Research Article

Habitat Use by Wintering Surf and White-Winged Scoters: Effects of Environmental Attributes and Shellfish Aquaculture

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Abstract

*Shellfish aquaculture is an expanding industry in coastal British Columbia, Canada, and occurs in important wintering areas for surf scoters (*Melanitta perspicillata*) and white-winged scoters (*M. fusca*). We quantified habitat use by scoters in relation to natural environmental attributes and habitat modifications associated with shellfish aquaculture. We found that, despite the extensive clam and oyster farming in our study area, densities of wintering surf scoters and white-winged scoters were related primarily to natural environmental attributes, particularly intertidal area, clam density, and sediment type; shellfish aquaculture variables were generally poor predictors of bird densities. We conclude that current levels and forms of shellfish aquaculture in our study site were not an important determinant of scoter distribution and abundance, suggesting that winter scoter populations and the shellfish aquaculture industry may be mutually sustainable. We caution that intensification or further industrialization of shellfish aquaculture in British Columbia could eventually lead to detrimental effects if some threshold level of habitat modification is exceeded.* (JOURNAL OF WILDLIFE MANAGEMENT 70(6):1754–1762; 2006)

Key words

British Columbia, habitat use, Melanitta fusca*,* Melanitta perspicillata*, shellfish aquaculture, surf scoter, white-winged scoter.*

In coastal British Columbia, Canada, some nearshore habitats have been modified for the benefit of the commercial shellfish aquaculture industry. This industry is expanding, leading to questions about potential effects on wildlife populations, as well as other environmental impacts. Previous research has suggested that a different form of commercial shellfish exploitation, harvest of wild shellfish stocks, can have deleterious effects on bird populations. For example, overharvesting of bivalves in the Dutch Wadden Sea was thought to be the main cause of starvation, mass mortality, and reduced reproductive output of common eiders (*Somateria mollissima*), and reduced condition and survival of oystercatchers (*Haematopus ostralegus*; Camphuysen et al. 2002, Oosterhuis and Van Dijk 2002, Verhulst et al. 2004). Similarly, in the Wash, England, commercial wild harvest of cockle and mussel stocks has been associated with decreased survival of oystercatchers and reduced recruitment by oystercatchers and knots (*Calidris canutus*; Atkinson et al. 2003). However, harvesting wild bivalve stocks is different from shellfish aquaculture with respect to the mechanisms that affect waterbirds; the former relates to direct and potentially extensive loss of food resources, whereas the latter is related to modification of foraging habitats. Although several authors have speculated that shellfish aquaculture practices in coastal British Columbia could have negative effects on bird populations (Bourne 1989, Vermeer and Morgan 1989, Price and Nickum 1995, Bendell-Young 2006), directed studies on the interactions between shellfish farming and bird populations are lacking.

We conducted this study to quantify relationships between the shellfish aquaculture industry and habitat use of surf scoters (*Melanitta perspicillata*) and white-winged scoters (*Melanitta fusca*). We conducted our research in Baynes Sound (Fig. 1), British Columbia, Canada, an important area both for the shellfish aquaculture industry and for wintering scoters. Baynes Sound produces approximately 50% of British Columbia's cultured shellfish (Ministry of Sustainable Resource Management 2002), with Manila clams (*Venerupis philippinarum*) and Pacific oysters (*Crassostrea gigas*) accounting for the vast majority of the crop. Unlike most of coastal British Columbia, Baynes Sound is particularly suitable for clam culture because of the presence of broad intertidal flats with sand and gravel sediments. Baynes Sound is also recognized as a globally significant area for scoters (Booth 2001), with thousands of surf and white-winged scoters wintering in the area, where they forage primarily on clams (Lewis et al. 2006). Scoters are of conservation concern continentally due to long-term, broad-scale numerical declines (Sea Duck Joint Venture 2003, 2004), the causes for which are unknown. A lack of data on the basic biology of scoters has hampered researchers' efforts to discern mechanisms leading to reductions in scoter

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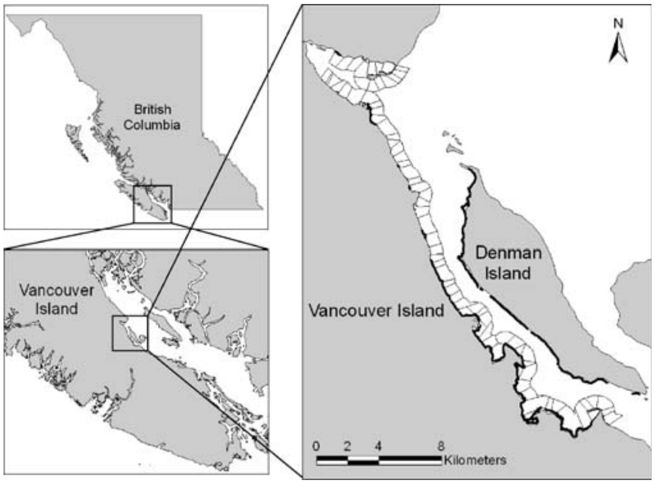

Figure 1. Geographical location of Baynes Sound, with index maps of the southern half of Vancouver Island and British Columbia, Canada. Continuous rectangular blocks along the western side of Baynes Sound indicate polygons in which white-winged scoters and surf scoters were surveyed during winters (Oct–Apr) from 2002–2003 to 2004–2005. Thickened shoreline indicates the linear extent of shellfish aquaculture leases (Ministry of Agriculture and Food and Fisheries Aquaculture Development Branch 2004).

numbers. Because scoters spend most of their annual cycle on nonbreeding areas, understanding the key factors associated with their winter habitat use is particularly relevant.

Given the overlapping distributions and high densities of both scoters and shellfish aquaculture activities, there is significant potential for interaction, both positive and negative. The presence of shellfish aquaculture could be detrimental for scoters through disturbance or habitat modifications, including exclusion of birds from important foraging sites due to use of antipredator netting or oyster cover on beaches. Alternatively, scoters could benefit from shellfish aquaculture through increased prey availability. Clam farmers actively seed the mid-intertidal zone with small Manila clams. Waves may wash seed clams from under antipredator netting or seed clams, along with larger size classes, may actively migrate to areas outside the netting, thereby increasing their densities and hence scoter prey availability. Also, seeded clams reach sexual maturity before they are harvested and presumably contribute to recruitment in surrounding areas. Our objectives were to 1) identify natural environmental features corresponding to densities of scoters during winter, 2) quantify effects of shellfish aquaculture after accounting for effects of natural environmental attributes, and 3) contrast relative effects of natural environmental attributes and shellfish aquaculture on space use by scoters.

Study Area

Baynes Sound (Fig. 1) is located between Vancouver Island and Denman Island in the Strait of Georgia, British Columbia, Canada (49°33′N, 124°51′W). Growers have used this area for commercial shellfish aquaculture since the early 1900s when Pacific oysters were introduced from Asia, and Baynes Sound remains the area with the most extensive shellfish aquaculture activity in the province. Manila clam farming has been a more recent activity, with the first commercial licenses issued in the early 1990s. Since then, intertidal clam culture has expanded dramatically (Jamieson et al. 2001) and constitutes roughly 90% of shellfish activities in Baynes Sound. By 2001 the government had leased 493 ha (32%) of the 1,530 ha of intertidal area in Baynes Sound for commercial shellfish aquaculture and had leased 61 ha of deeper waters for off-bottom shellfish culture (Ministry of Sustainable Resource Management 2002). However, growers did not intensively farm all leased areas and focused their intertidal culture on the mid- and lower intertidal zones, from vertical +2.5 to 0.0 m relative to hydrographic chart datum (the vertical tidal range is from +5.3 to 0.0 m in Baynes Sound). Typically, farmers seeded clams and deployed netting to prevent predation by marine invertebrate predators (e.g., sea stars and crabs) and birds, primarily scoters. Nearly one-third of the intertidal area in Baynes Sound was leased for shellfish aquaculture and approximately 76 ha was covered by antipredator netting in 2001 (based on June 2001 aerial photos; Ministry of Sustainable Resource Management 2002). The area covered by nets corresponded to roughly 5% of the Baynes Sound intertidal area or 15% of the area leased for shellfish farming. Another type of intertidal habitat modification involved the erection of beach fences, built of rigid plastic mesh extending 20–30 cm above and 10 cm below the substrate. Some lease holders positioned beach fences in the lower part of the intertidal area, parallel to the shore; the intention was to protect the beach from wave action and prevent clams and oysters from washing away. Once seeded, it takes 2–4 years for clams to reach marketable size (>35 mm). Shellfish farmers harvested clams exclusively by hand-raking. They left clams below marketable size in the plots and often reseeded the plots after harvesting. They also used off-bottom tenures in Baynes Sound for the culture of oysters, which were grown in trays or on lines suspended in the water column from rafts or buoys along lines anchored at both ends (Emmet 2002). Some shellfish farmers placed market-sized oysters in the intertidal zone for several months to harden their shells before shipping. They typically spread out oysters in a dense layer, which could restrict scoters from reaching clams.

Methods

Scoter Surveys

We surveyed the abundance and distribution of scoters along the Vancouver Island side of Baynes Sound biweekly from October to April 2002–2003 and 2003–2004 and monthly from October to April 2004–2005. We collected survey data in a spatially explicit manner, with all scoter observations linked to a geo-referenced survey polygon. These polygons ($n = 73$) were contiguous, extending 800 m from shore, averaging 840 m of shoreline each, and covering the entire western shore of the study area (Fig. 1). Our survey polygons encompassed a wide range of variation in

Table 1. Natural environmental and shellfish aquaculture attributes used to evaluate variation in wintering scoter densities in Baynes Sound, British Columbia, Canada, 2002–2005.

			Data distribution[a]		
Predictor variable	**Description**	**Units**	**Average**	**Range**	**Source**
Intertidal area	Percentage of intertidal area per survey polygon	%	42	1–100	Digitized nautical chart (Fisheries and Oceans Canada No. 3527)
Density of varnish clams	No. of 20- to 50-mm varnish clams per square meter of intertidal area	clams/m^2	38	0–222	Clam sampling in Aug 2003
Density of Manila and Pacific littleneck clams	No. of 20- to 50-mm Manila and Pacific littleneck clams per square meter of intertidal area	clams/m^2	45	0–198	Clam sampling in Aug 2003
Distance to the nearest stream mouth	The shortest distance by water from the central shoreline point of a polygon to the nearest stream mouth	m	1,339	68–3,676	Measured in GIS[b] using TRIM base-map of British Columbia (M 1:20,000)
Exposure	Modified effective fetch distance measured from the central shoreline point of a polygon	km	6.9	0.4–26.9	Estimated following Zacharias et al. (1999)
Sediment type	Dominant intertidal sediment category	Sediment category	Mud Sand Gravel Rock	7% 29% 29% 36%	Visual assessment
Season	One of 3 bird survey seasons: 2002–2003, 2003–2004, or 2004–2005	Season category	2002–2003 2003–2004 2004–2005	73 polygons 73 polygons 72 polygons	
Antipredator netting	Percentage of intertidal area covered with clam antipredator net	%	8	0–50	Visual assessment
Oyster rafts	Presence or absence of oyster aquaculture rafts	Yes or no	Present Absent	6% 94%	Visual assessment
Beach structures	Presence or absence of laid oysters or beach fences in the intertidal	Yes or no	Present Absent	38% 62%	Visual assessment

[a] Data distribution presented as an average and a range for continuous variables and a relative occurrence of each category in categorical variables.
[b] GIS = Geographic Informaiton System.

natural environmental attributes, as well as types and intensities of shellfish aquaculture (Table 1). Our analyses included only data that we collected during the core wintering period (late Oct–early Nov through early Mar), thus excluding data from migration periods and also from the Pacific herring (*Clupea pallasi*) spawn period in spring, when scoters dramatically alter their distributions in response to a superabundant food. We used data from 11 surveys in 2002–2003, 9 in 2003–2004, and 5 in 2004–2005 to calculate mean density of scoters per survey polygon for each winter. Variability of scoter numbers within survey polygons each winter was relatively low; wintering scoters in this area have high site fidelity and small home ranges (M. Kirk, Simon Fraser University, unpublished data).

Environmental Data

We assembled data on habitat features of Baynes Sound that we considered to be important predictors of scoter habitat use. We gleaned most of these data from existing data sources and ground-truthed in the field, whereas others we collected specifically for this study. We considered individual polygons as our sampling units and summarized environmental data accordingly. We used digitized survey polygon boundaries as an intersecting layer to obtain environmental information characterizing each polygon. We then intersected Geographic Information System (GIS) layers containing environmental information with survey polygons to acquire a number of environmental descriptors attributed for each polygon (Table 1). We performed all GIS analyses using ArcView GIS 3.2 (Environmental Systems Research Institute 1999).

We calculated the percentage of each polygon that consisted of the intertidal zone, based on a digitized 1:40,000 Baynes Sound nautical chart (Fisheries and Oceans Canada No. 3527). We used the bathymetric isoline for 0.0 m (i.e., the demarcation between the intertidal and subtidal zones) to create a polygon of the intertidal zone for each polygon. Then we divided the area of intertidal by the total polygon area to calculate the percent intertidal for each survey polygon.

We measured exposure to wind and waves from the central point of the highest high tide shoreline of each survey polygon, following guidelines for modified effective fetch calculation by Zacharias et al. (1999). We measured proximity to streams as the shortest distance by water from the central shoreline point of each polygon to the nearest stream mouth. We considered only streams with permanent inflow of freshwater during the winter period. We collected information on intertidal sediment types during low tides in spring 2004. We designated a single dominant sediment type for each polygon in the following 5 categories: mud, sand, gravel, cobble–rocks, and boulders–bedrock (Wentworth 1922).

We sampled clams, the primary and almost exclusive prey of scoters in Baynes Sound (Lewis et al. 2006), in summer 2003 across the entire study area. In our study design, we projected a single transect perpendicularly from shore at randomly selected starting points in each survey polygon. In some cases ($n = 26$), it was necessary to use data from a single transect to represent 2 survey polygons but only if the survey polygons were adjacent, small, and had similar environmental conditions. Along each transect, we excavated clams from 10 sampling points, distributed at equal distances between the highest high tide shoreline and the 0.0 m bathymetric isoline. At each sampling point we dug 4 cylindrical cores 15 cm in diameter, which we pushed 15 cm deep into the substrate or until solid sediments stopped the corer from penetrating deeper. We sieved the excavated contents through a 5-mm mesh screen. We sampled the upper 15 cm of the substrate under the assumption that clams below that depth range were not within the normal foraging reach of scoters. Foraging efficiency of sea ducks drops considerably with increasing burial depth (Richman and Lovvorn 2003), although some bivalves are known to occur deeper (Byers 2005). We identified all clams to species, sorted them into 5-mm size classes and counted them. We pooled data from the 4 cores collected from each sampling point to compose a single sampling unit. We did not sample cores that fell on shellfish aquaculture antipredator netting. We averaged clam densities (clams/m^2) across sampling points for each transect and used those values as inputs for analyses. We used only data for varnish clams (*Nuttallia obscurata*), Manila clams, and Pacific littleneck clams (*Protothaca staminea*), with shell lengths from 20 to 50 mm, as those species and size ranges dominate scoter diets in our study area (Lewis et al. 2006). We combined Manila and Pacific littleneck clams for analyses, as they have similar morphology, energy density (D. Esler, Simon Fraser University, unpublished data), and habitat requirements (Byers 2005) and hence should be of similar value for scoters. We recognize that our clam sampling represents a single point in time and, as such, cannot incorporate variation due to interannual differences or intraseasonal depletion due to predation (Lewis et al. 2006). However, we are comfortable with the assumption that observed clam densities are representative of the relative variation among polygons.

Shellfish Aquaculture Attributes

We assessed shellfish aquaculture type and extent within each survey polygon during spring 2004. For each survey polygon we visually estimated the percentage of intertidal area covered by antipredator nets, as well as the presence or absence of oyster rafts in subtidal areas, the presence or absence of oysters spread in the intertidal zone, and presence or absence of beach fences in the intertidal zone (Table 1). We later lumped beach fences and oysters spread on the beach into a single presence or absence category (termed beach structures) because they were frequently associated ($R = 0.70$). When designated as present, the density and extent of oyster cover varied, but was generally high.

Data Analysis

We quantified relationships between scoter densities and habitat features (natural environmental attributes and shellfish aquaculture) using multiple regression, and we used an information-theoretic approach to evaluate competing models (Burnham and Anderson 2002). We performed separate analyses for surf and white-winged scoters, with bird density (no./km^2) serving as the response variable and habitat attributes as potential explanatory variables (Table 1). We considered 16 candidate models for each scoter species. Our intent was to evaluate the relative importance of natural environmental attributes and aquaculture for explaining scoter distributions, and to quantify effects of different aquaculture features, after accounting for variation in the response related to natural environmental attributes.

To facilitate our analysis, we included or excluded natural environmental attributes as a single group, thus limiting the number of models in our candidate set. We labeled the natural environmental variable grouping BASE, and it included the following parameters: intertidal area, density of varnish clams, density of Manila and Pacific littleneck clams, distance to stream, exposure, sediment type, and season (Table 1). To test for shellfish aquaculture effects, in addition to BASE variables, we included percent cover of clam antipredator netting, presence of oyster rafts, and presence of beach structures using all possible additive combinations. We ran the same set of models, only without BASE variables, to allow consideration of the variability in scoter densities explained by shellfish aquaculture variables alone. We also included a null, or equal means, model in the candidate set, which is simply the mean and associated variation of the response variable. Support for the null model would indicate that factors other than those included in the candidate model set primarily determine variability of the response variable.

In multiple regression models, categorical variables always had one category fixed to zero, which served as a reference value. Sediment category Sand, survey season 2002–2003, absence of oyster rafts, and absence of beach structures were reference values for all models in which those categorical variables were included. We used SAS (version 8; SAS Institute 1999) for statistical analyses.

We applied Akaike's Information Criterion corrected for small sample size (AIC_c) to rank the support for each model within the candidate set (Burnham and Anderson 2002). We used ΔAIC_c to assess the explanatory value of each model, where we calculated ΔAIC_c as the difference between AIC_c of the best-supported model and each respective model in the set. We also calculated Akaike weights to compare the relative likelihood of each model in the candidate set (Burnham and Anderson 2002), and we presented R^2 values to describe overall model fit. To determine the relative importance of each explanatory variable within a candidate model set, we summed Akaike weights for all candidate models containing the explanatory variable under consideration, providing a parameter likelihood value, which is a measure of the strength of the variable for explaining variation in the response. Because we included or excluded BASE variables as a group, the parameter likelihood values for these variables are constrained to be the same. Finally, we calculated model-averaged parameter estimates and unconditional SE for each explanatory variable, based on Akaike weights for all candidate models, thus accounting for model uncertainty (Burnham and Anderson 2002). Because we included or excluded natural environmental attributes as a group, we made inferences about the influence of specific natural environmental attributes from examination of 95% CI (1.96 × the unconditional SE) relative to the parameter estimate. We considered attributes with 95% CI overlapping zero to have low explanatory value.

Results

Surf Scoter

Densities of surf scoters in survey polygons ranged from 0–1,079 individuals/km^2, with an average (± SE) of 99 ± 10.2 individuals/km^2 (n = 218). The best-supported model describing variation in surf scoter densities included BASE variables only, although support for a model including BASE variables and beach structures was essentially equivalent (Table 2). Variables characterizing shellfish aquaculture received little support, and models consisting solely of shellfish aquaculture attributes all ranked below the null model (Table 2). Model fit, based on R^2, and model support, based on ΔAIC_c values, were high when we included BASE parameters and fell dramatically when we removed them, indicating that natural environmental attributes explained most of the variation in densities. Similarly, the summed Akaike weights for natural environmental attributes, after accounting for rounding error, were essentially 1 (Tables 2, 3).

Weighted parameter estimates and associated SE derived from surf scoter candidate models indicated that intertidal area was an important environmental attribute. Surf scoter densities had a positive relationship with percentage of intertidal, and the parameter estimate was considerably higher than a 95% CI from zero (Table 3). Density of varnish clams also had a positive relationship with surf scoter densities. Surprisingly, the relationship with Manila and Pacific littleneck clams trended negatively, although the 95% CI broadly overlapped zero. Surf scoter densities were highest in sand, the reference level for the sediment categorical variable, particularly in relation to gravel and mud (Table 3). Surf scoter densities also tended to increase with increasing distance from fresh-water inflows. None of

Table 2. General linear multiple regression models used to evaluate habitat features related to variation in surf scoter densities in Baynes Sound, British Columbia, Canada, in winters 2002–2003 to 2004–2005.

Model	R^2	ΔAIC_c[a]	w_i
BASE[b]	0.42	0.00	0.26
BASE[b] + BeachStructures	0.42	0.02	0.25
BASE[b] + OysterRafts + BeachStructures	0.43	1.50	0.12
BASE[b] + OysterRafts	0.42	1.82	0.10
BASE[b] + %Net	0.42	1.93	0.10
BASE[b] + %Net + BeachStructures	0.43	2.14	0.09
BASE[b] + %Net + OysterRafts + BeachStructures	0.43	3.65	0.04
BASE[b] + %Net + OysterRafts	0.42	3.69	0.04
Null		96.76	0.00
BeachStructures	0.01	97.37	0.00
%Net	0.00	97.97	0.00
OysterRafts	0.00	98.76	0.00
OysterRafts + BeachStructures	0.01	99.43	0.00
%Net + BeachStructures	0.01	99.44	0.00
%Net + OysterRafts	0.00	100.05	0.00
%Net + OysterRafts + BeachStructures	0.01	101.52	0.00

[a] We ranked models according to ΔAIC_c values (Akaike's Information Criterion adjusted for small sample size), which indicate the relative support for each model, given the data. w_i indicates Akaike weight.

[b] BASE included Intertidal area, Density of varnish clams, Density of both Manila and Pacific littleneck clams, Distance to the nearest stream mouth, Exposure, Sediment type, and Season.

the shellfish aquaculture attributes showed strong relationships with surf scoter densities, with 95% CI broadly overlapping zero for all aquaculture variables (Table 3).

White-Winged Scoter

Densities of white-winged scoters in survey polygons ranged from 0–1,124 individuals/km^2, with an average (± SE) of 121 ± 12.2 individual/km^2 ($n = 218$). The best-supported model describing variation in white-winged scoter densities included BASE variables and presence of oyster rafts (Table 4), with more than twice the support of the next best model. The 4 models that included these 2 variables received almost all of the support from the data, based on summed Akaike weights of 0.96. However, the addition of the presence of oyster rafts added only 0.03 to the R^2 value beyond the model with BASE only. In addition, the model with presence of oyster rafts as the only variable fit the data poorly ($R^2 = 0.005$) and ranked below the null model. The other shellfish aquaculture variables received little support as explanatory variables, and models consisting solely of shellfish aquaculture attributes all ranked below those models including BASE environmental attributes (Table 4). Similarly, the summed Akaike weights for natural environmental attributes were nearly 1 (Table 3).

Weighted parameter estimates and associated SE from white-winged scoter candidate models indicated that intertidal area was an important environmental attribute. White-winged scoter densities had a positive, strong relationship with percentage of intertidal, with the 95% CI not overlapping zero (Table 3). Density of varnish clams

Table 3. Summed Akaike weights (w_i), weighted parameter estimates, and unconditional standard errors (SE_u) of weighted parameter estimates calculated from all candidate models of surf scoter and white-winged scoter densities in Baynes Sound, British Columbia, Canada, winters 2002–2003 to 2004–2005.

	Surf scoter			White-winged scoter		
Parameter[a]	Summed w_i	Weighted parameter estimate	SE_u	Summed w_i	Weighted parameter estimate	SE_u
Intercept	1	−7.32	37.78	1	52.58	45.97
% intertidal	1	2.52	0.32	1	2.08	0.39
Density of varnish clams	1	0.36	0.16	1	0.85	0.20
Density of Manila and Pacific littleneck clams	1	−0.26	0.21	1	0.30	0.27
Distance to stream	1	0.03	0.01	1	−0.01	0.01
Exposure	1	0.65	1.42	1	−2.42	1.71
Sediments						
Mud	1	−128.85	36.16	1	−74.28	45.37
Gravel	1	−73.58	27.19	1	−36.38	34.19
Rock	1	−27.59	25.68	1	−42.56	31.56
Season						
2003–2004	1	−27.02	19.36	1	−20.91	23.98
2004–2005	1	0.20	19.43	1	37.45	24.07
% net cover	0.27	0.01	0.97	0.27	0.14	1.18
Oyster rafts	0.31	−9.96	48.16	0.96	−146.06	52.63
Beach structures	0.50	16.73	27.96	0.34	−9.46	34.23

[a] We set categorical variables Sediments–Sand, Season 2002–2003, absence of Oyster rafts, and absence of Beach structures to zero in all candidate models.

had a positive association with white-winged scoter density, but our data did not support a relationship with density of Manila and Pacific littleneck clams (Table 3). Parameter estimates and associated SE of other natural environmental attributes indicated that their values and 95% CI broadly overlapped zero, and thus were not important predictors of white-winged scoter densities (Table 3). Presence of oyster rafts had a negative relationship with densities of white-winged scoters, with the 95% CI around the parameter estimate well below zero (Table 3).

Table 4. General linear multiple regression models used to evaluate habitat features related to variation in white-winged scoter densities in Baynes Sound, British Columbia, Canada, winters 2002–2003 to 2004–2005.

Parameter	R^2	ΔAIC_c[a]	w_i
BASE[b] + OysterRafts	0.39	0.0	0.48
BASE[b] + OysterRafts + BeachStructures	0.39	1.6	0.22
BASE[b] + %Net + OysterRafts	0.39	2.2	0.16
BASE[b] + %Net + OysterRafts + BeachStructures	0.39	3.1	0.10
BASE[b]	0.36	6.8	0.02
BASE[b] + BeachStructures	0.37	7.5	0.01
BASE[b] + %Net	0.36	9.1	0.01
BASE[b] + %Net + BeachStructures	0.37	9.1	0.01
%Net + BeachStructures	0.02	82.8	0.00
%Net + OysterRafts + BeachStructures	0.03	83.5	0.00
%Net	0.01	83.8	0.00
%Net + OysterRafts	0.02	83.8	0.00
Null		84.1	0.00
OysterRafts	0.00	85.1	0.00
BeachStructures	0.00	86.1	0.00
OysterRafts + BeachStructures	0.00	87.2	0.00

[a] We ranked models according to ΔAIC_c values (Akaike's Information Criterion adjusted for small sample size), which indicate the relative support for each model, given the data. w_i indicates Akaike weight.

[b] BASE included Intertidal area, Density of varnish clams, Density of both Manila and Pacific littleneck clams, Distance to the nearest stream mouth, Exposure, Sediment type, and Season.

Discussion

Our results show that, despite the extensive clam and oyster aquaculture in Baynes Sound, natural environmental attributes were the primary determinants of densities of wintering surf scoters and white-winged scoters. Shellfish aquaculture variables were generally poor predictors of bird densities for both scoter species. Although antipredator netting prevented scoters from accessing portions of their intertidal foraging habitat, we did not detect a relationship between the extent of netting and scoter densities. Farmers typically deployed the netting in the most productive areas, where clams also were abundant outside of netted zones, and thus represented good foraging habitat for scoters. In addition, we speculate that clam-farming activities could increase food density outside of nets, through movements of clams or through recruitment, although we found no evidence of a positive association that would be consistent with that hypothesis. Although beach structures (beach fences and oysters laid in the intertidal) modified intertidal habitat and may have influenced access to underlying sediment and prey, we did not find them to be important in shaping scoter distribution in Baynes Sound.

The only aquaculture variable identified as having an important relationship with scoters was presence of oyster rafts, which had a negative association with densities of white-winged scoters. The mechanism underlying this relationship is not clear. Farmers anchored oyster rafts in subtidal areas, beyond the intertidal foraging areas for white-winged scoters; therefore, one would not expect exclusion from feeding sites. Disturbance from human activity at oyster rafts could influence white-winged scoters, although these birds occurred in high densities in other areas of Baynes Sound with different forms of human disturbance. Further, disturbance might be expected to affect surf scoters as well. We recognize that there could be covariation between presence of oyster rafts and some habitat attribute relevant to white-winged scoters that we did not measure. The small number of polygons with oyster rafts (4 of 73) reduces our ability to explain the observed relationship, and we suggest that this issue deserves more attention. Given the lack of effects of the more common forms of shellfish aquaculture on white-winged scoter densities, as well as an increase in scoter abundance in our study area over the past 2 decades (D. L. Lacroix, Simon Fraser University, unpublished data), we are confident in concluding that current levels and forms of shellfish aquaculture are not an important determinant of scoter distribution and abundance.

Natural features of the environment were the dominant attributes related to variation in densities of surf and white-winged scoters. Of these habitat characteristics, the extent of the intertidal zone was an important predictor of densities of both scoter species, which is not surprising given that the intertidal area is where scoters forage in Baynes Sound. Densities of varnish clams were important in explaining densities of both scoter species. We would have expected stronger relationships between scoters and Manila and Pacific littleneck clams, as these species constitute a relatively high proportion of surf scoter and white-winged scoter diets in Baynes Sound (62% and 37%, respectively). White-winged scoters consume a higher proportion of varnish clams than surf scoters (46% and 20%, respectively; Lewis et al. 2006). One might expect that scoters target particular size classes of clams and, if size class differences exist between species, that might explain observed differences in effects on scoter distributions. However, size class distributions of Manila clams and varnish clams, measured in 5-mm increments, did not differ ($\chi^2 = 4.26$, $P = 0.51$, df $= 5$).

Substrate type also had a relationship with scoter densities in Baynes Sound. Both scoter species occurred at higher densities in areas with sand sediments compared to areas with other sediment types. Clam densities can be high in sandy areas (Byers 2002, 2005), and digging for clams in sandy substrates is presumably easier for scoters and hence more profitable. We found that exposure to wind and waves did not play an important role in scoter habitat selection; most of Baynes Sound is generally well sheltered and therefore there may not have been meaningful variation in the data. We found lower densities of surf scoters close to fresh water; this may be related to habitat preferences of their primary foods, Manila and Pacific littleneck clams, which prefer salinities above 20 ppm. White-winged scoter densities did not vary in relation to the proximity to stream mouths; their primary prey, the varnish clam (Lewis et al. 2006), is a euryhaline species and occurs in habitats with a wide range of salinities (Gillespie et al. 1999).

Our results indicating that scoters had a positive association with broad and sandy intertidal flats and high densities of clams corroborate findings of previous studies. Stott and Olson (1973) found that scoters (surf, white-winged, and black scoters [*Melanitta nigra*]) preferred sandy beaches to rocky headlands on the Atlantic coast of New Hampshire, USA, where they foraged on clams and mussels. Other authors indicate that white-winged scoters generally occur in soft bottom habitats and have a diet of clams and other invertebrates found in these habitats (Vermeer and Levings 1977, Vermeer and Bourne 1984, Stempniewicz 1986). Surf scoters, however, in addition to occurring in soft bottom areas, also frequent rocky shores where mussels are the primary item in their diet (Vermeer and Levings 1977, Vermeer 1981, Lacroix 2001). These habitats do not occur in Baynes Sound and therefore our findings do not fully reflect habitat use at a broader scale for surf scoters. In contrast to our finding that scoters had a strong association with the intertidal zone, white-winged scoters wintering in the Baltic Sea, which does not experience high-amplitude lunar tides, primarily used offshore waters with depths of 10–30 m (Nilsson 1972, Durinck et al. 1994). Clearly, scoter winter habitat use varies regionally, presumably in response to varying costs and benefits of the different types of habitats present.

We measured contemporary distributions of scoters, and it is possible that current levels of shellfish aquaculture caused displacement of scoters from the area over a longer time period. However, scoter numbers in Baynes Sound were considerably higher during our study than in winter 1980–1981 (Dawe et al. 1998), indicating that there has been positive growth, either through improved recruitment or through net immigration over the time period when the shellfish aquaculture industry was changing to its current form. This supports our conclusion that the shellfish industry, at current intensities and practices, is not having detrimental effects on scoter habitat quality. If shellfish aquaculture affects scoter habitat use at larger, landscape-level scales, areas with nearly continuous aquaculture activity (e.g., the west side of Denman Island) could show different relationships. However, the responsiveness of scoters to habitat variation among polygons demonstrated in this study, as well as the relatively small home ranges of scoters in Baynes Sound (M. Kirk, unpublished data), suggest that the spatial scale of our study was appropriate for quantifying habitat use of scoters and indicates that our conclusion that current levels of shellfish aquaculture in Baynes Sound are not adversely affecting scoter habitat use is robust.

Commercial shellfish aquaculture in other areas of coastal British Columbia is primarily deep-water oyster and mussel culture. These tend to be areas with steep, rocky shores and few wide and protected beaches suitable for clam farming. Because Baynes Sound supports a large number of scoters and is the area that the industry most intensively utilizes, it was important to evaluate habitat use in this area. However, studies of habitat use in other environments also would be valuable, particularly in the context of predicting effects in the event of industry expansion. Similarly, studies of other aspects of wintering ecology would be valuable for fully understanding potential effects of shellfish aquaculture on scoter populations. For example, studies of foraging ecology, movement, and survival of scoters in areas modified by shellfish aquaculture would provide important insights into effects of the industry, beyond habitat use described here. Finally, shellfish aquaculture may affect many other wildlife species. We chose scoters because of the overlap between the shellfish industry and important wintering sites, as well as the plausible mechanisms that might disproportionately affect scoters in comparison to other species. However, attention to other wildlife species, as well as other aspects of environmental quality, structure, and function is necessary.

Management Implications

We demonstrated that current intensities and practices of shellfish aquaculture in Baynes Sound do not strongly affect habitat use by surf scoters and white-winged scoters. This is encouraging, as there is strong pressure for economic development in coastal British Columbia that is environmentally sustainable. Because researchers have documented habitat alterations associated with wild shellfish harvesting to have effects on waterbirds (Camphuysen et al. 2002, Oosterhuis and Van Dijk 2002, Atkinson et al. 2003, Verhulst et al. 2004), managers should recognize that intensification or further industrialization of shellfish aquaculture in British Columbia could eventually lead to detrimental effects if the level of habitat change approaches that associated with wild shellfish harvest. Careful consideration and planning of industry activities is necessary to ensure that managers maintain carrying capacity for scoters in a working landscape.

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