identifiable and distinct impacts on eelgrass … density and growth … Most of the relationships were negative, though the direction and magnitude varied depending on the eelgrass parameter and aquaculture method considered." (p. 256)

- "The negative and positive effects of aquaculture on eelgrass are likely caused by the direct disturbance of aquaculture and the indirect response of plants to that disturbance … Although eelgrass does grow back in the beds over time (both via rhizomes and seeds; Wisehart *et al.* 2007), densities may not reach those of uncultivated beds within the typical harvest cycle (approximately 3 years)." (p. 256)

- "Higher growth rates of eelgrass in oyster beds are likely related to lower eelgrass density rather than the direct effect of oysters per se … Eelgrass growth is generally light limited in this region (Thom and Albright 1990, Wisehart *et al.* 2007), so lower eelgrass densities in dredged and hand picked beds … may release individual plants from intraspecific competition, increasing light levels, and leading to higher relative growth rates." (p. 256)

- "Eelgrass biomass and production data show that the slightly higher growth rates in disturbed areas were largely overshadowed by lower density and plant size … Compared with uncultivated areas, we found 70 percent fewer eelgrass plants in dredged beds, and 30 percent fewer in hand picked beds ... In addition, aboveground biomass of individual shoots … was consistently 32 percent lower in all aquaculture areas, showing no variation among aquaculture methods … Production, the measure that integrates eelgrass density, size (biomass) and relative growth rates, also varied strikingly and consistently across aquaculture methods … All aquaculture areas were [approximately] 70 percent less productive than uncultivated areas … In other words, when the cumulative effects of oyster aquaculture (oysters and practices) are considered, higher growth rates in dredged, and perhaps hand picked beds are cancelled out by lower plant densities and size in these areas … As a result, all current aquaculture methods have equal, and relatively large impacts on plant size and eelgrass production." (p. 257)

- "If the best measure of habitat is eelgrass production … we would conclude that all areas used for aquaculture under current practices provide less habitat than uncultivated areas." (p. 259)

- "We show that tradeoffs exist between oyster aquaculture and native eelgrass populations … None of the existing aquaculture methods in this region can be conducted whereas avoiding all impacts on eelgrass … Oysters can be cultivated using long lines with the least impact on eelgrass density, but eelgrass biomass (shoot size) and production will decline (as will eelgrass seed recruitment, Wisehart *et al.* 2007) … Similarly, growing oysters in dredged or hand picked beds can increase eelgrass growth rates, but leads to lower eelgrass density, shoot size, and production … If impact reduction, rather than avoidance, is identified as the management goal, our findings show that the degree of tradeoff between eelgrass habitat and oyster production can be mediated by the aquaculture method used." (Tallis *et al.* 2009, p. 260)

Therriault, Hay, and Schweigert (2009) have reported recent marine forage fish trends in the Salish Sea and their potential significance for seabirds:

- "During the spawning period, when adult herring (>50 g) move inshore and deposit their eggs in the shallow subtidal zone, their eggs are especially vulnerable to predators. The distributions of some waterbirds have been shown to change in response to changes in herring spawn distribution (Sullivan *et al.* 2002)." (p. 3)

- "Changes in spawning location are normal and would be expected if the timing of spawning varies with age structure (Hay 1985), is temperature-dependent (Alderdice and Velsen 1971, Hay 1985), or if variation in tidal cycles affects spawning times (Hay 1990)." (p. 4)

- "Since the late 1980s, systematic changes have occurred in spawn distribution … [and] a reduction in spawning duration has occurred … The implication of these changes for seabirds preying on herring spawn is that access to spawn has been reduced spatially in most areas and restricted temporally in all areas of the Salish Sea." (pp. 4, 5)

- "For seabirds that rely on age 0+ juvenile herring as a key food source, their prey source was seriously diminished, perhaps virtually negligible, in 2005 and 2007. In contrast, the abundance of age 0+ herring in other years was normal to good." (p. 5)

- "Growth of herring and other small forage species is affected by long-term cycles in ocean productivity, as evidenced by coastwide cycles in the size-at-age of herring (Schweigert *et al.* 2002). In the Salish Sea, as in other areas of the west coast of North America, herring size-at-age has declined since the late 1980s ... The implication for seabirds and other predators is that, while numeric abundance of herring has until recently been high, the energy return per unit energy expended by predators may be reduced because of the decrease in size-at-age of the prey." (p. 6)

- "Pacific sand lance is probably a key forage species in the Salish Sea (Willson *et al.* 1999), but quantitative data on their temporal patterns of abundance or distribution are lacking … The accessibility of benthic sand lance in the winter months may be especially important for some seabird predators, because other forage species appear to move to deeper water in winter months and become less accessible to seabirds." (p. 6)

- Northern anchovy and Pacific sardine "…would not be a dependable source of prey in the Salish Sea, because most remain off the west coast of North America." (p. 6)

- "The apparent collapse of the 2005 and 2007 herring cohorts most likely had negative consequences for seabirds that depend on juvenile and older herring … [and] has further implications for seabird predators that prefer older (age 1+) juvenile herring, either for self-feeding or for provisioning chicks (Davoren and Burger 1999, Suryan *et al.* 2000) … Although the specific causes of cohort failures remain unknown, they may be related to changing climate conditions in the Salish Sea." (Therriault, Hay, and Schweigert 2009, p. 6)

Thrush *et al.* (2001) have reported work that examines the often-ignored structural and biological diversity of soft-sediment habitats:

- "We investigated the habitat structure and macrofaunal diversity of relatively simple soft-sediment habitats over a number of spatial scales to identify the role of habitat structure in influencing macrobenthic diversity, and to assess the validity of using habitat structure as a surrogate measure for biodiversity." (p. 255)

- "Soft-sediment habitats are not generally considered highly structured habitats, although they can support high diversity (Etter and Grassle 1992, Coleman *et al.* 1997, Gray *et al.* 1997, Snelgrove 1999)." (p. 255)

- "Perception of habitat structure is of course scale-dependent … Complex seafloor habitats are generally thought of as distinct features such as reefs, kelp forests, or seagrass beds, despite the fact that organisms that modify the 3-dimensional structure above and below the sediment surface are widely distributed … (e.g., Rhoads *et al.* 1977, Reise 1981, van Blaricom 1982, Woodin 1983, Luckenbach 1987, Dame 1993, Graf and Rosenberg 1997, Green *et al.* 1998)." (p. 256)

- "To reach general conclusions on the influence of habitat structure on biodiversity, it is important to assess the role of a variety of features, not just variation in a single element of habitat structure." (p. 256)

- "Our goal was to estimate the relationship between habitat structure and macrobenthic diversity in a coastal environment, contrasting a variety of soft-sediment habitats … We employed a novel, nested sampling design that … allowed us to sample at multiple spatial scales, detecting locally important elements of habitat structure." (p. 256)

- "Macrobenthic diversity and habitat structure varied significantly between sites … Measures of habitat structure based on immobile biological features, sediment particle characteristics, and 'miscellaneous features' all showed differences amongst sites." (p. 259)

- "For all measures of biodiversity, sites with high average numbers of different habitat structural elements had high diversity … [and] the presence of habitat structure elements always had a positive effect on the 4 macrobenthic diversity indices" (p. 260)

- "The results support our prediction that there is a positive relationship between habitat structure and macrobenthic diversity in coastal soft-sediment habitats." (p. 261)

- "Our analysis implies that relatively low-density features creating small-scale structure on the seafloor (e.g., sponges; hydroids; horse mussels) can significantly influence macrobenthic diversity on … [larger] scales." (p. 261)

- "Across different measures of macrobenthic diversity, our results consistently suggest that small-scale macrofaunal biodiversity is affected directly or indirectly by immobile epifauna … 'miscellaneous aspects' … representing small-scale disturbance (e.g., ripples, mounds, feeding pits), and dead bivalve shells." (p. 261)

- "We found local variation in surficial sediment characteristics and the presence of other immobile features, many of which are biogenic, to be strongly related to diversity." (Thrush *et al.* 2001, p. 262)

Tucker and Hargreaves (eds. 2008, pp. 209-212) have provided information regarding lethal and non-lethal control of depredating birds:

- "All fish-eating birds are protected under the Migratory Bird Treaty Act and may not be killed without a depredation permit or depredation order. The U.S. Fish and Wildlife Service (USFWS) has regulatory authority for managing migratory birds. If fish-eating birds are causing problems at an aquaculture facility, the USFWS may issue a depredation permit that allows the producer to kill a limited number of some species to reinforce the effectiveness of nonlethal control measures. Some fish-eating birds also are protected by the Endangered Species Act. For example, wood storks (*Mycteria americana*) found east of the Mississippi-Alabama border receive this protection. No lethal or nonlethal control activities can be used to control any bird species using aquaculture facilities in this region if wood storks are nearby. The Bald and Golden Eagle Protection Act further protects eagles and prohibits all hazing activities near bald (*Haliaeetus leucocephalus*) and golden eagles (*Aquila chrysaetos*), except with special permission from the USFWS."

- "Most passive techniques discourage predation only for a short time because birds quickly lose their initial fear and become habituated to the deterrent device … Even the most aggressive passive deterrence program rarely eliminates wildlife predation and may quickly become ineffective in areas with heavy predation pressure. Active patrols employing nonlethal or lethal measures to reinforce passive measures are usually required for effective, long-term control, especially on large farms."

- "When all measures to disperse birds using nonlethal techniques have been exhausted, farmers may consider … killing birds to reinforce the fear of nonlethal measures. Depredation permits are required from the USFWS and, in some states from the state wildlife agency to kill almost any species of bird. For currently applicable laws, contact the nearest USDA Wildlife Services or USFWS office."

The **U.S. Fish and Widlife Service**'s **Pacific Region Migratory Birds and Habitat Program** provides the following information regarding depradation permits (USFWS 2016):

- "Depredation is a conflict between people and birds resulting in resource damage, economic loss, or a threat to health and human safety … The Depredation Regulation (50 CFR § 21.41) does not specifically define what constitutes depredation, but does require that the "nature of the crops or other interests being injured" be included in the application [for a Depredation Permit]."
- "The Migratory Bird Treaty Act [(MBTA)] protects most native birds in the United States … A list of birds protected by the MBTA is maintained by the U.S. Fish and Wildlife Service."
- "*Do I need a permit to harass, haze, or herd protected birds outside of the breeding season?* No. You do not need a permit to harass, haze, or herd protected birds, with the exception of birds that are actively breeding, eagles, and federally listed species … If you are sure birds are not breeding, any harassment that does not cause physical harm is legal without a permit."
- "*Do I need a permit to harass, haze, or herd protected birds during the breeding season?* Yes. If you are harassing birds that are actively breeding, you may cause abandonment of the nest. Any activity that causes abandonment of eggs or chicks is considered "take", and is illegal. A Depredation Permit is required to perform these activities."
- "*Do I need a permit to capture or kill protected birds?* Yes. If you would like to capture, relocate, and/or kill birds, a Depredation Permit is necessary."

Vilchis *et al.* (2014) recently published work using winter count data collected in the Salish Sea over the period 1994 to 2010, and epidemiological theory and data processing techniques, to evaluate common drivers for declines witnessed in marine avian predators:

- "We identified ecological traits and dietary specializations associated with species declines in a community of marine predators that could be reflective of ecosystem change … We propose that changes in the availability of low-trophic prey may be forcing wintering range shifts of diving birds in the Salish Sea … a large transboundary marine ecosystem in North America's Pacific Northwest." (p. 154)

- "Since the mid-1970s, fewer marine birds have been overwintering in the Salish Sea—an important staging area for numerous marine bird species wintering in the North American portion of the Pacific Flyway (Anderson *et al.* 2009; Bower 2009; Crewe *et al.* 2012) … Most marine birds are long-lived, migratory, and at upper levels of food webs, and therefore ideal indicators of changing productivity and ecosystem structure across broad spatial and temporal scales … Investigating ecosystem-level drivers of species abundance and distribution is most revealing when multiple species and broad spatial and temporal scales are examined … We analyzed … longitudinal data sets and interpreted wintering marine bird trends using an epidemiological framework—relating the incidence and distribution of unfavorable outcomes (i.e., species with regional declines past a meaningful threshold)—to determine ecological correlates." (p. 155)

- "We investigated two potentially complementary hypotheses that explain seabird declines in other ecosystems: declines in marine bird biomass are linked to changes in the availability of their low tropic-level prey (Cury *et al.* 2011; Smith *et al.* 2011), and species-specific energetic costs during foraging bouts determine the type of species assemblages most likely to respond to changes in prey availability (Ballance *et al.* 1997; Hyrenbach and Veit 2003; Ainley and Hyrenbach 2010)." (p. 156)

- "We assessed what types of diets, behaviors, and habitats increased the likelihood of particular bird species to decline … We evaluated the following ecological traits as risk factors associated with declining species: primary foraging method, prey preference, breeding status in the Salish Sea … and use of particular Salish basin-depth habitats." (p. 158)

- "The hypothesis associating changes in community structure of marine birds with bottom–up or top–down driven changes in prey availability (Ballance *et al.* 1997; Hyrenbach and Veit 2003; Ainley and Hyrenbach 2010), predicts that declines in population size due to changes in food availability are most extreme in species with higher foraging energy expenditure, namely diving birds with high wing loadings. Our results are consistent with this hypothesis … Diving species accounted for 93 percent (62 of 67) of all declines, whereas 7 percent (5 of 67) of declines occurred in surface foraging species … Declines were most prevalent among Alcids. Other diving species such as grebes, diving ducks, and loons also exhibited declines." (p. 158, 159)

- "Ecological traits as risk factors … were strongly associated with foraging strategy, dietary specialization, and local breeding status. Specific traits associated with declines included diving as a primary foraging strategy, diets of forage and demersal fish, and whether species breed locally within the Salish Sea … The full model indicated that diving birds wintering in the Salish Sea were approximately 11 times more likely to have undergone declines in their winter counts compared with surface-foraging species, such as dabblers, scavengers, and surface seizing or intertidal foraging birds … Bird species feeding on forage fish were approximately 8 times more likely to have undergone declines than species that do not feed on forage fish." (p. 159)

- "In the case of locally breeding piscivorous divers, species including demersal fishes in their diet (e.g., pigeon guillemots [*Cepphus columba*] and double-crested cormorants [*Phalacrocorax auritus*]) had a predicted probability of undergoing regional declines of 2 percent, versus 27 percent for diving forage fish specialists (e.g., marbled murrelets [*Brachyramphus marmoratus*] and rhinoceros auklets [*Cerorhinca monocerata*])." (p. 160)

- "Our results reinforce previous spatially restricted research that suggests abundance of wintering marine birds in the Salish Sea has been declining since the mid-1990s. At the larger regional scale, our results indicate that these patterns have been consistent throughout the entire Salish Sea … Species with declining trends were not from random assemblages; instead, they were correlated with specific ecological traits and dietary specializations. In particular, pursuit divers that primarily feed on forage fish." (p. 161)

- "We propose that shifts in the availability and quality of low trophic level prey could explain why diving forage fish specialists were less likely to overwinter in the Salish Sea … Regarding forage fish availability, half of all Pacific herring (*Clupea pallasii*) stocks in Puget Sound are either depressed or have such low abundance that recruitment failure is likely or has already occurred (Stick and Lindquist 2009), and in British Columbia the only herring stock within the Salish Sea is experiencing marked declines (Schweigert *et al.* 2010). Large herring have also proportionally declined in the Salish Sea (Therriault *et al.* 2009), which may decrease diet quality and calories per catch for diving forage fish specialists (Norris *et al.* 2007; Schrimpf *et al.* 2012)." (p. 161)

- "The eastern Pacific did revert to cool and more productive conditions in late 1998 (Bond *et al.* 2003; Chavez *et al.* 2003), as is indicated by the change in the Pacific Decadal Oscillation to a cold phase that mostly persisted through 2010. A change that perhaps is drawing diving forage fish specialists to overwinter in the California Current as a result of poor forage fish prey conditions in the Salish Sea." (Vilchis *et al.* 2014, p. 162)

Wagner *et al.* (2012) evaluated density-dependent effects of oyster cultivation on native eelgrass:

- "[There is] scientific uncertainty about the degree of tradeoff between sea grasses and bivalves." (p. 149) "We manipulated the structural and biogeochemical aspects of oysters in a crossed experimental design … We added oysters across a range of densities. A key consideration for the coexistence of bivalves and eelgrass involves the functional shape of potential tradeoffs (Koch *et al.* 2009) … specifically, thresholds beyond which eelgrass responds more strongly than expected from the effects of displacement and space competition with bivalves alone." (p. 150)

- "Five replicate plots were designated randomly among 6 treatments: eelgrass control, 30 percent live oyster (low-density), 70 percent live oyster (high-density), 70 percent empty shell, 70 percent empty shell plus nutrients, [and nutrient addition alone] … [Oysters] were spread across the plots singly and unattached." (p. 151)

- "A [second] experiment was set up to record responses of eelgrass to live oyster addition simulating typical aquaculture densities and procedures, in which shell with juvenile oysters (cultch) is distributed on the sediment, and the oysters increase in size over several years prior to harvest." (p. 152)

- "Steep declines [in eelgrass shoot density and size,] indicating density-dependent space competition, occurred at different thresholds after 1 (1.3 percent oyster cover), 2 (12.4 percent), and 3 years (21.9 percent)." (p. 149)

- "Structure emerged as a likely factor underlying space competition in our experiments … Eelgrass responded to the presence of oysters (both live adults and empty shells) by reducing shoot density and size." (p. 157)

- "We found that 1:1 tradeoffs in space occupancy do not describe the interactions … One year after treatments were established … the decline in eelgrass shoot density exceeded the cover of oysters even at low oyster shell cover (≤ 5 percent) … The superior fit … models relating eelgrass density to oyster cover … [show] exponential declines in eelgrass shoot density when oyster cover exceeded 10 to 20 percent … This experimental result corresponds to a negative interaction strength that changes with density." (p. 158)

- "Our results indicate that low densities of oysters can be compatible with eelgrass … but that tradeoffs reliably occur both after initial establishment and above 20 percent oyster cover. Oyster cover >50 percent is essentially impenetrable by eelgrass … Current onground oyster culture practices in Willapa Bay typically result in oyster cover that starts below 20 percent … and then oysters grow and cover increases (average 20 percent, range = 5–35 percent cover) … Cover can be 100 percent when oysters are left to form patchy reefs or hummocks, as occurs in the southern half of Willapa Bay (Dumbauld *et al.* 2006)." (p. 158)

- "Ecological consequences … are likely to be location-specific and density dependent … [but] our results indicated disproportionately large tradeoffs between space occupants at high oyster density." (Wagner *et al.* 2012, p. 158)

Willner (2006) discussed the effects of geoduck dive harvest:

- "This method of harvesting is considered to be the most environmentally benign method available (Palazzi *et al.* 2001)." (p. 11)

- "[However,] The physical disturbance associated with … geoduck harvest has the potential … [to alter] the availability and distribution of physical microhabitat and biogenic structures." (p. 2)

- "Sediment Structure. Disturbances, such as geoduck harvesting, homogenize the area by breaking up structures and disturbing materials … reducing the structural complexity of the area (Hewitt *et al.* 2005) … As the water jet overturns sediments, organic material and organisms in and adjacent to the harvesting hole are resuspended and/or buried." (p. 31)

- "Large sediment particles … may have sinking rates of 105 centimeters/second with a probability of settling rapidly within the area that is disturbed, whereas, clay and fine particles resuspended at the same time settle at a slower rate … and therefore may be carried away from the area (Pilskaln *et al.* 1998) … With larger particles settling quickly and finer materials being carried away, the result is a larger sediment grain composition with a lower concentration of nutrients." (pp. 31, 32)

- "The resuspended sediment settles in an unconsolidated form and is susceptible to resuspension and erosion by currents and waves … The State of Washington *Commercial Geoduck Fishery Supplemental Environmental Impact Statement* (Palazzi *et al.* 2001) reported that the silt and clay content of undisturbed substrate averaged 3.5 percent, whereas the average found in the immediate harvested area is 2.3 percent (Palazzi *et al.* 2001)." (p. 32)

- "Water jet harvesting causes the sediment to lose adhesiveness by breaking the mucilaginous bonds between particles, making the sediment more susceptible to erosion and resuspension, which increases … the release of nutrients … Resuspension of 1 millimeter of surface sediment may potentially double the nutrient flux into the water column … (Pilskaln *et al.* 1998)." (p. 33)

- The activity overturns anaerobic sediments, from below the oxidized top layer, into the aerobic sediment water interface. "Artificially resuspended sediments have important implications for nutrient cycling (Pilskaln *et al.* 1998) … Resuspension can result in higher nutrient concentrations in the water column by releasing nutrient rich pore water, desorption or absorption of nutrients from or to particles, and stimulated remineralization with oxidization in the oxygen rich water column (Tengberg *et al.* 2003) … Nutrients are naturally released from the sediment pore water through diffusion; however, a disturbance resuspending as little as 2.4 centimeters of sediment would significantly increase the amount of nutrients available in the water column (Tengberg *et al.* 2003) … [and] Studies have shown that resuspension can increase oxygen consumption in the water column by 10 times … (Tengberg *et al.* 2003)." (Willner 2006, pp. 34, 45, 46)

Wisehart *et al.* (2007) described seed production, seedling densities, natural recruitment, and recovery of eelgrass in dredge harvested and longline cultured oyster beds:

- "Dredge harvesting typically occurs during winter months, when above-ground shoot densities are lowest; however, some above and below-ground plant structures may still be removed during the harvest dredging operation (Simenstad and Fresh 1995)." (p. 72)

- "In some areas, 'off-bottom' methods (e.g. longlines, stakes, and racks) are implemented due to unsuitable conditions for ground culture (Simenstad and Fresh 1995); however, in Willapa Bay, both on- and off-bottom culture occur intermixed on tideflats and, over time, even on a single bed (J. Ruesink pers. obs.)." (p. 72)

- "Eelgrass meadows can grow and persist by vegetative spread (Bell and Tomlinson 1980, Hemminga and Duarte 2000), but the establishment of new meadows is controlled by seed recruitment (Orth *et al.* 2006a) … Seeds are especially important in re-establishing meadows that are subject to seasonal perturbations or other disturbances that reduce eelgrass biomass (Thayer *et al.* 1984, Plus *et al.* 2003) … Dredge harvesting of oysters reduces eelgrass biomass and shoot density, but oyster growers have reported that eelgrass rapidly reappears in areas planted with oysters, anecdotally suggesting that eelgrass recruitment is high into these disturbed areas … There are two potential mechanisms to explain high recruitment: (1) oysters influence eelgrass seed production, seed germination, and/or seedling survival by altering the nutrient or light environment through filter feeding and feces/pseudofeces deposition (Reusch *et al.* 1994) or by trapping/protecting seeds, and (2) aquaculture disturbance affects eelgrass seed production, seed germination, and/or seedling survival by removing neighboring adult eelgrass plants or modifying the physical characteristics of the environment (e.g. loss of fine sediments following dredge harvest)." (p. 72)

- "Significantly fewer seedlings were observed in the longline beds compared to [both] the dredged and reference beds, which did not significantly differ." (p. 74)

- "Flowering shoot densities were similar among dredged, longline, and eelgrass reference areas … However, seed production varied significantly between the aquaculture types and reference areas … More seeds were produced in the dredged beds than in the reference beds, and lowest seed production occurred in the longline beds." (p. 74)

- "Observational and experimental results showed that seedlings are most abundant and have higher initial success in dredged beds compared to longline culture areas." (p. 77)

- "We found higher seedling densities in dredged beds that had low density of adult plants compared to reference areas where adult density was significantly greater … Furthermore, when neighbors were removed, seedlings survived better … and were significantly larger … Dredge harvest of oysters, which results in decreased eelgrass density due to the removal of aboveground plant structures, may facilitate seed germination and/or seedling growth and survival, by reducing competition for light or other resources." (p. 77)

- "We observed very few naturally recruiting seedlings in longline areas, and survivorship of seedlings in longline seed addition plots was zero … The pattern of low seedling abundance in the longline beds and higher densities in dredged areas may be due to differences in seed supply … Our data suggest that seed production and seed bank densities are high in dredged areas compared to longline areas … Low seed densities in longline areas may be related to elevation, or other factors associated with the longline structures … Longlines may also act as 'clotheslines,' causing plants to become entwined in the ropes at high tide resulting in severe desiccation at low tide, thus reducing the density of both vegetative and flowering shoots (Pregnall 1993, Everett *et al.* 1995)." (p. 78)

- "Seed dispersal and deposition in longline beds may be limited due to altered water flow … the reduction in flow causes longline areas to accrete sediment at much greater rates than would naturally occur (Everett *et al.* 1995) and could lead to burial of seeds and young seedlings." (p. 78)

- "More attention should be paid to the mechanisms of recovery of eelgrass and how these mechanisms interact not only with the type of aquaculture disturbance produced but the spatial and temporal scales over which it occurs (Simenstad and Fresh 1995, Neckles *et al.* 2005)." (p. 78)

- "Previous work has shown that recovery periods for eelgrass following oyster harvest vary depending on a combination of factors, including the type of oyster culture, duration of culture, spatial configuration of culture operations and nearby meadows, and the frequency of oyster harvest events (Waddell 1964; Orth *et al.* 2002)" (p. 78)

- "[For] eelgrass populations subject to disturbance from oyster harvest … large contiguous eelgrass meadows surrounding the impacted areas may provide a seed source that could facilitate recovery of the disturbed beds." (p. 79)

- "Our data have important management implications … but we know little about how these results vary among sites (either within or among estuaries) … Tidelands used for aquaculture in Willapa Bay comprise a mosaic of disturbance … some beds may have little to no eelgrass cover due to frequent harvest and management activities, while other beds are left unmanipulated for long periods, enabling dense stands of eelgrass to form and persist." (Wisehart *et al.* 2007, p. 79)

Zydelis *et al.* (2009) have reported:

- "Shellfish aquaculture typically occurs in shallow, nearshore waters, which also tend to harbor the greatest densities and diversity of marine birds. However, only a relatively small number of studies have evaluated the effects of shellfish aquaculture on birds. To date, bird responses to the presence of shellfish aquaculture structures have been shown to vary, with the abundance and density of some species increasing in association with aquaculture and other species decreasing (Hilgerloh *et al.* 2001; Connolly and Colwell 2005). Most studies have described the effects of shellfish aquaculture as being neutral (Roycroft *et al.* 2004; Zydelis *et al.* 2006) or even beneficial (Caldow *et al.* 2003; Kirk *et al.* 2007). The nature of the relationship depends on the bird species involved, the type and intensity of activity, and the habitats affected. Additional studies of interactions between shellfish aquaculture and bird populations are clearly warranted, to fully understand the degree and direction of any effects, and the underlying mechanisms by which effects are manifested." (p. 2)

- "Sea ducks are … particularly likely to interact with the shellfish aquaculture. These birds are inextricably linked to … the same areas where most shellfish aquaculture occurs. In addition, both sea ducks and shellfish mariculturists tend to use coastal areas that are highly productive and offer some degree of protection from open ocean wind and waves. Finally, sea duck diets include high proportions of bivalves, making them potential predators of farmed shellfish." (p. 2)

- "Shellfish aquaculture could negatively affect sea ducks through habitat transformation or exclusion, or by disturbance arising from farming activities and boat traffic. Much of the literature to date has focused on marine waterfowl depredation of cultured bivalve stocks, which in turn sometimes leads to active disturbance or exclusion by shellfish farmers (Vermeer and Morgan 1989; Thompson and Gillis 2001; Caldow *et al.* 2004; Dionne 2004)." (p. 2)

- "The results of [our] study indicate that both sea duck species, surf scoter [*Melanitta perspicillata*] and Barrow's goldeneye [*Bucephala islandica*], were strongly attracted to shellfish aquaculture operations … The strong positive relationship observed between shellfish aquaculture and sea duck densities is almost certainly explained by the introduction of novel structures that become heavily fouled with mussels, the primary food of both Barrow's goldeneyes and surf scoters in wintering areas with rocky shorelines (Vermeer 1981, 1982; Vermeer and Ydenberg 1989)." (pp. 6. 7)

- "Sea duck predation on epifauna, chiefly wild mussels fouling aquaculture structures, was not negatively perceived by shellfish farmers ... on the contrary [they] appreciated birds cleaning their equipment of unwanted ballast." (p. 8)

- "Positive interactions between industrial development and wildlife populations are ... rare ... Careful consideration will be necessary to maintain this positive interaction ... The mussel culture industry in British Columbia is increasing (Salmon and Kingzett 2002), which in turn could lead to conflict if sea ducks start consuming significant amounts of cultured mussels." (Zydelis *et al.* 2009, p. 9)

Zydelis, Small, and French (2013, p. 82) have reported:

- "Common guillemot remains the species most frequently caught in coastal gillnets in Washington State and British Columbia. Hamel *et al.* (2009) assessed marine bird strandings in the Salish Sea area and found that common guillemot carcass records were frequently associated with bycatch, and that such mortality added 0.2–2.9 percent to annual mortality rates. In Puget Sound, 109 birds, mostly common guillemots, were recorded caught in non-tribal salmon fishery in 1993 by monitoring 606 sets or about 1.5 percent of fishing effort (Pierce *et al.*, 1994). Similarly, Beattie and Lutz (1994) found that common guillemots and rhinoceros auklets (*Cerorhinca monocerata*) frequently entangle in salmon nets of tribal fisheries: 128 birds were recorded in 184 observed sets. Due to declining salmon stocks fishing effort has been decreasing in Washington State in both tribal and non-tribal fisheries – 5 to 10-fold between the 1980s and the late-1990s (McShane *et al.* 2004). The risk of bycatch of marbled murrelets (*Brachyramphus marmoratus*) prompted introduction of fisheries regulations to reduce bycatch in Puget Sound starting from 1999, but these regulations affected only state-regulated fisheries and were not immediately adopted by tribal fisheries, nor fisheries in neighbouring British Columbia (Harrison 2001). We found no information about levels of compliance since then."

- "Similarly, in the assessment of seabird bycatch in British Columbia, Smith and Morgan (2005) found that common guillemots were the most frequent victim in salmon gillnet fisheries. The authors estimated that on average 12,085 seabirds were caught annually during 1995–2001, 69 percent being common guillemots, 23 pecent rhinoceros auklets, and lower numbers of marbled murrelets, sooty shearwaters (*Puffinus griseus*), pelagic cormorants (*Phalacrocorax pelagicus*), pigeon guillemots (*Cepphus columba*), common loons, pacific loons (*Gavia pacifica*), Brandt's cormorants and Cassin's auklets (*Ptychoramphus aleuticus*)(Smith and Morgan, 2005)."

- "The declining marbled murrelet has been extensively studied along the west coast of North America. Due to reduced fishing effort and fisheries restrictions gillnet mortality has decreased recently in California, Oregon, and Washington compared to bycatch in the 1980s and 1990s, and latest gillnet mortality levels are not considered responsible for the continuing population declines (McShane *et al.* 2004). Through extensive review of population status and threats Piatt *et al.* (2007) concluded that annual bycatch mortality of marbled murrelets is ‘likely in the low thousands per year’ in British Columbia and Alaska … Authors [have] suggested that bycatch, along with oil pollution and competition with fisheries, is unlikely to account for the observed population decline alone (Piatt *et al.* 2007).” (Zydelis, Small, and French 2013, p. 82)
