Exxon Valdez Oil Spill
Restoration Project Final Report

Recovery Status of Barrow’s Goldeneyes

Restoration Project 00466
Final Report

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Study History: This project was initiated in 1998 due to concerns that Barrow's goldeneye populations may have been injured by the *Exxon Valdez* oil spill, may not have fully recovered, and, further, may have continued to suffer negative effects of the oil spill. These concerns were based on data indicating different population trends in oiled and unoiled areas within Prince William Sound (Restoration Project 98159; Lance et al. 1999) and evidence of continued exposure to residual oil (Restoration Project 98025; Holland-Bartels 2000). This project was designed to assemble and analyze all existent, relevant data to provide a critical and comprehensive evaluation of the recovery status of Barrow's goldeneye populations and to identify any potential constraints to full recovery.

Abstract: Barrow's goldeneye (*Bucephala islandica*) population recovery from the *Exxon Valdez* oil spill was evaluated by examining potential constraints to recovery including food limitation, demographic limitations to population growth, and continued exposure to oil. Food abundance likely did not limit Barrow's goldeneye population recovery. Although mussel (*Mytilus trossulus*) biomass was greater on unoiled Montague Island than oiled Knight Island, body mass and nutrient reserves were similar or larger on Knight Island. Demographic data were mixed regarding recovery status. Densities of Barrow's goldeneyes did not differ between oiled and unoiled areas after accounting for habitat effects, consistent with full population recovery. However, marine bird surveys indicated different population trends between oiled and unoiled areas, with increasing densities on unoiled areas and stable densities on oiled. Continued oil exposure through 1997 was indicated by higher induction of cytochrome P450 1A in birds from oiled areas than unoiled. Further, elevated hydrocarbon levels in intertidal sediments and mussels in 1999 indicate potential mechanisms for continuing exposure. However, little evidence indicated physiological or population-level consequences of this exposure. Most data suggest population recovery or at least no strong residual effects, although additional demographic data would allow for a more critical evaluation of that conclusion.

Key Words: Barrow's goldeneye, body composition, *Bucephala islandica*, density, food, *Exxon Valdez*, habitat, mass, mussels, *Mytilus trossulus*, Prince William Sound, population recovery.

Project Data: Data for this project were assembled from a number of *Exxon Valdez* oil spill restoration projects. These projects, and their associated restoration project numbers, are referenced in the text and should be consulted to determine access to the data. Much of the data presented in this final report was collected as part of the Nearshore Vertebrate Predator (NVP) project (Restoration Project 95025-00025). NVP data conform to the 1995 Data Management Plan, written by Tom Dean, Coastal Resources Associates, Inc. and are available in ASCII text format via the data custodian: Mary Whalen, U.S. Geological Survey, Alaska Biological Science Center, 1011 East Tudor Road, Anchorage, Alaska 99503 (phone: 907 786-3496; email: mary_whalen@usgs.gov).

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EXECUTIVE SUMMARY

Post-spill data indicated that Barrow's goldeneye populations in Prince William Sound were injured by the *Exxon Valdez* oil spill and had not recovered by 1991 (Day et al. 1997). More recent data also were suggestive of lack of recovery. Marine bird survey data indicated different population trends on oiled and unoiled areas through 1998 (Lance et al. 1999) and Trust et al. (2000) documented that goldeneyes continued to be exposed to residual oil through at least 1997, suggesting a potential mechanism constraining recovery. Due to concerns raised by these data, this project was undertaken to provide a comprehensive assessment of Barrow's goldeneye population recovery through compilation of all available information.

Evaluation of population recovery status and potential constraints to recovery followed the logic of the Nearshore Vertebrate Predator study (Holland-Bartels 2000), in which food limitation, demographic limitation, and continued exposure to oil were assessed as possible mechanisms of lack of recovery.

Food limitation was evaluated through comparisons of (1) abundance of mussels (the primary prey) in the size range consumed by Barrow's goldeneyes and (2) body mass and composition of collected goldeneyes. Under a hypothesis of food limitation of population recovery on spill-affected areas, one would predict that per capita prey biomass would be lower on oiled areas than unoiled, and that body mass, lipid reserves, or protein reserves would be lower on oiled areas. Although mussel biomass was lower on oiled areas than unoiled areas, body mass and nutrient reserves were comparable or larger. These data provide strong support for a conclusion of lack of food limitation of population recovery.

Demographic limitation of Barrow's goldeneye population recovery would be indicated by differences between oiled and unoiled areas in population attributes such as abundance, density, or trends. Densities were negatively related to oiling intensity in immediate post-spill studies (Day et al. 1997). Also, marine bird surveys indicated lower rates of population growth on oiled areas than unoiled (Lance et al. 1999), consistent with lack of recovery. However, these surveys described stable populations on oiled areas (Lance et al. 1999) and densities on oiled Knight Island were not difference from those on unoiled Montague Island, after accounting for effects of habitat (Appendix B), suggesting population recovery. Full evaluation of population differences between areas is hampered by a lack of data describing the demographic processes (i.e., survival and dispersal) underlying dynamics of Barrow's goldeneye populations.

Data consistent with lack of population recovery due to continued exposure to residual oil would include both evidence of exposure and indications of physiological or population effects of that exposure. Based on induction of cytochrome P450 1A, Barrow's goldeneyes were exposed to residual oil through at least 1997 (Trust et al. 2000). Sediment and mussel contamination data show that residual oil remained in the environment, and thus was available to goldeneyes, through 1999. However, body mass and composition were not related to P450 induction, and population data did not indicate clear negative effects of exposure. These data suggest that observed levels of exposure to oil were not high enough to cause strong negative consequences

for the population, although the uncertainties regarding demographic data warrant caution in this interpretation.

Overall, Barrow's goldeneye populations appear to have recovered or, at least, are not suffering strong negative effects related to the oil spill. Again, this conclusion must be made with caution, as data are lacking for important demographic processes that would allow full interpretation. In light of the assembled data, several recommendations can be made with regard to potential restoration actions: (1) monitor oil exposure and population trends, (2) conduct directed research to understand the demographic processes underlying population dynamics, and (3) establish a nest box program, which would enhance populations, allow local involvement in direct restoration activity, and facilitate studies of Barrow's goldeneye ecology.

INTRODUCTION

Acute effects of the 1989 *Exxon Valdez* oil spill on bird populations were dramatic, with hundreds of thousands of birds suffering direct mortality (Piatt et al. 1990, Piatt and Ford 1996). Sea ducks were one of the taxa for which immediate mortality was most significant, constituting approximately 25% of the carcasses recovered in Prince William Sound (Piatt et al. 1990). Although populations of some species of birds showed little effect of the oil spill or recovered quickly (Wiens et al. 1996, Bowman et al. 1995, 1997), long-term chronic effects have been documented for some sea duck populations (Esler et al. 2000), as well as other vertebrates that rely on the nearshore environment (Holland-Bartels 2000).

Barrow's goldeneyes (*Bucephala islandica*) winter almost exclusively in nearshore marine environments and the Gulf of Alaska coast is prime wintering habitat for the species (Bellrose 1980). Goldeneye numbers in Prince William Sound (which include a small proportion of common goldeneyes [*B. clangula*]) during March 1998 were estimated to be around 39,000 (Lance et al. 1999). However, directed assessments of oil spill injury, recovery, and constraints to recovery of Barrow's goldeneye wintering populations had not been conducted prior to this study.

Barrow's goldeneyes have a number of traits that make their populations potentially vulnerable to chronic effects of the oil spill. They occur in nearshore habitats of Prince William Sound, the environment that received about 40% of the oil spilled after the *Exxon Valdez* ran aground (Galt et al. 1991). Because of their close affiliation with these habitats, which still contain oil in some areas (Pat Harris, Auke Bay Laboratory, NOAA, pers. comm.), Barrow's goldeneyes may continue to be exposed. Further, winter diets of Barrow's goldeneyes consist primarily of mussels (*Mytilus trossulus*; Koehl et al. 1982, Vermeer 1982), which have been demonstrated to contain hydrocarbon residues as recently as 1995 (Babcock et al. 1997). Also, initial effects of the spill and subsequent clean up reduced mussel abundance in some areas in the years immediately post-spill (Highsmith et al. 1996, Houghton et al. 1996). Finally, Barrow's goldeneyes, like other sea ducks, are long-lived with relatively low annual productivity. Population dynamics of species with these life history characteristics have relatively low rates of potential population growth (Goudie et al. 1994, Schmutz et al. 1997). Thus, recovery of Barrow's goldeneye populations would be expected to take many years, even in the absence of long-term, chronic effects.

This species warrants concern not only for population recovery, but also because Barrow's goldeneyes are an important subsistence resource for local residents. For example, in Chenega goldeneyes were harvested by over 25% of households and constituted the majority of harvested waterfowl (Scott et al. 1996). Prince William Sound residents have expressed concern over recovery of populations of harvested waterfowl species, including Barrow's goldeneyes (Dan Rosenberg, Alaska Department of Fish and Game, pers. comm.).

OBJECTIVES

This project was designed to evaluate Barrow's goldeneye population recovery, and determine any constraints to full recovery, based on analysis of all available information. This approach involved assembling data from all relevant sources, mostly other restoration projects funded by the *Exxon Valdez* Oil Spill Trustee Council. Data were then analyzed and interpreted in the context of potential constraints to recovery, following the logic of the Nearshore Vertebrate Predator (NVP) project in which potential constraints were categorized as food limitation, demographic limitation of population growth rates, and continued exposure to residual oil. Specific objectives were:

1. Analyze data collected during NVP studies and report on results regarding:
   a. Foraging ecology of Barrow's goldeneyes, including body composition, diet, and size class of consumed mussels.
   b. Factors corresponding to winter densities of Barrow's goldeneyes, including mussel biomass, habitat characteristics, and oiling history.
2. Summarize data from other sources relevant to assessment of Barrow's goldeneye recovery status and impediments to recovery.
3. Generate conclusions regarding recovery status, identify impediments to recovery (if any), and recommend research needed to fill in data gaps to fully evaluate recovery status or impediments to recovery (if necessary).

This document is formatted such that the main body of the report focuses on data synthesis and interpretation and recommendations for future restoration work. Appendices A and B are draft manuscripts addressing the specific topics listed in Objective 1.

METHODS

Because this report is an assimilation of information from a number of research and monitoring efforts, primary sources should be consulted for specific methodological detail. Field and analytical techniques are presented here in brief and primary sources are cited.

In general, this work was designed to test predictions about potential constraints to population recovery. Based on the protocol for NVP studies, relative support for three hypotheses were contrasted based on the data available. The three mechanisms hypothesized as potential constraints to population recovery were food limitation, demographic limitation, and continued exposure to oil. As defined within the NVP project (Holland-Bartels 2000), food limitation could constrain population recovery if the oil spill resulted in reduction in abundance of Barrow's goldeneye prey. Demographic limitation was defined as a situation in which deleterious effects of the oil spill had ceased, yet populations had not yet fully recovered due to the time necessary for intrinsic population processes to operate. Population limitation due to continued exposure to oil could result if Barrow's goldeneyes were exposed to residual *Exxon Valdez* oil, either through ingestion or external oiling, resulting in physiological and subsequent population-level consequences of that exposure. Lack of evidence that any of these mechanisms were constraining population recovery would be consistent with a conclusion that population recovery had been achieved.

Food Limitation

Barrow's goldeneye diets during winter consist almost exclusively of mussels (Koehl et al. 1982, Vermeer 1982, Patten et al. 1998). Reduction in mussel abundance, which could potentially result in subsequent food limitation, could occur from either direct effects of the oil spill (e.g., acute toxicity or habitat destruction during cleanup activities) or indirect effects (e.g., perturbations of food web structure and interactions; Peterson 2000).

To assess the role of food limitation, evidence from studies done in years immediately following the spill was reviewed to evaluate spill-related changes in mussel abundance (Highsmith et al. 1996, Houghten et al. 1996, Stekoll et al. 1996). Also, as part of NVP studies (Holland-Bartels 2000), we compared mussel biomass and density between heavily oiled Knight Island and unoiled Montague Island (Fig. 1) during 1996 and 1997 (Appendix A). To select sites for mussel sampling, the shoreline of each study area (75.7 km on Knight Island and 74.1 km on Montague Island) was divided into contiguous 200 m segments. From randomly selected start points, segments were then systematically selected as sampling sites. For comparisons between areas, we used data for mussels with shell lengths in the range of 5-25mm, which we documented constituted most of the diet of wintering Barrow's goldeneyes (Fig. 2). To quantify mussel biomass, we established 10 transects within each site perpendicular to the shoreline at 20 m intervals, with the first at a randomly selected position. We removed all mussels from within a 500 cm^2 quadrat placed at a randomly selected location along each transect and recorded the width of the mussel zone. Collected mussels were sorted by size class and counted. Lengths of all mussels between 5 and 25 mm were measured. Ash-free dry weight (AFDW) of each mussel was estimated based on predictive equations of biomass by length derived from samples collected at the study locations during May-July 1996. Average biomass density (g AFDW/100 m^2) was calculated for each site and compared between areas using a *t*-test. Total mussel biomass for each site was estimated as the average biomass density expanded to the area of the mussel zone (i.e., 200 m X average width of the mussel zone). Food abundance was compared in relation to goldeneye abundance, under the premise that assessments of density dependent population limitation require per capita resource availability. We calculated food abundance per duck for each area as the average food abundance per site divided by the average duck abundance per site. Lower density or biomass of mussels on oiled areas would be consistent with the food limitation hypothesis, although other data would need to be considered (see body mass and condition, below) to fully evaluate the biological significance of that result.

To confirm diet composition of Barrow's goldeneyes and to quantify size class structure of mussels in the diet, we collected birds from Montague and Knight Island study sites (Fig. 1) in winter 1996-1997 as part of NVP studies (Appendix A). Upon collection, birds were immediately dissected. We tied off and removed the esophagus and proventriculus and injected these with alcohol to halt digestion and preserve contents. Upon return to the main vessel, we removed contents of the esophagus and proventriculus and placed them in separate whirlpaks in alcohol. Composition and size class of the diet were later analyzed in the lab.

Critical data for assessing the food limitation hypothesis go beyond documenting diet and abundance and density of prey. Although lower density or abundance of mussels in oiled areas would be consistent with food limitation, this result is difficult to interpret with respect to food limitation without an understanding of the role of food in population regulation or limitation. Unlike for sea otters (*Enhydra lutris*), for example, there are no data addressing causal, mechanistic relationships between food and carrying capacity for Barrow's goldeneyes during winter. Thus, body mass and composition data provide a stronger indication of whether food may be limiting population recovery (Appendix A). Body mass and composition often are used as indicators of individual and population health under the assumption that fitness increases with increases in energy reserves (with the corollary that animals are always striving to maximize their energy reserves). This assumption is likely untrue in a number of situations (King and Murphy 1985), i.e., optimal body mass may not be the maximum. However, in our situation, in which we were comparing populations of Barrow's goldeneyes experiencing similar extrinsic environmental conditions with the exception of oiling history (and thus presumably similar body mass optima), differences in body mass between areas could reflect food limitation. We would predict that changes in prey abundance related to the oil spill that would result in food limitation would be indicated by lower body mass and smaller lipid reserves on oiled areas than unoiled.

We estimated body composition of collected Barrow's goldeneyes through proximate analysis following standard methods (e.g., Esler and Grand 1994). In the laboratory, collected birds were thawed, weighed, plucked and reweighed. Wet and dry feather masses were determined. Digestive contents were removed and weighed. The liver was dissected and wet and dry masses measured; composition of the liver was analyzed separately. The remaining carcass was ground into a homogenate, weighed, dried, and weighed again. Samples of the homogenate and the liver were lipid-extracted in a modified Soxhlet apparatus using petroleum ether. The carcass sample was then ashed in a muffle furnace to determine relative protein and mineral levels. Total body composition was estimated by extrapolating the results from the homogenate samples to the carcass mass of the bird and then adding composition of the liver. We used general linear models to evaluate variation in body mass, total lipid, and total ash-free lean mass (i.e., protein) related to age (juvenile versus adult based on bursal involution), sex, season (December vs. February), and area (oiled Knight Island vs. unoiled Montague Island). We used Mallow's C_p values to direct model selection (Burnham and Anderson 1998). This selection method contrasts a number of models and uses the principle of parsimony to determine which model is best fit by the data (Hilborn and Mangel 1997), avoiding assumptions and biases of traditional stepping (i.e., forward, backward, and stepwise) model selection procedures (Anderson et al. 1994, Flack and Chang 1987). Using this approach to model selection, the model with the lowest C_p value is the one best supported by the data and, thus, provides the strongest inference. We interpreted inclusion of a given parameter in a selected model as evidence that the parameter was related to Barrow's goldeneye body mass or composition, after accounting for effects of other included parameters.

Demographic Limitation

Potential demographic limitation of Barrow's goldeneye recovery was evaluated through comparisons of population attributes between oiled and unoiled areas of Prince William Sound, including abundance, trends, and densities. Reduced abundance or density, or suppressed trends, on oiled areas relative to unoiled would be consistent with demographic limitation under the premise that population attributes should be similar between areas in the absence of residual oil spill effects. These kinds of data are best interpreted when differences among areas that may confound evaluation of disturbance effects can be accounted for (Wiens and Parker 1995). As defined within NVP studies (Holland-Bartels 2000), the demographic limitation hypothesis would be invoked only after food limitation and oil exposure were no longer affecting the population, but intrinsic population growth had not yet compensated for past reductions related to the oil spill.

Immediate post-spill studies (Day et al. 1997) examined bird densities within 10 bays along a gradient of oiling intensities. Day et al. (1997) interpreted negative associations of densities and an oiling index, after accounting for habitat effects, as evidence of population-level effects of the oil spill. They also compared among years to evaluate recovery. Analyses for Barrow's goldeneyes were included in 6 (fall 1989; midwinter, late winter, spring, and fall 1990; and late winter 1991) of their 11 survey periods.

The U.S. Fish and Wildlife Service (USFWS), Migratory Bird Management, has conducted marine bird surveys during winter throughout Prince William Sound since 1990 (Lance et al. 1999; Restoration Project 98159). Data generated from these surveys were used to evaluate population trends of goldeneyes (primarily Barrow's goldeneyes but also including a small proportion of common goldeneyes). Trends during the years following the oil spill were calculated based on estimates of goldeneye densities (birds/km^2) in oiled and unoiled areas. Lance et al. (1999) used linear models to test homogeneity of slopes of population trends between oiled and unoiled areas. For taxa with populations thought to be injured, significantly lower slopes ($\alpha = 0.20$ for all trend comparisons) on oiled areas than unoiled were interpreted as evidence of continuing effects of the oil spill, similar slopes were thought to indicate lack of full recovery, and significantly higher slopes on oiled areas were interpreted as evidence of progress towards recovery. Also, population trends on oiled areas were described by linear regressions.

As part of NVP studies, we evaluated variation in densities of Barrow's Goldeneyes during winter (Appendix B) over 214 sites (the same sites at which mussel data were collected) within oiled Knight Island and unoiled Montague Island study areas (Fig. 1). The intent of this work was to determine residual effects of the oil spill on Barrow's goldeneye densities after accounting for any effects of physical habitat attributes or mussel biomass. To describe Barrow's goldeneye densities, we conducted censuses of shorelines within the main study areas during winters 1995-1996 and 1996-1997. We mapped locations and flock sizes of all Barrow's Goldeneyes on mylar overlays of 1:15,000 aerial photos. Locations were digitized using a geographic information system (GIS). To determine average Barrow's Goldeneye densities associated with each site, we calculated the number of ducks detected during shoreline censuses within 200 m linear shoreline distance of the midpoint of each sampling site using a GIS. Duck densities were expressed as the average number of birds within the designated shoreline distance over all replicate surveys. At each site, a number of habitat characteristics were documented during summers of 1996 and 1997 that we felt could be related to winter Barrow's Goldeneye densities, including exposure, dominant substrate, distance to stream mouth, distance to reef, and intertidal slope (see Appendix B for details). We conducted general linear model analyses to assess relationships of habitat attributes and mussel biomass (explanatory variables) to average Barrow's Goldeneye densities (the response variable), using each sampling site as an observation. After finding the models best fit by the data (using Mallow's C_p values to direct model selection), we evaluated the effect of area (oiling history) after accounting for significant effects of habitat attributes. Lower densities on oiled areas than unoiled, after accounting for habitat differences, would be consistent with lack of full recovery and potential demographic limitation.

Continued Exposure to Oil

A conclusion that continued exposure to oil limits Barrow's goldeneye population recovery would require evidence of hydrocarbon exposure and associated physiological or population consequences of that exposure.

Immediate post-spill data on oil exposure were collected by the Alaska Department of Fish and Game (Patten et al. 1998). Proventricular food samples were analyzed for oil contamination and bile samples were analyzed for hydrocarbon metabolites.

One of the most sensitive and specific biochemical measurements for assessing exposure to polycyclic aromatic hydrocarbons (PAHs) is the induction of cytochrome P450 (P450), mixed-function oxygenase systems (Woodin et al. 1997). Certain PAHs induce P450 responses, therefore measuring resultant enzyme production or activity can indirectly indicate exposure to oil constituents. As part of NVP studies, liver samples were collected from the Barrow's goldeneyes collected at the primary study sites on Montague and Knight Islands (Fig. 1). Immediately upon retrieval of each carcass (within 10 minutes), approximately one gram of liver was dissected, wrapped in aluminum foil, and placed into liquid nitrogen. We assessed P450 induction by measuring hepatic 7-ethoxyresorufin-O-deethylase (EROD) activity. Lab methods are described in detail by Trust et al. (2000). EROD activity was compared between areas using a *t*-test.

Also, data on oil persistence and contaminant levels in mussels and sediments (Babcock et al. 1996, Short and Babcock 1996, Hayes and Michel 1999) were reviewed as possible mechanisms of continued exposure of Barrow's goldeneyes to residual *Exxon Valdez* oil.

Using NVP data from collected Barrow's goldeneyes, we evaluated effects of oil exposure, as indexed by EROD activity, on body mass and composition, as potential physiological consequences of oil exposure. We used two analysis approaches to address this question. First, we included EROD activity as a potential main effect in procedures to select models describing variation in body mass, lipid, and protein (using Mallow's C_p values as described above). Inclusion of EROD activity in the most parsimonious model would be interpreted as evidence that oil exposure was related to body mass or condition. Also, we added the EROD activity term to the best-fitting models describing body mass and composition variation; we assessed whether EROD activity explained additional variation based on type III sum of squares F statistics and $\alpha = 0.05$.

RESULTS

Food Limitation

Consistent with findings of other studies (Koehl et al. 1982, Vermeer 1982, Patten et al. 1998), we found in our NVP research that mussels comprised the vast majority of the diet of Barrow's goldeneyes in our study areas. We found trace occurrence of whelks and fish eggs, but in amounts insignificant for understanding food constraints to population recovery. The size class distribution of consumed mussels (Fig. 2) indicated that nearly all mussels in the diet were between 5 and 25 mm, which is the size class interval that we used in subsequent analyses of NVP data.

As a result of direct effects of the spilled oil, as well as high-pressure hot-water treatment for oil cleanup, intertidal mussel populations within the oil spill area were negatively affected in the years immediately following the spill. Highsmith et al. (1996) found that mussel abundance and biomass tended to be higher in unoiled sites than in oiled sites; some of these differences were no longer apparent by 1991, although differences were still evident in some habitats. Stekoll et al. (1996) also found that mussels tended to be less abundant at oiled sites. Mussels and other intertidal biota were strongly affected in areas that were oiled and in areas that were washed with hot water in the years following the spill (Houghton et al. 1996); by 1992 the recovery process was well underway, although some areas had not fully recovered. These data are consistent with potential food limitation of recovery of Barrow's goldeneye populations, at least during the years immediately post-spill. More contemporary mussel data are needed to evaluate longer-term food limitation.

On our NVP study areas (Fig. 1) mussel biomass densities were similar between unoiled Montague Island and oiled Knight Island (Table 1). However, average mussel biomass per site was higher on Montague Island than Knight Island. The difference in biomass between areas is likely not an artifact of the oil spill, given the similar mussel densities, but rather is due to a difference in the width of the intertidal zone and hence appropriate habitat for mussels. The mussel zone averaged much wider on Montague Island than Knight Island (Table 1), a function of the intertidal slope, which was considerably steeper on Knight Island. Because densities of Barrow's goldeneyes were similar between areas (Table 1), per capita mussel biomass was higher on Montague Island (61.2 kg AFDW/duck) than Knight Island (27.4 kg AFDW/duck). These data are consistent with potential food limitation of populations of Barrow's goldeneyes on oiled areas, if per capita food abundance was too low to meet energetic costs.

Models describing variation in body mass, lipid, and protein of Barrow's goldeneyes collected as part of NVP studies are presented in Table 2. Our measure of body mass was the weight of the carcass when it was thawed in the lab for proximate analysis. Because food contents and a small piece of liver were removed in the field upon collection, thawed mass was less than the field mass; however, as the same field protocol was applied to all birds, comparisons between areas are valid and informative. The best-fitting model describing body mass variation included terms for season, age, sex, and area (Table 2). Body mass averaged lower in February than December, consistent with winter body mass dynamics of many waterfowl (e.g., Thompson and Baldassarre 1990). Also, juvenile and female body mass averaged lower than adults and males, respectively, again consistent with previous studies (e.g., Whyte et al. 1986). After accounting for these effects, Barrow's goldeneye body mass was related to area (Table 2); however, body mass averaged nearly 60 g higher on oiled Knight Island, the opposite of the prediction under a hypothesis of food limitation. Similarly, protein levels varied predictably in relation to season, age, and sex, but were higher on Knight Island than Montague Island, again inconsistent with the food limitation hypothesis. Lipid reserves did not differ between areas after accounting for other sources of variation (Table 2). In sum, these data provide strong evidence that food is not limiting population recovery.

Demographic Limitation

Habitat use studies of Day et al. (1997) documented negative relationships between Barrow's goldeneye numbers and oiling intensity, after accounting for habitat attributes. Also, between year comparisons indicated no reduction in the strength of the relationship over time. Day et al. (1997) interpreted these results as evidence that goldeneye populations were injured by the oil spill and had not recovered by the end of their study in 1991. These data are important for understanding effects of the oil spill on Barrow's goldeneyes, as these are the only data that describe immediate post-spill, population-level consequences. These data are consistent with potential demographic limitation of population recovery.

Based on data from winter 1990-1998, USFWS marine bird surveys (Lance et al. 1999) describe a stable goldeneye population on oiled areas (average annual rate of change = 0.01; $P = 0.75$ that slope is not different from 0) and a growing population (0.09; $P = 0.09$) on unoiled areas. Slopes between areas were different ($P = 0.15$). Results from the homogeneity of slopes test are consistent with lack of recovery, under the assumptions that populations would be changing at similar rates in the absence of oil spill effects and that recovery of populations on oiled areas would require higher rates of change on oiled areas than unoiled. However, lack of population declines on oiled areas is an encouraging sign of potential recovery.

NVP data indicated that Barrow's goldeneye densities were related to a number of habitat attributes (Table 3; Appendix B), including degree of exposure, dominant substrate type, and distance to the nearest stream mouth. After accounting for these habitat features, densities did not differ between oiled and unoiled areas for any of the top 5 models (Appendix B). These results are inconsistent with a hypothesis of demographic limitation and, in fact, suggest lack of residual oil spill effects and hence full population recovery. However, demographic processes (survival, recruitment, and dispersal) of Barrow's goldeneye populations are poorly known and thus the endpoints (e.g., density) may not be the best measure of demographic effects.

Continued Exposure to Oil

Studies conducted by the Alaska Department of Fish and Game in the immediate post-spill years (Patten et al. 1998) indicated that levels of certain PAH compounds in Barrow's goldeneye bile did not differ between oiled and unoiled parts of Prince William Sound, although Prince William Sound samples were higher than those from other areas (e.g., Southeast Alaska). These data are difficult to interpret, as oil spill related contamination would be predicted to be expressed in oiled areas at higher levels than in unoiled areas, unless very high rates of movements between areas occur. Patten et al. (1998) also found that one of 33 collected Barrow's goldeneyes had oil spill contaminated prey in the proventriculus, although this low rate of occurrence in the "snapshots" represented by one-time diet samples can not be assumed to represent the degree of exposure to individuals or populations.

Cytochrome P450 data collected during NVP studies provide a less ambiguous measure of hydrocarbon exposure. Trust et al. (2000) documented that hepatic EROD activity averaged higher (Fig. 3) in Barrow's goldeneyes from oiled Knight Island (94.3 pmol/min/mg protein; n = 22) than in those from unoiled Montague Island (49.5 pmol/min/mg protein; n = 19; $P = 0.0014$), which almost certainly reflected continued exposure to *Exxon Valdez* oil up to 8 years after the oil spill. Alternative sources of P450 inducing compounds, including PCBs and non-*Exxon Valdez* hydrocarbons, were found to be unlikely causes of observed results (Trust et al. 2000). These results are consistent with P450 results from a range of nearshore vertebrates in oiled areas (Holland-Bartels 2000), corroborating the conclusion of continued oil exposure.

Mussels clearly accumulate hydrocarbons in the environment and serve as a potential route of oil exposure for Barrow's goldeneyes (Short and Harris 1996). A number of studies have indicated that residual *Exxon Valdez* has remained in intertidal environments through the years following the oil spill (Babcock et al. 1996, Irvine et al. 1999, Short and Babcock 1996, Hayes and Michel 1999) and thus Barrow's goldeneyes may have been vulnerable to exposure. Data collected from oiled mussel beds in Prince William Sound during summer 1999 by the Auke Bay Lab, NOAA are still being analyzed, but preliminary results indicate that oil remains in these areas, sometimes at concentrations that are little reduced from 1996 samples (Pat Harris, pers. comm.).

These data, in conjunction with the P450 data, are consistent with a hypothesis of continued oil exposure limiting Barrow's goldeneye population recovery. However, available data suggest few physiological or population-level consequences of this exposure. Body mass and condition of collected goldeneyes were not related to P450 induction. When EROD activity was included as a potential main effect in model selection procedures, it was not included in any of the top models for body mass, lipid, or protein. Also, when EROD was added as a model parameter to the best-fitting models (Table 2), it explained no additional variation in the data ($P > 0.80$). Demographic data are mixed with respect to population effects of oil exposure. As described above, USFWS surveys could be interpreted as lack of full recovery, although the population on the oiled area is not declining. Also, densities of Barrow's goldeneyes on oiled areas were not lower than expected (Appendix B), contrary to a prediction of demographic effects of oil exposure.

DISCUSSION

Much of the data available for addressing potential constraints to Barrow's goldeneye population recovery suggests that recovery has occurred, or at least that strong negative effects are not apparent. In particular, densities of birds were not different between oiled and unoiled areas after accounting for habitat (Appendix B), and body mass and composition were not lower on oiled areas than unoiled (Appendix A). However, the data indicating potential lack of full population recovery at the onset of this project (different population trends between oiled and unoiled areas and evidence of exposure to oil) continue to be of concern, particularly in light of uncertainties about demographic processes due to lack of data on survival and movements.

Food limitation likely is not constraining Barrow's goldeneye population recovery. This conclusion rests primarily on the body mass and composition data, which indicated that mass and nutrient reserve levels were as high or higher on oiled areas compared to unoiled areas. This result, despite differences in mussel biomass between areas, suggests both that Barrow's goldeneye populations are not normally limited or regulated by winter food abundance and that population recovery on Knight Island was not limited by available mussel biomass (Appendix A). The differences in mussel biomass between areas was likely a result of geomorphology (Table 1), not oil spill effects. Results from studies of Barrow's goldeneye habitat associations (Appendix B) are consistent with lack of food limitation. Densities of goldeneyes were not related to mussel biomass and we speculated that mussel standing stock and annual productivity far exceeded predation demands, and thus food was not limiting. Other studies (Nilsson 1969, 1972) have similarly concluded that diving duck predation has little influence on annual mussel abundance and productivity.

Demographic data are somewhat mixed with regard to population recovery and hence indicate the need for continued concern. Although Barrow's goldeneye densities on oiled areas were not different from the level expected given the habitat (Appendix B), data from the broader USFWS marine bird surveys indicated divergent population trends. However, the USFWS data indicate stable or slightly growing populations on oiled areas (Lance et al. 1999), which could be interpreted as a lack continued effects of the oil spill. Population trends are best interpreted when the underlying demographic processes are understood. In the case of Barrow's goldeneyes, there are few data addressing winter survival or dispersal. Some studies have shown between-year site fidelity (Savard 1985) for some individuals, but rates of dispersal for all age and sex cohorts are unknown. Further, winter survival of the species has never been studied. These data constraints make it difficult to differentiate between population recovery and demographic attributes that mask effects of the oil spill. For example, poorer survival on oiled areas could be overshadowed by high levels of dispersal among areas, resulting in a source/sink dynamic (Pulliam 1988), with no discernible effect on local duck densities.

Because Barrow's goldeneyes continued to be exposed to residual oil through at least 1997 (Trust et al. 2000) and oil remains in the intertidal environment, population-level consequences of contamination remain a concern. Barrow's goldeneyes are susceptible to continuing effects of oil because of their reliance on mussels, which are still contaminated in some areas, and their association with mixed substrate (Appendix B), which is more likely to hold residual oil than rocky substrate. Although the available data suggest little physiological or population-level effects of this exposure, these results should be treated with some caution. First, as described above, the demographic data necessary to fully understand population dynamics are lacking. Also, physiological attributes such as body mass and condition and biomarkers can be measured only for individuals that survived until the sampling period; if effects of oil exposure are expressed quickly and fatally, affected individuals may be unlikely to be sampled. Other studies have indicated that waterfowl body mass was related to contaminants (Hohman et al. 1990). Because body mass has been shown to be related to subsequent survival (Conroy et al. 1989, Bergan and Smith 1993) and productivity (Esler and Grand 1994), population level effects of contaminants are plausible. Also, continued exposure to oil was thought to be related to lower survival on oiled areas than unoiled for ecologically similar harlequin ducks (*Histrionicus histrionicus*), with significant population implications (Esler et al. 2000).

CONCLUSIONS/RECOMMENDATIONS

Based on the weight of evidence from available data, Barrow's goldeneye populations appear to be recovering or recovered, although this conclusion must be made with caution, as full interpretation is hampered by lack of data on potentially important processes. Also, some data, for example divergent population trends on oiled and unoiled areas (Lance et al. 1999) and evidence of continued exposure to oil (Trust et al. 2000), are not fully concordant with that conclusion. Restoration of Barrow's goldeneye populations could be enhanced in the following ways:

1. *Monitor oil exposure*. Because of uncertainty associated with the conclusion that oil exposure had no population-level effects, along with evidence that this conclusion is not true for similar species (Esler et al. 2000), monitoring the level and duration of exposure to residual oil may be appropriate. Data from NVP studies described similar patterns of exposure in Barrow's goldeneyes and harlequin ducks (Trust et al. 2000); harlequin duck exposure will be monitored as part of Restoration Project 00423, which may provide adequate inference for Barrow's goldeneyes.

2. *Monitor population trends*. Although interpretation of population surveys is uncertain without a better understanding of demographic processes, ongoing work may be useful for monitoring the endpoints of demography, i.e., abundance, density, and trends. Continuation of USFWS marine bird surveys (Restoration Project 98159; Lance et al. 1999) and ADFG harlequin duck surveys (Restoration Project 00407) will result in population trend data.

3. *Study demographic processes underlying population change*. The most glaring research

gap is the lack of understanding of the relative effects of survival and dispersal on population fluctuations at local wintering areas. These data are necessary to make final conclusions about population recovery status through differentiation of recovery from a source/sink situation. A radio telemetry program, as per Esler et al. (2000), would generate the appropriate data for addressing these issues.

4. *Establish a nest box program*. Direct restoration through population enhancement could be facilitated by an effort to place nest boxes in appropriate breeding habitat. Previous studies have indicated that Barrow's goldeneye populations can be limited by available nesting cavities (Erksine 1990) and that establishment of nest boxes can result in population increases (Savard 1988). This type of habitat enhancement in breeding areas associated with Prince William Sound wintering populations (e.g., in lakes within the Prince William Sound watershed) would have population benefits for Barrow's goldeneyes, would be appropriate for involvement by residents of local communities, and has proven to be extremely useful for facilitating breeding biology studies (e.g., Eadie and Fryzell 1992).

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Throughout this report I have intentionally used "we" instead of "I" in recognition that, although I have been responsible for compiling the information, the data included in this report were collected, and in many cases analyzed and originally reported, by a large number of other researchers and field assistants. Thus, a general thanks is due to all of those who have participated in this process in one form or another. However, the interpretation of these data in the context of this report is my own, and I take full responsibility for any misinterpretations or faulty logic.

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Table 1. Comparisons of mussel and Barrow's goldeneye abundance metrics (± SE), and associated intertidal physical attributes, between unoiled Montague Island and oiled Knight Island.

Parameter	Montague Island (unoiled; n = 102)	Knight Island (oiled; n = 112)	*P*
Mussel Biomass Density (g AFDW[a]/100 m^2)	1234.8 ± 139.0	1452.4 ± 153.2	0.29 (*t* = 1.04)
Mussel Abundance (kg AFDW/200 m shoreline)	57.5 ± 8.3	23.9 ± 2.5	<0.01 (*t* = 4.04)
Mussel Zone Width (m)	26.0 ± 2.8	8.7 ± 0.6	<0.01 (*t* = 6.41)
Intertidal Slope (degrees)	5.8 ± 0.4	25.5 ± 1.7	<0.01 (*t* = 10.81)
Barrow's Goldeneye Density (ducks/200 m shoreline)	0.94 ± 0.10	0.87 ± 0.09	0.60 (*t* = 0.53)

[a] Ash free dry weight.

Table 2. Results of general linear model analyses to evaluate variation in body mass, lipid, and protein in relation to age, sex, season, and area (oiled Knight Island vs. unoiled Montague Island).

Variable	r^2	Parameter	Estimate (± SE)
Body Mass	0.90	Intercept	1211.78 (± 19.68)
		Season[a]	-32.92 (± 20.39)
		Age[b]	-125.87 (± 24.95)
		Sex[c]	-357.60 (± 19.99)
		Area[d]	59.50 (± 19.56)
Lipid	0.28	Intercept	92.87 (± 8.20)
		Season	-15.91 (± 9.28)
		Age	-20.97 (± 11.32)
		Sex	-30.95 (± 9.06)
Protein[e]	0.91	Intercept	213.20 (± 3.24)
		Season	-8.70 (± 3.36)
		Age	-18.09 (± 4.11)
		Sex	-65.88 (± 3.29)
		Area	9.17 (± 3.22)

[a] Reference value for season is December; the parameter estimate is the difference in February.
[b] Reference value for age is adult; the parameter estimate is the difference of juveniles.
[c] Reference value for sex is male; the parameter estimate is the difference of females.
[d] Reference value for area is unoiled Montague Island; the parameter estimate is the difference on oiled Knight Island.
[e] Ash-free dry lean mass.

Table 3. Results from the best-fitting general linear model describing variation in densities of Barrow's goldeneyes (square root transformed) in relation to habitat attributes. The area term was added after selection of the best model and calculation of parameter estimates, to evaluate any effect of oiling history (oiled Knight Island vs. unoiled Montague Island) after accounting for differences due to habitat.

Variable	r^2	Parameter	Estimate (± SE)
Duck Density	0.25	Intercept	0.77 (± 0.07)
		Substrate[a]	0.28 (± 0.10)
		Distance to Stream[b]	0.90 (± 0.15)
		Exposure[c]	0.25 (± 0.10)
		Area[d]	0.04 (± 0.10)

[a] Reference value for substrate is rocky; the parameter estimate is the difference for mixed substrate.

[b] In this model, the parameter estimate is the difference for sites with streams within 200 m in relation to all others.

[c] In this model, the parameter estimate is the difference for unexposed sites compared to all others.

[d] Reference value for area is unoiled Montague Island; the parameter estimate is the difference on oiled Knight Island. The *P* value for the area term = 0.72.

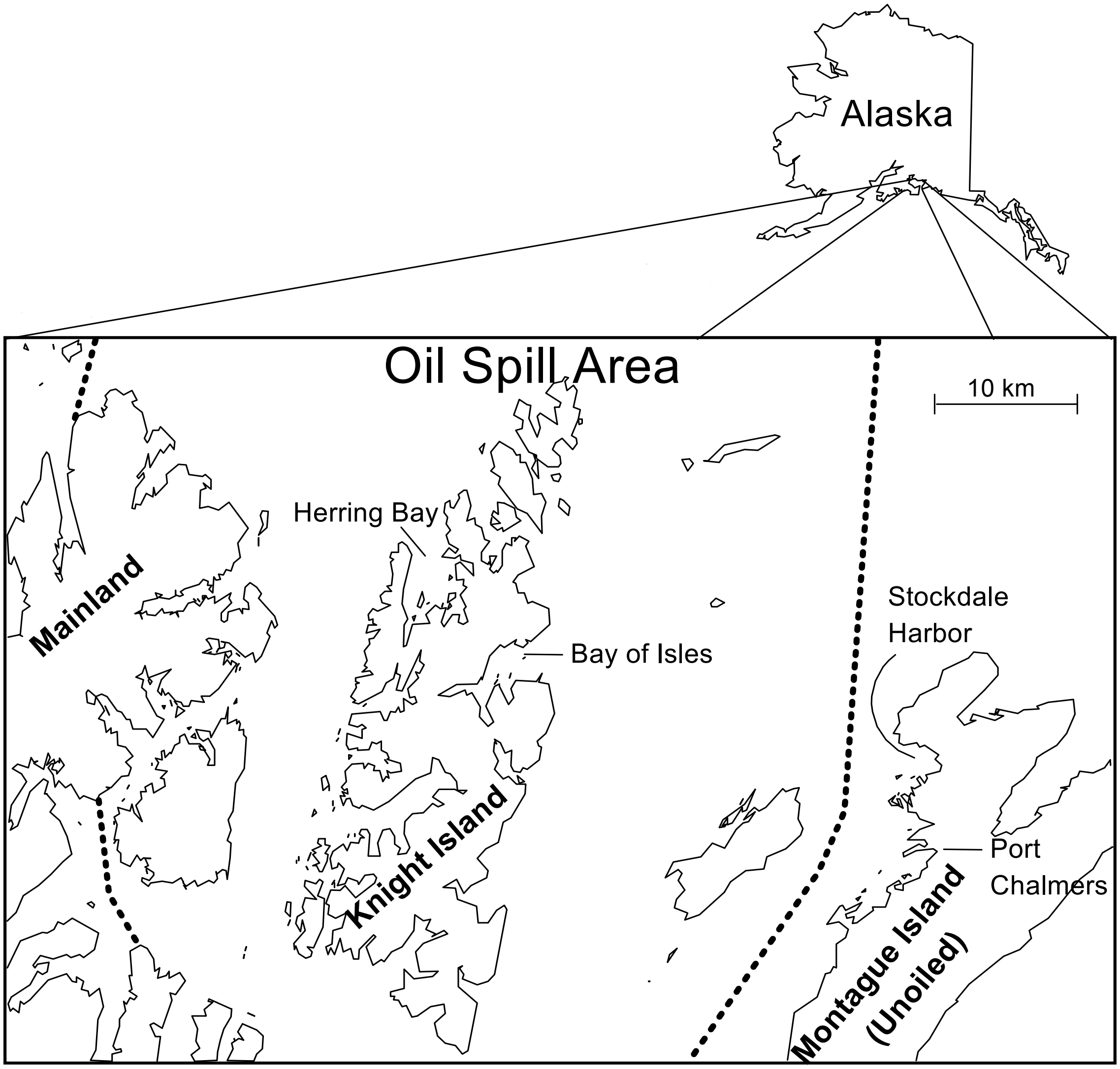

Figure 1. Study areas for Barrow's goldeneye data collected as part of the Nearshore Vertebrate Predator project. The bold dashed line indicates the bounds of the oiled area. The oiled study area included Herring Bay and Bay of Isles on Knight Island and the unoiled area included the Stockdale Harbor and Port Chalmers regions of Montague Island.

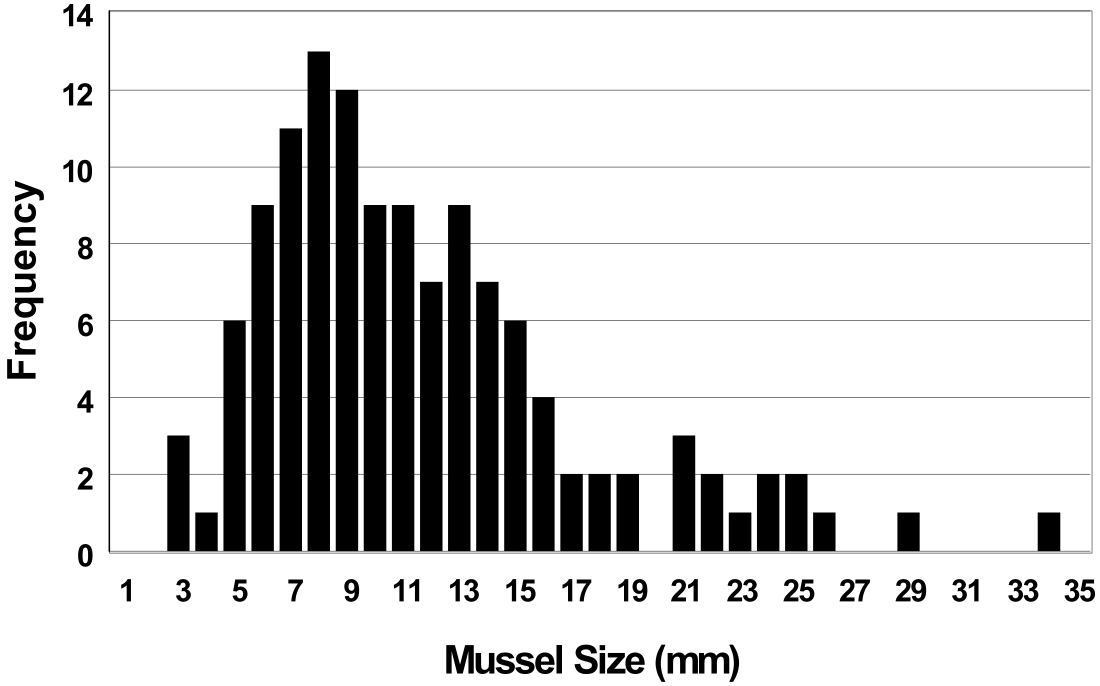

Figure 2. Mussel size class distribution in Barrow's goldeneye diets from Prince William Sound, 1996-1997.

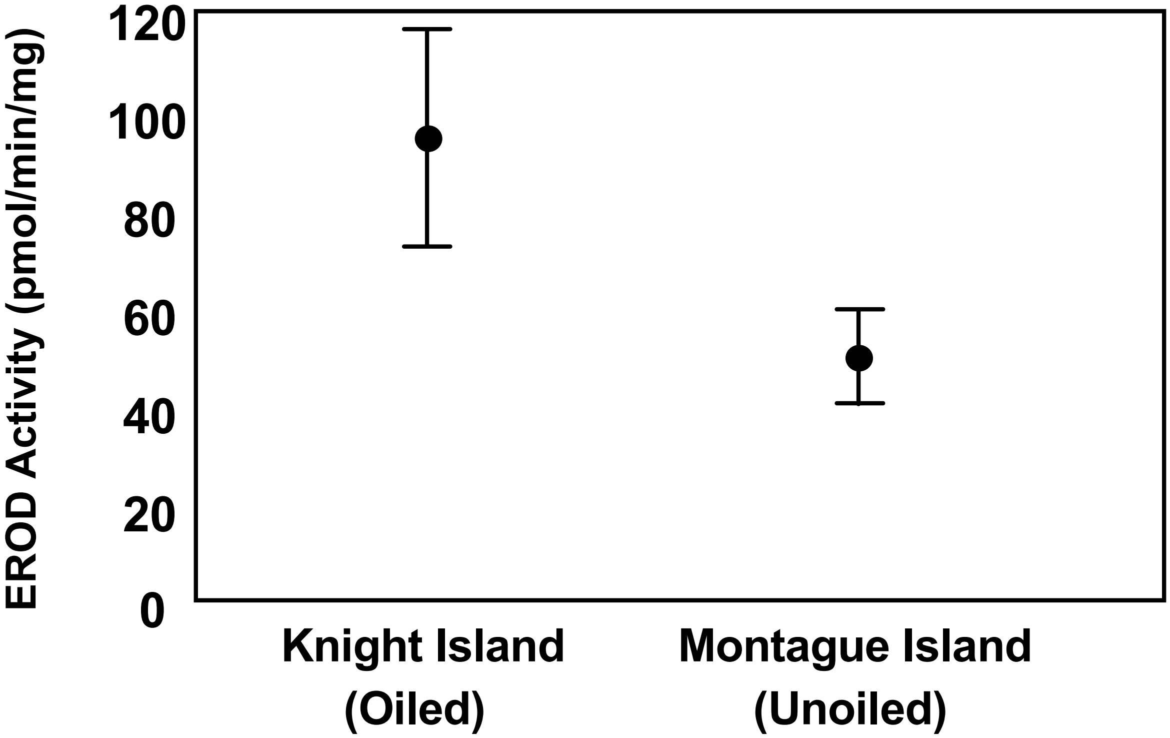

Figure 3. Comparison of average (± 95% confidence intervals) hepatic EROD activity of Barrow's goldeneyes collected from oiled and unoiled areas of Prince William Sound, 1996-1997 (from Trust et al. 2000).

APPENDIX A

Winter Foraging Ecology of Barrow's Goldeneyes and the Role of Food Limitation on Population Recovery from the *Exxon Valdez* Oil Spill[1]

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INTRODUCTION

The factors regulating or limiting populations of sea ducks are largely uncertain. Understanding mechanisms of population limitation, and the life stage at which regulation or limitation may occur, has become increasingly important in light of recent population declines of many species within the tribe Mergini (Goudie et al. 1994). Another uncertainty is the capacity of sea duck populations to recover following anthropogenic perturbations, as well as factors that dictate the rate of recovery. In this paper we test predictions about one potential regulating process, food limitation during winter, for Barrow's Goldeneye (*Bucephala islandica*) populations in the context of recovery following the *Exxon Valdez* oil spill.

The *Exxon Valdez* ran aground in March 1989, spilling approximately 11 million gallons of crude oil into Prince William Sound, Alaska, an area of rich bird life that includes an estimated 39,000 goldeneyes during winter (Lance et al. 1999). Bird mortalities as an immediate result of the oil spill were dramatic (Piatt et al. 1990, Piatt and Ford 1996), and sea ducks were one of the most affected taxa, constituting nearly 25% of the carcasses recovered in Prince William Sound (Piatt et al. 1990). Long-term consequences of this major perturbation on bird populations remain a concern. Populations of some species apparently recovered quickly from effects of the oil spill (Bowman et al. 1995, 1997), while full recovery for others had not occurred

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[1] In preparation for journal submission.

nearly a decade following the spill, including the harlequin duck (*Histrionicus histrionicus*; Esler et al. 2000), a sea duck that occurs in nearshore habitats similar to those occupied by Barrow's goldeneyes.

Day et al. (1997) identified Barrow's goldeneyes as one of the bird species for which population injury was evident in the immediate post-spill years and recovery was not apparent by 1991. Also, over the period from 1990 to 1998, population trends of Barrow's goldeneyes during March differed between oiled and unoiled areas, which Lance et al. (1999) interpreted as continuing effects of the oil spill and, hence, lack of recovery. However, mechanisms potentially constraining population recovery have not been evaluated for this species.

Winter diets of Barrow's goldeneyes consist almost exclusively of mussels (*Mytilus trossulus*; Koehl et al. 1982, Vermeer 1982). As a result of direct effects of the spilled oil, as well as high-pressure hot-water treatment for oil removal, intertidal mussel populations were negatively affected in the years immediately following the spill (Highsmith et al. 1996, Houghton et al. 1996, Stekoll et al. 1996). These data suggest that food limitation is a plausible mechanism constraining recovery of Barrow's goldeneye populations.

Distributional associations of waterfowl and food during winter are well-documented (Vermeer 1982, Pehrsson 1986, Buxton 1981, Lovvorn 1989, Guillemette et al. 1993, Guillemette and Himmelman 1996). However, understanding whether winter food limits populations is a more difficult question, in many cases. Several studies have suggested that food of wintering diving ducks on marine areas, under natural conditions, does not limit populations based on an apparent abundance of food in relation to demands (Nilsson 1969, 1972, Faldborg et al. 1994), although dramatic exceptions may occur (Suter and Van Eerden 1992). Effects of anthropogenic habitat perturbation on food limitation of wintering waterfowl populations are uncertain. Although distributional responses of ducks to winter habitat change have been documented (Lovvorn 1989), physiological or population-level consequences of this are unclear. Food limitation as a result of habitat disturbance, if it occurs, certainly has potential demographic consequences. For example, waterfowl body mass and condition likely would be affected by food limitation, which in turn have been related to subsequent survival (Conroy et al. 1989, Longcore et al. 1991, Bergan and Smith 1993) and productivity (Esler and Grand 1994).

To evaluate food limitation as a constraint to Barrow's goldeneye population recovery from the oil spill, we compared oiled and unoiled study areas within Prince William Sound. To satisfy a hypothesis of food limitation of population recovery from the oil spill, 2 predictions must be met. First, food abundance must be lower, per capita, on oiled areas than unoiled. Second, there must be evidence of physiological consequences of lower abundance (i.e., lower body mass or nutrient reserves). Satisfying the first condition only would not be adequate for confirming food limitation because, as suggested by some studies (Nilsson 1969, 1972, Faldborg et al. 1994), food may be superabundant under natural conditions and reductions in food would not affect individuals or populations. Similarly, differences in body mass or composition, in the absence of differences in per capita food abundance, would suggest that some factor (e.g., contaminats; Hohman et al. 1990) other than food limitation may be limiting populations. Body mass and composition often are used as indicators of individual and population health under the assumption that fitness increases with increases in energy reserves (with the corollary that animals are always striving to maximize their energy reserves). This assumption is likely untrue in a number of situations (King and Murphy 1985), i.e., optimal body mass may not be the maximum. However, in our situation, in which we were comparing populations of Barrow's goldeneyes experiencing similar extrinsic environmental conditions with the exception of oiling history (and thus presumably similar body mass optima), differences in body mass or composition between areas could reflect food limitation.

METHODS

Study Areas

Prince William Sound, located on the southcentral coast of Alaska, encompasses about 39,000 km^2 including 4,800 km of shoreline. A temperate rainforest dominated by Sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*) covers most of the convoluted shoreline and islands in Prince William Sound. Temperatures seldom drop below -20° C and, except for a few coves and lagoons, most areas remain ice-free during winter. Tidal amplitude averages about 4 m. Nearshore marine vegetation included rockweed (*Fucus gardneri*), eelgrass (*Zostera marina*), and several kelps (*Agarum clathratum, Laminaria saccharina, L. bongardiana,* and *Nereocyctis luetkeana*). All areas are undeveloped and human disturbance is generally low. Specific study areas included two bays on oiled Knight Island, Herring Bay and Bay of Isles, and the northwest section of northwestern Montague Island, including the Port Chalmers and Stockdale Harbor areas.

Population Surveys

Estimates of the number of Barrow's goldeneyes on each area were necessary for describing food abundance on a per capita basis. We conducted surveys of Barrow's Goldeneye numbers and distribution during 4-12 December 1995, 12-24 February 1996, 4-14 December 1996, and 14-23 February 1997, completing five replicates on Knight Island and seven on Montague Island. Surveys involved a census of a 200 m band from shore along 75.7 km of shoreline on Knight Island and 74.1 km on Montague Island. Survey craft were staffed by a two or three person team consisting of a boat operator/observer and at least one observer/data recorder.

Mussel Size Class in Diet

To understand the size class of mussels in the diet, and thus the size class to focus on for evaluating food limitation, Barrow's goldeneyes were collected under permit by shotgun within both study areas during December 1996 and February 1997. Upon collection, birds were immediately dissected. We tied off and removed the esophagus and proventriculus and injected these with alcohol to halt digestion and preserve contents. At the main research vessel, we removed contents of the esophagus and proventriculus and placed them in separate whirlpaks in alcohol. Mussel size was measured in the lab as the maximum length in the longest dimension.

Mussel Biomass and Density

Intertidal mussels were sampled to estimate biomass and density for each area. To select sites for mussel sampling, the shoreline of each study area was divided into contiguous 200 m segments. From randomly selected start points, segments were then systematically selected, resulting in 214 sampling sites (112 on Knight Island and 102 on Montague Island). For comparisons between areas, we used data for mussels with shell lengths in the range of 5-25mm, which we documented constituted most of the diet of wintering Barrow's goldeneyes (see below). To quantify mussel biomass, we established 10 transects within each site perpendicular to the shoreline at 20 m intervals, with the first at a randomly selected position. We removed all mussels from within a 500 cm^2 quadrat placed at a randomly selected location along each transect and recorded the width of the mussel zone. Collected mussels were sorted by size class and counted. Lengths of all mussels between 5 and 25 mm were measured. Ash-free dry weight (AFDW) of each mussel was estimated based on predictive equations of biomass by length. To derive equations, mussels were collected during May-July 1996 from each study location (99 from Montague Island, 81 from Bay of Isles, and 100 from Herring Bay). We assumed that length to weight relationships of summer mussels would provide an unbiased index of winter biomass, that is, even if winter mass of mussels differed from summer mass, there would be no systematic bias that would affect any of our comparisons. Mussels were chosen from both mixed and rocky strata in as wide a range of shell lengths as possible. To do this we queried the mussel database for samples containing a broad range of mussel sizes. We then selected groups of six or seven mussels from each sample based on size over the range of sizes available. The first group contained mussels in the range 10-15 mm, the second group contained mussels in the range 15-20 mm, etc. until the entire size range was subsampled and a total of about 100 mussels was included in the collection from each location. We assumed that results from these samples would hold for the unsampled 5-10 mm size class. Approximately 50 mussels were taken from the mixed stratum and 50 from the rocky stratum. To obtain data on mussel mass we weighed 100 numbered crucibles (noncombustible and nonabsorbant containers) of various sizes to the nearest milligram on a top-loading balance. The same balance was used throughout the procedure. We measured the length of each mussel and placed the mussel on a paper towel until it was completely thawed and most fluids had drained from the mantle cavity of the mussel so that the mussel tissue became damp (~1-4hrs). Each mussel was placed in a crucible and weighed. The damp mass was then calculated by subtracting the weight of the empty crucible from the weight of the crucible and the mussel. After the damp mass was obtained, the crucibles with mussels contained within them were placed in a drying oven for 24 h at 60˚C. At the end of the 24 h period the crucibles with mussels were weighed and then returned to the oven. This procedure was repeated until the mass of each crucible and mussel stabilized. The crucibles with mussels were kept in a dessication chamber while they were being held outside the oven for weighing on the balance. To obtain ash-free dry mass we placed crucibles with mussels in a muffle furnace for 5 hours at 550˚C. After ashing and cooling, we reweighed the crucibles and mussel ash. The ash-free dry mass was calculated by substracting the mass of the ash from the dry mass of the mussel. When the values of these variables were obtained for all of the mussels in this subsample, log AFDW was regressed against log shell length to create the equations for predicting AFDW from shell length.

Average biomass density (g AFDW/100 m^2) was calculated for each site and compared between areas using a *t*-test. Total mussel biomass for each site was estimated as the average biomass density expanded to the area of the mussel zone (i.e., 200 m X average width of the mussel zone). Food abundance was compared in relation to goldeneye abundance, under the premise that assessments of density dependent population limitation require per capita resource availability. We calculated food abundance per duck for each area as the average food abundance per site divided by the average duck abundance per site.

Body Mass and Composition

We determined body composition of collected Barrow's goldeneyes through proximate analysis following standard methods (e.g., Esler and Grand 1994). In the laboratory, collected birds were thawed, weighed, plucked and reweighed. Wet and dry feather masses were determined. Digestive contents were removed and weighed. Because a small amount of liver tissue (average = 0.46 g; range 0.11-1.29 g) was removed from each bird for analyses of cytochrome P450 1A (Trust et al. 2000), liver composition (protein and lipid) was analyzed separately to allow for a correction of final endogenous nutrient levels including estimates of the composition of the missing liver tissue. The liver was dissected and wet and dry masses measured. The remaining carcass was ground into a homogenate, weighed, dried, and weighed again. Samples of the homogenate and the liver were lipid-extracted in a modified Soxhlet apparatus using petroleum ether. The carcass sample was then ashed in a muffle furnace to determine relative protein and mineral levels. Total liver composition was calculated by estimating the amount of lipid and protein in the dissected piece by extrapolating the proportional composition of the entire liver to the weight of the dissected piece, and then adding estimated lipid and protein of the dissected piece to the values obtained for the liver remainder. For 6 birds, the removed liver sample was not weighed, so average sample mass was used for composition correction. Total body composition was estimated by extrapolating the results from the homogenate samples to the carcass mass of the bird and then adding the calculated composition of the liver. We used general linear models to evaluate variation in body mass, total lipid, and total ash-free lean mass (i.e., protein) related to age (juvenile versus adult based on bursal involution), sex, season (December vs. February), and area (oiled Knight Island vs. unoiled Montague Island). We used Mallow's C_p values to direct model selection (Burnham and Anderson 1998). This selection method contrasts a number of models and uses the principle of parsimony to determine which model is best fit by the data (Hilborn and Mangel 1997), avoiding assumptions and biases of traditional stepping (i.e., forward, backward, and stepwise) model selection procedures (Anderson et al. 1994, Flack and Chang 1987). Using this approach to model selection, the model with the lowest C_p value is the one best supported by the data and, thus, provides the strongest inference. We interpreted inclusion of a given parameter in a selected model as evidence that the parameter was related to Barrow's goldeneye body mass or composition, after accounting for effects of other included parameters.

RESULTS

Mussel Biomass and Density

Consistent with findings of other studies (Koehl et al. 1982, Vermeer 1982, Patten et al. 1998), we found that mussels comprised the vast majority of the diet of Barrow's goldeneyes in our study areas. We found trace occurrence of whelks and fish eggs, but in amounts insignificant for understanding food constraints to population recovery. The size class distribution of consumed mussels (Fig. 1) indicated that nearly all mussels in the diet were between 5 and 25 mm, which is the size class interval that we used in subsequent analyses of NVP data.

Mussel biomass densities were similar between unoiled Montague Island and oiled Knight Island (Table 1). However, average mussel biomass per site was higher on Montague Island than Knight Island. The difference in biomass between areas was likely not an artifact of the oil spill, given the similar mussel densities, but rather was due to a difference in the width of the intertidal zone and hence appropriate habitat for mussels. The mussel zone averaged much wider on Montague Island than Knight Island (Table 1), a function of the intertidal slope, which was considerably steeper on Knight Island. Because densities of Barrow's goldeneyes were similar between areas (Table 1), per capita mussel biomass was higher on Montague Island (61.2 kg AFDW/duck) than Knight Island (27.4 kg AFDW/duck). These data are consistent with potential food limitation of populations of Barrow's goldeneyes on oiled areas, if per capita food abundance was too low to meet energetic costs.

Body Mass and Composition

Forty-seven Barrow's goldeneyes were collected, including 23 on Montague Island and 24 on Knight Island. Models describing variation in body mass, lipid, and protein of Barrow's goldeneyes are presented in Table 2. Our measure of body mass was the weight of the carcass when it was thawed in the lab for proximate analysis. Because food contents and a small piece of liver were removed in the field upon collection, thawed mass was less than field mass; however, as the same field protocol was applied to all birds, comparisons between areas are valid and informative. The best-fitting model describing body mass variation included terms for season, age, sex, and area (Table 2). Body mass averaged lower in February than December, consistent with winter body mass dynamics of many waterfowl (e.g., Thompson and Baldassarre 1990). Also, juvenile and female body mass averaged lower than adults and males, respectively, again consistent with previous studies (e.g., Whyte et al. 1986). After accounting for these effects, Barrow's goldeneye body mass was related to area (Table 2); however, body mass averaged nearly 60 g higher on oiled Knight Island, the opposite of the prediction under a hypothesis of food limitation. Similarly, protein levels varied predictably in relation to season, age, and sex, but were higher on Knight Island than Montague Island, again inconsistent with the food limitation hypothesis. Lipid reserves did not differ between areas after accounting for other sources of variation (Table 2).

DISCUSSION

Our data suggest that population recovery of Barrow's goldeneyes following the *Exxon Valdez* was not limited by food, due to lack of concordance of our data with the twin predictions under a food limitation hypothesis that mussel abundance would be lower on oil-affected areas and body mass or nutrient reserve levels would be lower. Mussel biomass per goldeneye was lower on oiled Knight Island, likely a result of differences in geomorphology (Table 1) rather than oil spill effects. However, despite differences in mussel biomass, body mass and composition data indicated that birds on oiled areas were not suffering physiological consequences of lower food availability; in fact, body mass and protein reserves were higher for birds from oiled areas than those from unoiled areas (Table 2). These data suggest not only that population recovery from the oil spill was not limited by food, but also that Barrow's goldeneye populations likely are not limited by food availability under natural conditions. Mussel abundance on Knight Island was apparently high enough to support duck densities similar to Montague Island (Table 1), without deleterious physiological consequences. Therefore, per capita mussel abundance on Montague Island greatly exceeded the amount necessary to support the numbers of goldeneyes in the study area, indicating that something other than winter food availability dictated goldeneye density in this natural, undisturbed area. Results from studies of Barrow's goldeneye habitat associations (Appendix B) are consistent with the conclusion of lack of food limitation. Densities of goldeneyes were not related to mussel biomass; under a hypothesis of food limitation, we would predict a positive association of duck densities and mussel biomass, and thus we speculated that food was not limiting and that mussel standing stock and annual productivity far exceeded predation demands.

Lack of winter food limitation of Barrow's goldeneye populations under natural conditions is supported by examination of their natural history and life history traits. Like many sea duck species, Barrow's goldeneyes exhibit philopatry to wintering sites. Winter philopatry has adaptive advantages including site familiarity (Robertson and Cooke 1999) and interannual pair reunion (Savard 1985). Strong site fidelity evolves under stable conditions (Johnson and Gaines 1990), suggesting that winter food availability is a predictable and non-limiting trait of Barrow's goldeneye winter habitats. Further, like other sea ducks, Barrow's goldeneye life histories include relatively low productivity compared to other ducks, delayed maturation, and long reproductive life spans (Goudie et al. 1994). These traits require relatively high rates of annual survival (Stearns 1992), which in turn require stable and predictable winter environments.

Different species of waterfowl have different strategies for accommodating energy demands during winter. Some species, faced with unpredictable weather or food resources, employ a strategy of flexibility in winter distribution, moving among areas in response to habitat change (Lovvorn 1989). Others have variable strategies of nutrient reserve storage and maintain reserves that are optimum based on average local conditions and degree of predictability of the wintering environment (Thompson and Baldassarre 1990). Different species have constraints regarding the energetic strategies that they can employ, based on body size (Goudie and Ankney 1986) or evolved life history or natural history characteristics. Within the range of strategies, Barrow's goldeneyes apparently return annually to areas with predictable food resources, reflecting the relative stability of coastal environments (Diefenbach et al. 1988) and mussel populations under natural conditions. However, this strategy leaves them potentially vulnerable to anthropogenically-induced changes to winter food abundance, if their strategy does not facilitate movement to other areas in the face of habitat degradation (Cooch et al. 1993). In the case of the *Exxon Valdez* spill, mussel abundance likely returned to pre-spill conditions within a few years (Highsmith et al. 1996, Houghton et al. 1996, Stekoll et al. 1996). However, if damage to mussel populations had been more severe, or persisted over longer periods, significant consequences for Barrow's goldeneyes may have resulted.

Under natural conditions, Barrow's goldeneye populations may be limited by factors on breeding areas (Savard 1988, Einarsson 1990, Erksine 1990), such as nest cavities and breeding territories. Thus, densities on wintering areas may be well below the carrying capacity of the environment. If populations are not naturally limited by food on wintering areas, effective restoration following anthropogenic disturbance may be most appropriately directed towards both ameliorating effects of the disturbance and increasing carrying capacity of breeding areas, e.g., by establishing nest boxes (Savard 1988).

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Table 1. Comparisons of mussel and Barrow's goldeneye abundance metrics (± SE), and associated intertidal physical attributes, between unoiled Montague Island and oiled Knight Island.

Parameter	Montague Island (unoiled; n = 102)	Knight Island (oiled; n = 112)	*P*
Mussel Biomass Density (g AFDW[a]/100 m^2)	1234.8 ± 139.0	1452.4 ± 153.2	0.29 (*t* = 1.04)
Mussel Abundance (kg AFDW/200 m shoreline)	57.5 ± 8.3	23.9 ± 2.5	<0.01 (*t* = 4.04)
Mussel Zone Width (m)	26.0 ± 2.8	8.7 ± 0.6	<0.01 (*t* = 6.41)
Intertidal Slope (degrees)	5.8 ± 0.4	25.5 ± 1.7	<0.01 (*t* = 10.81)
Barrow's Goldeneye Density (ducks/200 m shoreline)	0.94 ± 0.10	0.87 ± 0.09	0.60 (*t* = 0.53)

[a] Ash free dry weight.

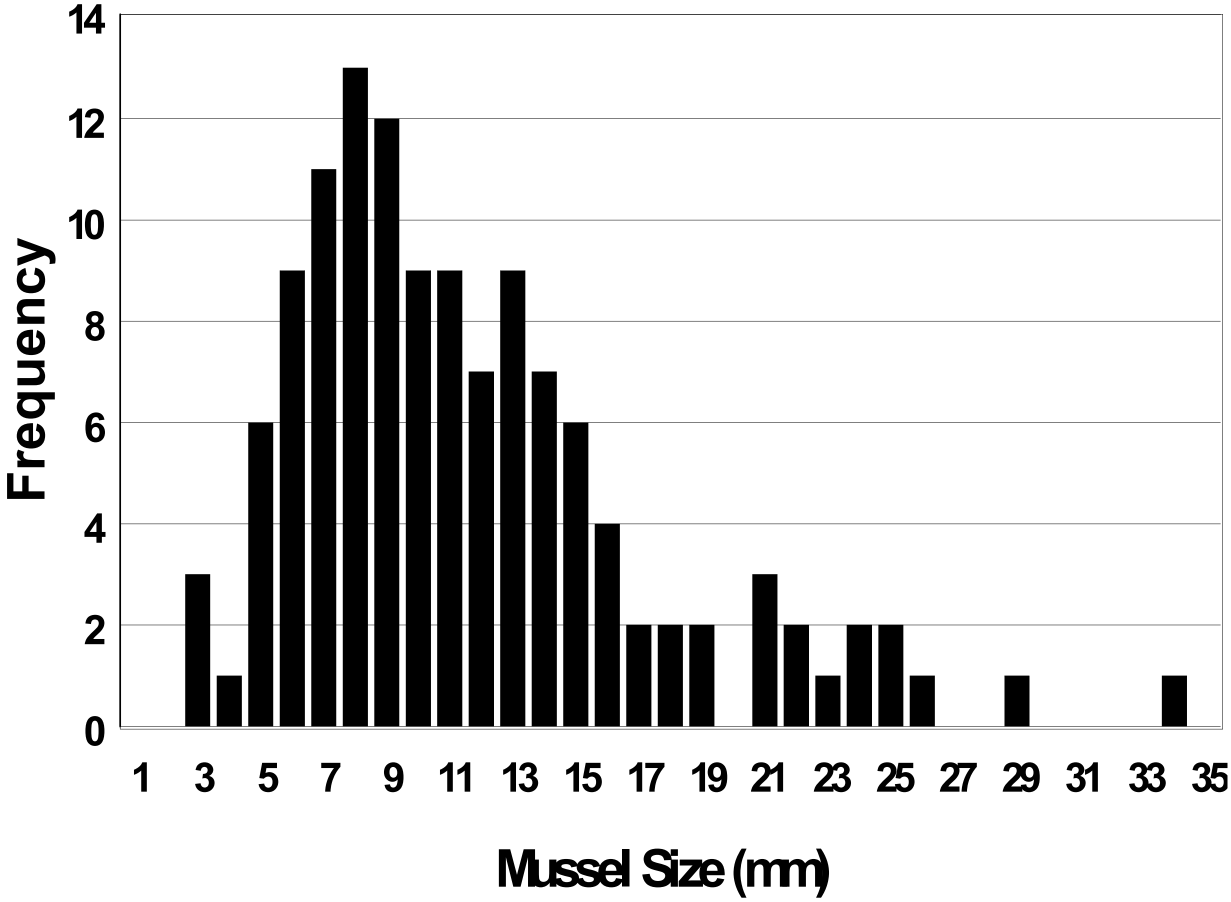
Table 2. Results of general linear model analyses to evaluate variation in Barrow's goldeneye body mass, lipid, and protein in relation to age, sex, season, and area.

Variable	r^2	Parameter	Estimate (± SE)
Body Mass	0.90	Intercept	1211.78 (± 19.68)
		Season[a]	-32.92 (± 20.39)
		Age[b]	-125.87 (± 24.95)
		Sex[c]	-357.60 (± 19.99)
		Area[d]	59.50 (± 19.56)
Lipid	0.28	Intercept	92.87 (± 8.20)
		Season	-15.91 (± 9.28)
		Age	-20.97 (± 11.32)
		Sex	-30.95 (± 9.06)
Protein[e]	0.91	Intercept	213.20 (± 3.24)
		Season	-8.70 (± 3.36)
		Age	-18.09 (± 4.11)
		Sex	-65.88 (± 3.29)
		Area	9.17 (± 3.22)

[a] Reference value for season is December; the parameter estimate is the difference in February.
[b] Reference value for age is adult; the parameter estimate is the difference of juveniles.
[c] Reference value for sex is male; the parameter estimate is the difference of females.
[d] Reference value for area is unoiled Montague Island; the parameter estimate is the difference on oiled Knight Island.
[e] Ash-free dry lean mass.

FIGURE HEADINGS

Figure 1. Mussel size class distribution in Barrow's goldeneye diets from Prince William Sound, 1996-1997.


Frequency
0
2
4
6
8
10
12
14
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
Mussel Size (mm)

APPENDIX B

Densities of Barrow's Goldeneyes During Winter in Prince William Sound, Alaska in Relation to Habitat, Food, and History of Oil Contamination[2]

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Abstract.--We evaluated variation in densities of Barrow's Goldeneyes (*Bucephala islandica*) during winter over 214 sites within oiled and unoiled study areas in Prince William Sound, Alaska in relation to physical habitat attributes, prey biomass, and history of habitat contamination by the 1989 *Exxon Valdez* oil spill. Using general linear model analyses, we found that goldeneye densities were positively associated with occurrence of a stream within 200 m, lack of exposure to wind and waves, and mixed (versus rocky) substrate; we speculate

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that these associations relate to habitat profitability via selection of beneficial attributes and avoidance of detrimental features. We also determined that biomass of blue mussels (*Mytilus trossulus*), the primary prey, was not related to Barrow's Goldeneye densities; we suggest that mussel standing stock exceeds predation demands on our study areas and, thus, does not dictate goldeneye distribution. After accounting for habitat effects, we detected no effect of history of oil contamination on Barrow's Goldeneye densities, suggesting that populations have recovered from the oil spill. Although other studies documented hydrocarbon exposure in Barrow's Goldeneyes through at least 1997, either the level of exposure did not affect populations via reductions in survival or productivity, or effects of oil exposure were offset by immigration.

Key words.--Barrow's Goldeneye, *Bucephala islandica*, density, *Exxon Valdez* oil spill, food, habitat, population recovery.

Waterbirds 23(3):425-431.

Winter habitat affiliations of sea ducks, and effects of anthropogenic perturbations of winter habitats on sea duck populations, are poorly known. Due to their life histories, sea ducks require low annual mortality relative to other ducks (Goudie et al. 1994), suggesting that stable and undisturbed nonbreeding environments are particularly important for maintaining healthy populations. Therefore, management of human activities in sea duck winter habitats is enhanced through definition of habitat attributes that are associated with sea duck abundance and distribution.

Barrow's Goldeneyes (*Bucephala islandica*) winter almost exclusively in coastal marine areas (Bellrose 1980), where they feed primarily on blue mussels (*Mytilus trossulus*)(Koehl et al. 1982, Vermeer 1982, D. Esler, unpubl. data). Although distributions of Barrow's Goldeneyes have been described in relation to habitat and food resources during the breeding season (e.g., Einarsson 1988, 1990), factors related to winter densities have rarely been addressed (Vermeer 1982).

In this study we evaluated Barrow's Goldeneye densities in relation to a suite of physical habitat characteristics and blue mussel biomass to document environmental attributes important to wintering populations of this sea duck. We also assessed the effect of history of contamination from the 1989 *Exxon Valdez* oil spill, in which nearly 42 million liters of oil were leaked into Prince William Sound, Alaska. Immediate and direct mortality of birds following the oil spill was high and, within Prince William Sound, nearly a quarter of recovered carcasses were sea ducks (Piatt et al. 1990).

Barrow's Goldeneyes are a conspicuous and abundant member of the winter avifauna of Prince William Sound (Lance et al. 1999) and their populations may be particularly susceptible to injury and constraints to recovery from the *Exxon Valdez* oil spill. As much as 40% of the spilled oil was deposited in intertidal and shallow subtidal zones of Prince William Sound (Galt et al. 1991, Wolfe et al. 1994), the areas used by Barrow's Goldeneyes. Barrow's Goldeneyes were one of a small number of species that Day et al. (1997) described as having not recovered from initial oil spill effects by 1991. Initial effects of the spill and clean up reduced mussel abundance in some areas in the years immediately post-spill (Highsmith et al. 1996, Houghton et al. 1996). Longer-term, chronic effects of the oil spill also are a concern for Barrow's Goldeneye populations because, although much of the oil dissipated within a few years of the spill, some residual oil was still documented in intertidal habitats as recently as 1997 (Hayes and Michel 1999) and 1999 (Pat Harris, National Oceanographic and Atmospheric Administration, Auke Bay Laboratory, pers. comm.). Further, mussels in heavily oiled areas contained hydrocarbon contamination through at least 1995 (Babcock et al. 1997). Finally, Barrow's Goldeneyes, like other sea ducks, have intrinsically low rates of population growth because they are long-lived with relatively low annual productivity (Goudie et al. 1994). Thus, high potential exists for injury and lack of recovery of Barrow's Goldeneye populations following the *Exxon Valdez* oil spill.

Recognizing that oiled areas of Prince William Sound likely had habitat attributes that differed from unoiled areas, we evaluated oil spill effects using a design in which we compared densities of Barrow's Goldeneyes between oiled and unoiled areas after controlling for intrinsic area differences (Wiens and Parker 1995). Lower densities than expected on oiled areas (after accounting for other environmental factors) would lead to an interpretation of lack of full population recovery. Lack of recovery could result from either failure of the population to fully rebound following initial oil spill effects or from persistent residual effects.

METHODS

Prince William Sound is located on the southcentral coast of Alaska (Fig. 1). Specific study areas included two bays on Knight Island, Herring Bay and Bay of Isles, which were heavily oiled by the *Exxon Valdez* spill, and the Stockdale Harbor and Port Chalmers region of northwestern Montague Island, which was selected as the unoiled study area because of the close proximity to the oil spill zone, thus minimizing area differences beyond habitat attributes (e.g., climate).

Our approach was to (1) measure Barrow's Goldeneye densities, habitat attributes, and food abundance at a large number of sites within oiled and unoiled study areas, (2) use general linear models to evaluate relationships of habitat and food with duck densities, and (3) determine effects of oiling history on Barrow's Goldeneye densities after accounting for habitat and food effects.

Data Collection

We collected data on Barrow's Goldeneye abundance, physical habitat characteristics, and mussel biomass at 214 sites (112 on Knight Island and 102 on Montague Island) within our study areas. To select sites for sampling, the shoreline of each study area (75.7 km on Knight Island and 74.1 km on Montague Island) was divided into contiguous 200 m segments. From randomly selected start points, segments were then systematically selected as sampling sites.

We conducted surveys of Barrow's Goldeneye numbers and distribution during 4-12 December 1995, 12-24 February 1996, 4-14 December 1996, and 14-23 February 1997, completing five replicates on Knight Island and seven on Montague Island. Surveys involved a census of the zone within 200 m from shore along the entire shoreline for each study area. Survey craft were staffed by a two or three person team consisting of a boat operator/observer and at least one observer/data recorder. We mapped locations and flock sizes of all Barrow's Goldeneyes on mylar overlays of 1:15,000 aerial photos. Locations were digitized using a geographic information system (GIS).

To calculate average Barrow's Goldeneye densities associated with each site, we calculated the number of ducks detected during shoreline censuses within 200 m linear shoreline distance of the midpoint of each sampling site using a GIS. Duck densities were expressed as the average number of birds within the designated shoreline distance over all replicate surveys.

At each site, a number of habitat characteristics were documented during summers of 1996 and 1997 that we felt could be related to winter Barrow's Goldeneye densities, including: *exposure* - a description of wind and wave action, categorized as full exposure, partial exposure, and not exposed; *dominant substrate* - categorized as rocky (bedrock and boulder areas) and mixed (unconsolidated, i.e., various mixtures of sand, pebbles, and cobble); *distance to stream mouth* - straight line distance from the midpoint of the sampling site to nearest stream mouth measured by a GIS and categorized as < 200 m, 200-500 m, 500-1000 m, and > 1000 m; *distance to reef* - straight line distance from the midpoint of the sampling site to the nearest offshore reef (defined as covered at high tide but exposed at lower tides) measured by a GIS and categorized as 200-500 m, 500-1000 m, and > 1000 m; and *intertidal slope* - the average slope (in degrees) of the mussel zone.

At each site we also estimated biomass of blue mussels with shell lengths between 5 and 25 mm, the size range that Barrow's Goldeneyes consume (D. Esler, unpubl. data). We established 10 transects within each site perpendicular to the shoreline at 20 m intervals, with the first at a randomly selected position. We removed all mussels from within a 500 cm^2 quadrat placed at a randomly selected location along each transect and recorded the width of the mussel zone. Collected mussels were sorted by size class and counted. Lengths of all mussels between 5 and 25 mm were measured. Ash-free dry weight (AFDW) of each mussel was estimated based on predictive equations of biomass by length derived from samples collected at the study locations during May-July 1996. Average biomass density (g AFDW/100 m^2) was calculated for each site. Total blue mussel biomass for each site was estimated as the average biomass density expanded to the area of the mussel zone (i.e., 200 m X average width of the mussel zone).

Data Analysis

We conducted general linear model analyses using SAS (SAS Institute Inc., Cary, North Carolina, USA) to assess relationships of habitat attributes and mussel biomass (explanatory variables) to average Barrow's Goldeneye densities (the response variable), using each sampling site as an observation. In examination of scatterplots of Barrow's Goldeneye densities by our continuous variables (intertidal slope and mussel biomass), we found that the distributions violated the assumption of linearity; by conducting a square root transformation of Barrow's Goldeneye densities, the assumption of linearity was met, therefore we used the square root of average Barrow's Goldeneye densities in subsequent regression analyses. Categorical variables were included as a set of indicator variables, with one level of each variable designated as the reference level and, thus, not included in model selection procedures (Ramsey and Schafer 1997).

Our approach was to first describe variation in duck densities related to habitat attributes and mussel biomass and then assess effects of oiling history after accounting for effects of habitat and food. Therefore, we first analyzed data from each area (oiled Knight Island and unoiled Montague Island) separately, using Mallow's C_p values to direct model selection (Burnham and Anderson 1998). This selection method contrasts a number of models and uses the principle of parsimony to determine which model is best fit by the data (Hilborn and Mangel 1997), avoiding assumptions and biases of traditional stepping (i.e., forward, backward, and stepwise) model selection procedures (Anderson et al. 1994, Flack and Chang 1987). Using this approach to model selection, the model with the lowest C_p value is the one best supported by the data and, thus, provides the strongest inference. We interpreted inclusion of a given parameter in a selected model as evidence that the parameter was related to Barrow's Goldeneye densities, after accounting for effects of other included parameters. For our analyses, we considered the inference from the top five models (i.e., lowest five C_p values) to accommodate uncertainty inherent in any model selection process. After determining factors related to duck densities for each area separately, we then selected models that best explained variation in duck densities for both areas combined, using any variable that was included in the best-fitting model for either area along with interaction terms for these variables by area. Finally, an area (oiling history) term was added to each of the five best-fitting models for both areas combined to determine whether oiling history explained additional variation in the data (i.e., variation beyond that already explained by the habitat variables), based on the type III sum of squares *F* statistic for the area term and $\alpha = 0.05$.

RESULTS

Average numbers of Barrow's Goldeneyes per site were similar between oiled Knight Island and unoiled Montague Island study areas (Table 1). Some habitat attributes differed between areas. Intertidal slope averaged steeper on Knight Island than Montague Island and rocky substrate dominated on Knight Island, whereas mixed substrate was more prevalent on Montague Island. Also, average mussel biomass per site was higher on Montague Island than Knight Island; mussel biomass densities (g AFDW/100 $m^2 \pm$ SE) were similar (1234.8 ± 139.0 versus 1452.4 ± 153.2, respectively) between areas but the mussel zone averaged much wider on Montague Island than Knight Island (26.0 ± 2.8 m versus 8.7 ± 0.6 m, respectively), due to the shallower intertidal slope. Our intent was to account for differences in habitat attributes between areas before evaluating the effect of oiling history on Barrow's Goldeneye densities.

On unoiled Montague Island, Barrow's Goldeneye densities were positively related to presence of a stream within 200 m in all five best-fitting models (Table 2), relative to all other stream distance categories. Also, goldeneye densities at unexposed sites were consistently higher than at partially or fully exposed sites. No other habitat attributes showed strong, consistent relationships to goldeneye densities on Montague Island. On oiled Knight Island, occurrence of a stream within 200 m was positively associated with higher duck densities in the five best-fitting models (Table 2), similar to results from Montague Island. However, unlike Montague Island, Barrow's Goldeneye densities on Knight Island were not consistently related to level of exposure and were consistently, positively associated with mixed substrate.

Model selection for both areas combined included the indicator variables for mixed substrate, occurrence of a stream within 200 m, and no exposure, as well as their interactions with area. These three main effects were the only variables included in the best model for either area considered separately and, further, were the only variables for which $P < 0.05$ in any of the top five models for either area. In the best-fitting model for both areas combined (Model 1; Table 2), only the three main effects were selected and they were all positively associated with duck densities. That pattern was generally consistent throughout the other four best-fitting models. Main effects of no exposure were positively associated with goldeneye densities in all models; however, negative interactions of area and the no exposure variable in three of the models indicated that the effect of the no exposure variable was stronger on Montague Island, in agreement with results for each area separately. Main effects of mixed substrate were positively associated with goldeneye densities in four of the five best-fitting models. In the model where the mixed substrate main effect was not included (Model 2), and in Model 5 where the parameter estimate for mixed substrate was smaller than other models, positive interaction terms were included, suggesting a stronger effect of mixed substrate on Knight Island than Montague Island, which is consistent with analyses of each area separately.

Because none of the variables included in the best-fitting model for areas combined (Model 1; Table 2) violated the assumption of linearity for general linear models, we ran an analysis with these variables using untransformed Barrow's Goldeneye densities as the response variable. This analysis provided parameter estimates (± SE) that are directly interpretable as the effect of these variables on the average number of Barrow's Goldeneyes per 400 m of shoreline. The resultant model was:

Barrow's Goldeneye Numbers = 0.9629 (± 0.1618) + 0.6428 (± 0.2417) No Exposure + 0.6063 (± 0.2435) Mixed Substrate + 2.9144 (± 0.3729) Stream Distance < 200 m

None of the five best-fitting models for areas combined indicated an effect of area on winter Barrow's Goldeneye densities (Table 2), which we interpreted as evidence that history of oil contamination was not related to goldeneye densities. In other words, Barrow's Goldeneye densities on oiled Knight Island were similar to what would be expected based on habitat attributes alone. Parameter estimates for area were small and, further, were positive, the opposite of the expected direction under a hypothesis of oil spill effects on goldeneye densities.

DISCUSSION

Barrow's Goldeneye densities were related to several of the habitat attributes that we measured. Presumably, these associations relate to habitat profitability and reflect solutions to the optimization process of balancing benefits of habitats (e.g., energy intake) against risks (e.g., from predation or weather)(Rosenzweig 1985). Life histories of sea ducks, which typically include relatively low and variable annual production (Goudie et al. 1994), require long reproductive life spans and, hence, low rates of annual mortality (Stearns 1992). Therefore, winter habitats used by sea ducks, including Barrow's goldeneyes, must provide resources to meet energetic demands and must predictably confer a high likelihood of survival.

Occurrence of a nearby stream was consistently, strongly, and positively related to Barrow's Goldeneye densities. Presence of a stream may have the benefit of providing fresh water to reduce salt stress of ducks that feed on marine invertebrates (Nyström and Pehrsson 1988). Barrow's goldeneye densities tended to be higher at unexposed sites, perhaps reflecting protection from inclement winter weather. This relationship was strongest on Montague Island, which had relatively more fully exposed sites than Knight Island (Table 1). Also, mixed substrate was positively associated with goldeneye densities, particularly on Knight Island, where the mixed substrate type was less common. We speculate that mussels may be more difficult to remove from rocky substrate than from other substrates, which may influence this relationship.

We found no evidence that the occurrence of reefs was related to Barrow's Goldeneye densities. We measured reef distance primarily for concurrent studies of Harlequin Duck (*Histrionicus histrionicus*) density variation because of the documented affiliation of this species with offshore reefs (Goudie and Ankney 1988). While we found strong associations between Harlequin Duck densities and occurrence of a reef (D. Esler, unpubl. data), the lack of a relationship for Barrow's Goldeneyes is not surprising given their strong affiliation with unexposed sites, their preference for mixed rather than rocky substrate, and our observation that they almost never occurred offshore during the day. Intertidal slope also showed little relationship to Barrow's Goldeneye densities, despite areas with shallower slopes having correspondingly larger foraging areas.

Other studies have suggested that sea duck distribution is affected by food abundance (Nilsson 1972, Stott and Olson 1973, Guillemette et al. 1993). However, our results indicate that Barrow's Goldeneye densities were not strongly related to mussel biomass. We speculate that mussel standing stock far exceeded predation demands on our study areas and, thus, other habitat attributes had stronger influences on duck distributions. Other studies (Nilsson 1969, 1972) have similarly concluded that diving duck predation has little influence on annual mussel abundance and productivity.

We found no evidence for deleterious effects of the *Exxon Valdez* oil spill on Barrow's Goldeneye densities. However, Trust et al. (2000) found that Barrow's Goldeneyes from oiled areas had higher levels of cytochrome P4501A induction (an indicator of hydrocarbon exposure) than those from unoiled areas. Either the level of contamination from residual oil was too low to cause individual physiological consequences that would lead to population-level demographic differences (e.g., survival reductions) or, alternatively, individuals were affected but dispersal rates were high enough to mask loss of individuals as habitats were reoccupied (i.e., source/sink dynamic; Pulliam 1988). The latter alternative seems unlikely given high levels of philopatry seen in many sea ducks throughout the annual cycle (Savard and Eadie 1989, Cooke et al. 2000). However, site fidelity, dispersal, and survival of Barrow's Goldeneyes during winter are essentially unknown, so relative support for these alternative hypotheses can not be determined.

Our results for Barrow's Goldeneyes are dramatically different from those of concurrent studies of Harlequin Ducks (D. Esler, unpubl. data), for which densities were significantly lower on oiled areas than unoiled, after controlling for effects of habitats. Harlequin ducks may be particularly susceptible to environmental perturbations during winter due to their inability to accommodate increased energetic demands (Goudie and Ankney 1986) and, thus, may have been especially vulnerable to effects of the oil spill. Barrow's Goldeneyes, with their larger body mass, may be less sensitive. Harlequin ducks are known to have high fidelity to nonbreeding sites (Cooke et al. 2000) and winter survival on oiled areas of Prince William Sound was documented to be lower than on unoiled areas (Esler et al. 2000); these parameters are unknown for Barrow's Goldeneyes.

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Table 1. Barrow's Goldeneye winter densities and habitat attributes at sampling sites (200 m shoreline segments) within Prince William Sound, Alaska, 1995-1997. Data for categorical variables are shown as number of sites and, parenthetically, percentage of sites within each category.

Parameter	Montague Island (Unoiled) (*n* = 102)	Knight Island (Oiled) (*n* = 112)
Average (± SE) Barrow's Goldeneyes (ducks/400 m)	1.88 (±0.21)	1.74 (±0.17)
Average (± SE) intertidal slope (degrees)	5.85 (±0.39)	25.46 (±1.69)
Average (± SE) mussel biomass (kg AFDW)	57.49 (±8.26)	23.87 (±2.51)
Exposure		
Full	24 (24%)	15 (13%)
Partial	35 (34%)	48 (43%)
None	43 (42%)	49 (44%)
Dominant substrate		
Rocky	38 (37%)	82 (73%)
Mixed	64 (63%)	30 (27%)
Distance to stream mouth		
0-200 m	10 (10%)	12 (11%)
200-500 m	10 (10%)	19 (17%)
500-1000 m	14 (14%)	22 (20%)
> 1000 m	68 (67%)	59 (53%)
Distance to reef		
200-500 m	10 (10%)	8 (7%)
500-1000 m	18 (18%)	22 (20%)
> 1000 m	74 (73%)	82 (73%)

Table 2. Estimated parameters from general linear models describing variation in winter (1995-1997) Barrow's Goldeneye densities (square root transformed) in Prince William Sound, Alaska in relation to habitat attributes, mussel biomass, and history of contamination by the *Exxon Valdez* oil spill. The 5 best-fitting models (lowest C_p values) are presented for Montague (unoiled) and Knight (oiled) islands separately. Also, parameter estimates are presented for an analysis in which areas were combined, habitat variables included in Model 1 from each area (and their interactions with area) were included in model selection, and the effect of area (oiling history) was evaluated after having accounted for intrinsic habitat differences between areas.

		Habitat model parameter estimates[a]											Interaction terms[b,c]			
	Mallow's		Intertidal	Mussel	Exposure		Substrate	Stream distance (m)			Reef distance (m)		No	Mixed	Stream	
Model	C_p	Intercept	slope	biomass	None	Partial	Mixed	0-200	200-500	500-1000	200-500	500-1000	exposure	substrate	0-200m	Area[c,d]
Montague Island																
1	-1.8712	0.7997	-------[e]	-------	0.5434	-------	-------	1.0742	-------	-------	-------	-------	NA[f]	NA	NA	NA
2	-0.7063	0.7426	-------	-------	0.4597	-------	0.1546	1.0269	-------	-------	-------	-------	NA	NA	NA	NA
3	-0.6898	0.8297	-------	-0.0007	0.5746	-------	-------	1.0643	-------	-------	-------	-------	NA	NA	NA	NA
4	-0.5484	0.8952	-0.0147	-------	0.5348	-------	-------	1.0138	-------	-------	-------	-------	NA	NA	NA	NA
5	-0.2338	0.8270	-------	-------	0.5242	-------	-------	1.0690	-------	-------	-------	-0.1060	NA	NA	NA	NA
Knight Island																
1	2.3998	0.8821	-------	-------	-------	-------	0.3800	0.8412	-------	-------	-------	-------	NA	NA	NA	NA
2	2.8801	0.8211	-------	0.0032	-------	-------	0.3267	0.8304	-------	-------	-------	-------	NA	NA	NA	NA
3	3.1943	0.7390	-------	0.0041	0.1850	-------	0.2670	0.7916	-------	-------	-------	-------	NA	NA	NA	NA
4	3.4915	0.8514	-------	-------	-------	-------	0.3592	0.8823	-------	0.1620	-------	-------	NA	NA	NA	NA
5	3.5152	0.8365	-------	-------	0.1296	-------	0.3485	0.8162	-------	-------	-------	-------	NA	NA	NA	NA
Areas combined																
1	3.6617	0.7737	NA	NA	0.2589	NA	0.2853	0.8976	NA	NA	NA	NA	-------	-------	-------	0.0361(0.1003);0.7192

2	4.0966	0.8200	NA	NA	0.5425	NA	-------	0.9355	NA	NA	NA	NA	-0.4131	0.3412	-------	0.0221(0.1241);0.8590
3	4.7992	0.7846	NA	NA	0.3493	NA	0.2432	0.9117	NA	NA	NA	NA	-0.1426	-------	-------	0.1382(0.1235);0.2646
4	5.3341	0.7761	NA	NA	0.2639	NA	0.2746	0.9910	NA	NA	NA	NA	-------	-------	-0.1670	0.0559(0.1044);0.5928
5	5.4172	0.7967	NA	NA	0.4505	NA	0.1237	0.9163	NA	NA	NA	NA	-0.3000	0.2313	-------	0.0895(0.1403);0.5245

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[a] Reference values for categorical model parameters were set as: exposure = full; substrate = rocky; stream distance = >1000 m; and reef distance = >1000 m. When parameter estimates are not listed for all levels of a categorical variable, the estimate should be interpreted as the effect of the listed level in relation to all unlisted levels combined.

[b] Interactions of habitat parameters by area; only interactions included in model selection procedures are listed.

[c] Reference value for area = unoiled Montague Island.

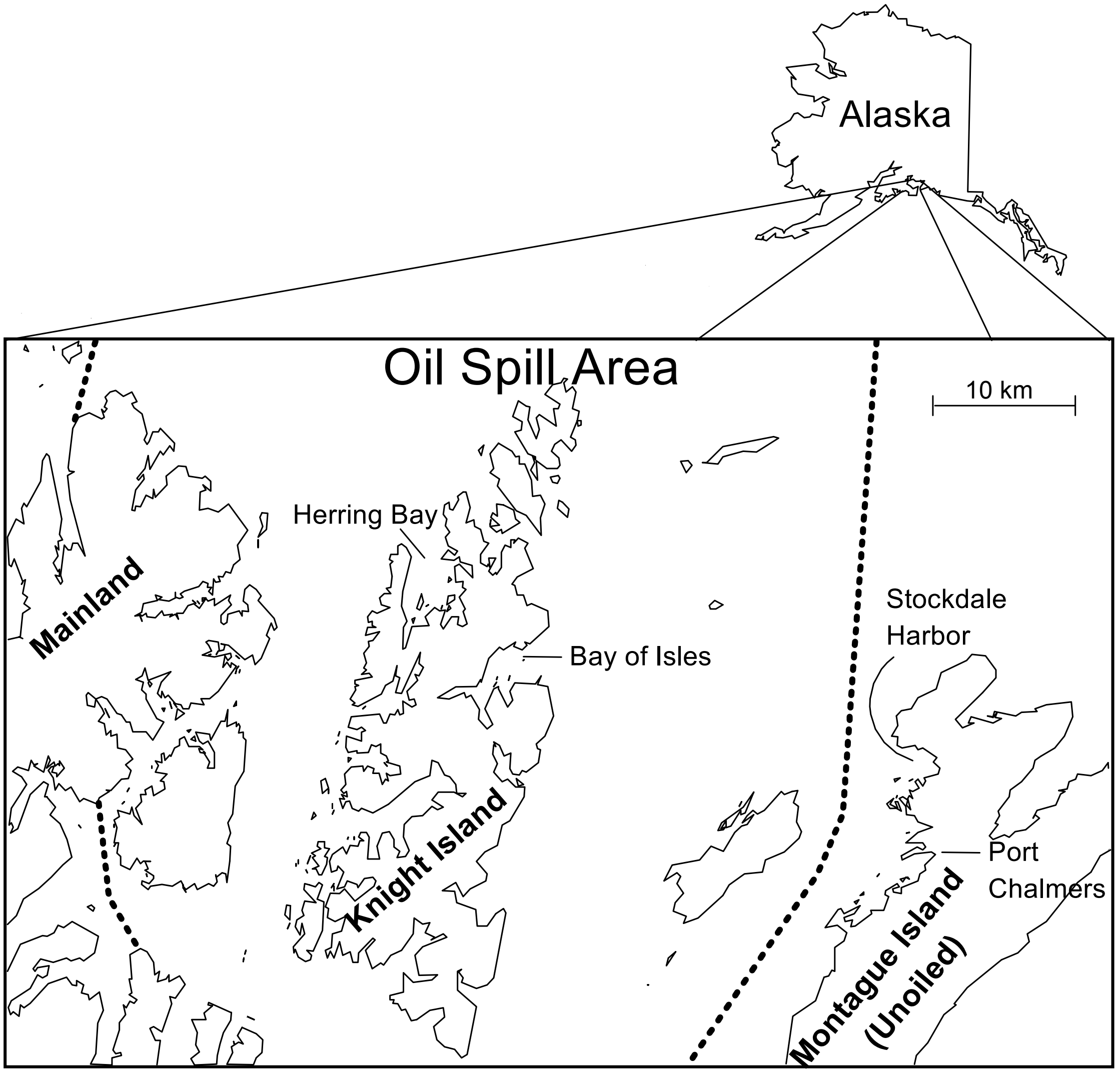
[d] Results of area term are presented as the parameter estimate (SE); *P* value; results are interpreted as the effect of oiling history.

[e] ------- indicates that the parameter was not selected for inclusion in the model.

[f] NA = not applicable; parameter was not included in model selection procedures.

FIGURE LEGENDS

Figure 1. Study areas for evaluating variation in winter Barrow's Goldeneye densities, Prince William Sound, Alaska, 1995-1997. The area contaminated by the *Exxon Valdez* oil spill is bounded by bold, dashed lines.


Alaska
Oil Spill Area
10 km
Herring Bay
Mainland
Bay of Isles
Knight Island
Stockdale Harbor
Port Chalmers
Montague Island (Unoiled)