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Northern Abalone Case Study for the Determination of SARA Critical Habitat

Étude de cas sur l’ormeau nordique visant à déterminer son habitat essentiel dans le contexte de la LEP

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Abstract

This evaluation of critical habitat (SARA context) is one of a series of seven national case studies to investigate what critical habitat means for aquatic and marine species. It looks at this question for northern abalone (*Haliotis kamtschatkana*) in British Columbia, a cryptic, broadcast spawning, benthic gastropod of limited mobility that has been listed as "threatened" by COSEWIC. Little is know about this species' larval planktonic dispersal or coastal adult spatial distribution. However, populations are widespread and contagious in distribution, and recruitment has been declining for the past two decades. Over-harvesting during the fishery, which was terminated in 1990, and subsequent poaching are believed to have contributed to the recent low recruitment. To determine critical habitat for abalone, the following steps were adopted: 1) estimate total potential habitat suitable for northern abalone over selected areas of the BC coast; 2) model potential abalone larval dispersal to determine dispersal characteristics and the likely scale of source and sink populations, and 3) identify subsequent studies to evaluate predictions made, and to refine the critical habitat assessment procedure for abalone developed and proposed here. Predictions of suitable abalone habitat for the west coast of Vancouver Island and Haida Gwaii (Queen Charlotte Islands) were produced, and larval dispersal modeling was conducted within the Broken Islands in Barkley Sound. This latter portion of the study suggested that specific spatial areas may have larger, more consistent abalone recruitment than others. Suggestions as to how to identify critical abalone habitat are made, given the data that are currently available.

Résumé

Cette évaluation de l'habitat essentiel (dans le contexte de la LEP) fait partie d'une série de sept études de cas nationales visant à étudier ce que l'habitat essentiel signifie pour des espèces aquatiques. Ce rapport aborde donc l'habitat essentiel l'ormeau nordique (*Haliotis kamtschatkana*) en Colombie-Britannique; il s'agit d'un gastropode benthique cryptique, à mobilité restreinte, qui expulse ses gamètes dans l'eau et qui a été désigné espèce « menacée » par le COSEPAC. On en sait peu sur la dispersion des larves planctoniques et la répartition spatiale le long des côtes des adultes de cette espèce. Ses populations sont largement répandues et présentent une répartition contagieuse; le recrutement diminue depuis deux décennies. On croit que la surpêche avant 1990, année à laquelle la pêche de l'ormeau nordique a été interdite, et le braconnage par la suite ont contribué au faible recrutement. Les étapes suivantes ont été suivies pour déterminer l'habitat essentiel de l'ormeau : 1) estimer la superficie totale de l'habitat qui conviendrait à l'ormeau nordique dans certaines régions côtières de la C.-B., 2) modéliser la dispersion potentielle des larves d'ormeau pour déterminer les caractéristiques de dispersion ainsi que l'ampleur des populations sources et des populations réceptrices et 3) déterminer les études à effectuer pour évaluer les prévisions faites et améliorer la procédure d'évaluation de l'habitat essentiel de l'ormeau mise au point et proposée dans la présente étude. Des prévisions de l'habitat qui convient à l'ormeau le long de la côte ouest de l'île de Vancouver et à Haida Gwaii (îles de la Reine-Charlotte) ont été faites, et la dispersion des larves dans le secteur des îles Broken (baie Barkley), a été modélisée. Cette dernière partie de l'étude porte à croire que le recrutement de l'ormeau pourrait être plus fort et plus uniforme dans certaines régions que dans d'autres. Des suggestions sont présentées sur la façon de déterminer l'habitat essentiel de l'ormeau à partir des données actuellement disponibles.

TABLE OF CONTENTS

1 Introduction

In November 2001, a recovery team was formed to prepare the National Recovery Strategy for northern abalone (*Haliotis kamtschatkana,* presently listed as “threatened”). The immediate goal of the recovery strategy was to halt the decline of existing wild northern abalone populations in order to reduce the risk of northern abalone becoming listed as “endangered” in British Columbia (BC). The long-term recovery goal was to increase the number and densities of wild northern abalone to levels where the population become self-sustainable in BC within each of the five biogeographic zones, i.e., Haida Gwaii (Queen Charlotte Islands (QCI)), Queen Charlotte and Johnstone Straits, North and Central Coast, Georgia Basin, and the West Coast of Vancouver Island (VI), in order to remove northern abalone from threatened status (Abalone Recovery Team 2002). The recovery team identified the following activities that were needed to facilitate the goals of the recovery strategy:

- maintain fishery closures;
- develop and implement a proactive protective plan;
- develop a communication campaign to stop illegal harvest and raise public awareness;
- undertake research and rebuilding experiments;
- monitor population status

The short-term objectives of the recovery strategy for the next five years are to: 1) ensure that mean densities of marketable adult (>100 mm in length) abalone do not decline below 0.1 per m^2 at surveyed index sites, 2) that the percentage of surveyed index sites without these adult abalone (at 0.1 per m^2) does not increase to greater than 60%, and 3) to develop indices of abundance for other areas of the coast (DFO 2003b). In August 2003, the recovery team completed a draft action plan, a component of the National Recovery Strategy for northern abalone in British Columbia.

“Critical habitat” (May 2004, R:/Critical Habitat/Guidelines/DRAFT Guidelines - Tech Guide for ID of Population & Distribution Objectives + Identification of Critical Habitat) refers to habitat that is necessary for the survival or recovery of a listed wildlife species and that is identified as the species’ critical habitat in the recovery strategy or in an action plan for the species.

Ideally, critical habitat is the habitat upon which populations of the species are thought to depend for viability (from low to high depending how ambitious the goal ~ survival or recovery, conceivably to a level that could allow some exploitation). In this paper, we consider critical habitat to be the minimum value referred to above, i.e., the habitat required to support spatially discrete viable populations sufficient to permit the species to be down-listed from “threatened” to of “special concern”. A number of populations will be needed to ensure that an accidental catastrophic destruction of a few will not acceptably affect survival of the species in BC as a whole.

According to the Species at Risk Act (SARA), critical habitat identification is to proceed if there are sufficient data to: (1) determine the species' primary biological needs and key habitat attributes, (2) identify threats to the species, (3) identify the general distribution as well as some specific local populations, (4) develop a conceptual or quantitative model of species' habitat and species' demography, and (5) conduct adequate model validation. We believe the data are sufficient to initiate critical habitat designation for abalone in British Columbia, and present below our initial efforts to do so. Given the limited resources available, the full identification of critical habitat for abalone was not completed. However, we have obtained significant, promising results that we suggest can lead to critical habitat identification if pursued further.

This paper in one of a number of case studies being undertaken on both aquatic and marine species to identify what critical habitat might mean in the context of these species, and to provide initial thoughts with respect to the development of “critical habitat guidelines for marine and aquatic species”. As such, the approach taken in this paper needs to be considered in the context of how it might be applied to other similar benthic species that are also listed by COSEWIC, and that will later need to have their critical habitats also identified.

2 Abalone Biology

2.1 Background Research of Species Life History and Ecology

2.1.1 Life History

Northern abalone are believed to have a 1:1 sex ratio, and reach sexual maturity at about three years, have a harvestable size (100 mm, when there was a fishery) at about 6-8 years, and live to a maximum age of perhaps 50 years (Breen 1980, Sloan and Breen 1988), although the average longevity of northern abalone is likely much less.

2.1.2 Spawning

Northern abalone broadcast spawn synchronously, with groups of males and females in close proximity in shallow waters, releasing their gametes into the water column (Breen and Adkins 1980). Cues that cause mass spawning in abalone can include environmental factors such as temperature changes (Sloan and Breen 1988), and minor storms and in the South Pacific, typhoons (Sasaki and Shepherd 1995). Current understanding of viable abalone populations suggests there that local densities of mature abalone must be sufficiently high within suitable abalone habitat, with abalone close enough together to successfully spawn and produce viable offspring (Abalone Recovery Team 2002). Although abalone are mobile, adults likely only move over a range of a few hundred metres at most during their lives (Jamieson 1999a). The research of Babcock and Keesing (1999) indicated that in populations of *H. laevigata* where spawning individuals are separated by distances of 1.6 m or greater, fertilization may be expected to be 50% or less and decreases rapidly with increasing distance. Other research (Rothaus and Friedman 2003) reported that based on a density between 0.15 and 0.33 per m^2, abalone must be within 1.0-2.0 m of one another for successful fertilization.

Levitan et. al (1992) investigated the fertilization success of sea urchin (*Strongylocentrotus franciscanus*) by examining the number of spawning individuals and their degree of aggregation. The results indicated that both the distribution and abundance of spawning organisms can have a profound influence on individual reproductive success and that sperm limitation may be a typical condition in many populations. These results also suggest that the “Allee effect” (Allee et al. 1949), the extent to which reproductive success becomes depressed at low densities, (Shepherd and Partington 1995) can play an important role in the dynamics of free-spawning populations (Levitan et. al 1992) leading to reduced population growth and possible extinction in abalone.

Northern abalone fecundity is greatly influenced by size, and northern abalone of 70, 100, 120 and 140 mm shell length is estimated at 1, 2, 5 and 12 million eggs per female (Campbell et al. 2003).

2.1.3 Larval Dispersal

The fertilized eggs of northern abalone sink and hatch within days into phototactic, free-swimming larvae which rise in the water column and become available for potential transport in currents (Olsen 1984; Calderwood 1985). The planktonic phase of abalone species is generally short (Mottet 1978) and in northern abalone is reported to be 5 to 6 days (Olsen 1984). Prince et. al (1988) studied *H. rubra* and found that larval dispersal was in the range of 10-100 m. Pearce et al. (2003) reported 10-11 days for egg hatching to settlement time at 11^o-12^o C, which is within the summer surface water temperature range in Barkley Sound. However, since known about the dispersal of larvae from northern abalone populations in the field, it was assumed that species larval dispersal characteristics were similar to other haliotids (Jamieson 1999a) and for the purpose of the preliminary dispersal modeling presented below, a three to four day time period before settlement was used. The initial plan was to investigate three, five and nine competency periods, but resolving unanticipated software issues left resources only sufficient to consider the three day scenario.

Shepherd and Partington (1995) found that in a 2.4 km study area, recruitment strength was independent of adult density within 100 m segments, but varied spatially according to features of coastal topography.

Recruitment was highest in inlets and in the lee of submerged pinnacles and lowest on headlands. They deduced that abalone larvae are transported in near-bottom tidal currents for distances of at least hundreds of metres and are concentrated in places where the bottom and shore topography cause eddies and stagnation zones. If so, then these larvae may not be phototactic. Whether there are truly differences between species, or the photactic observations of northern abalone a laboratory artifact, is unknown.

2.1.4 Recruitment

Estimates of the age at which northern abalone in BC reach the recruit size of 100 mm shell length (SL) are between six to eight years (Quayle 1971; Breen 1986). Northern abalone growth can vary considerably between areas depending on the extent of exposure to wave action and availability and quality of food. Abalone found at highly exposed outer coastal areas, also known as "surf" abalone, tend to have stunted growth because of limited food supply and strong wave actions and water currents. As a result, these "surf" abalone may never reach the recruit size of 100 mm SL (Sloan and Breen 1988). If moved to areas of greater food availability, surf abalone will commence growing again, confirming that their stunted growth is a result of a lack of food (Emmett and Jamieson 1988).

Generally, high densities of adult northern abalone are believed to be required to ensure sufficient recruitment (Abalone Recovery Team 2002). Shepherd and Partington (1995) suggested that there was a critical stock density threshold of 0.15 per m^2 for *H. laevigata* in Waterloo Bay, South Australia, below which recruitment failure was high. Shepherd and Brown (1993) found that a minimal viable population of more than 800 individuals of *H. laevigata* was required at West Island, Australia; anything less caused recruitment failure. Recruitment failures were also reported for populations of *H. laevigata* when densities fell below 0.3 per m^2 (Babcock and Keesing 1999). Breen (1986) estimated that the pre-recruit and new recruit northern abalone densities that would be required to maintain an estimated pre-fishery density of 2.5 per m^2 would be 0.55 and 0.45 per m^2 respectively.

The interaction between fecundity, spawning period, spawning duration and density has been implicated in the success of abalone recruitment (Shepherd 1986; Tegner 1993; Karpov *et al.* 1998).

2.2 Habitat

2.2.1 Habitat requirements of all life stages

Northern abalone are normally found on firm substrates, such as rocks, boulders, or bedrock, and in areas of moderate to high sea water exchange such as in exposed or semi-exposed coastlines (Abalone Recovery Team 2002). Generally, abalone occur from the low intertidal zone to about 100 m in depth but most of the BC northern abalone adult population is found at <10 m depth (Sloan and Breen 1988). Juvenile northern abalone are generally distributed deeper than the adults (Breen and Atkins 1979, 1982). Small juvenile (<10 mm SL) northern abalone are hard to find, but are usually associated with crustose algae (Sloan and Breen 1988). Juvenile northern abalone (10-70 mm SL) are found under and on exposed areas of rocks, whereas the majority of adults (>70 mm SL) are found on exposed rock surfaces (Abalone Recovery Team 2002).

Post larvae, juveniles and adults require hard substrate for attachment. The type and extent of rocky bottom materials largely determine abalone abundance. Optimum habitat consists of various combinations of ledges, cutbacks, depressions in stones, boulder piles and other hard surfaces where food is abundant. Different microhabitats are necessary for the growth and survival of abalones of different sizes and ages, as are an abundance of particular algae species for food (Emmett and Jamieson 1988).

Abalone growth is more rapid in moderately exposed areas with giant kelp (*Macrocystis integrifolia*) or bull kelp (*Nereocystis luetkeana*) forests than at highly exposed areas with *Pterygophora californica* kelp forests (Sloan and Breen 1988). As the juveniles develop to maturity, their diet changes from benthic diatoms and micro-algae to drifting macro-algae as they move to shallower, more exposed areas to feed on. The general habitat areas of the adults and their juvenile offspring could be within close proximity of each other (Abalone Recovery Team 2002).

Although there is currently believed to be ample habitat available for northern abalone in BC and there has been no known significant reduction in available habitat on the coast of BC, abalone populations have still declined. Therefore, habitat loss is not considered a major concern in the recovery of northern abalone.

2.2.2 Ecological Relevance

Northern abalone are one of a number of potentially important (depending on relative abundance by site) herbivores in the coastal ecosystem. Northern abalone feed on diatoms and micro-algae when they are young and switch to macro-algae and kelp as they mature. The recovery of northern abalone may therefore be related to the abundance and health of kelp forests in certain areas (Abalone Recovery Team 2002). Northern abalone compete for food with red sea urchins (*Strongylocentrotus franciscanus*), another large herbivore in the rocky intertidal.

Northern abalone are a prey species for the sea otter (*Enhydra lutris*), river otter (*Lutra canadensis*), mink (*Mustela vison*), crabs (*Cancer spp*.), sea stars (*Pycnopodia helianthoides*), octopus, (*Octopus dofleini*), wolf eel (*Anarrhichthys ocellatus*), cabezon (*Scorpaenichthys marmoratus*) and other sculpin fish species (Abalone Recovery Team 2002). Eradication of sea otters in the 1800's resulted in ecosystem changes which likely affected abalone. Because abalone and sea urchins are both favourite prey items for the sea otter, it has been assumed that after the sea otter population decreased, there was an increase in both abalone and sea urchin abundance (Jamieson 1999a). However as urchin populations increased, "sea urchin barrens" – large areas populated mostly with urchins and virtually devoid of marine macroalgae – were established. In such food-limited environments, abalone growth appears to be reduced (Emmett and Jamieson 1988; Jamieson 1999a).

2.3 Distribution

2.3.1 Range

The northern abalone can be found on the west coast of North America from Yakutat, Alaska (O'Clair and O'Clair 1998) to Turtle Bay, Baja California (McLean 1966). Northern abalone are distributed in patches throughout their range with an affinity for exposed and semi-exposed coasts (Sloan and Breen 1988). Populations are contagious rather than evenly distributed (Jamieson 1999a).

2.3.2 Abalone Population sizes and trends from surveys

Data is not available on precise locations of historic abalone concentrations mainly because fishers were not required to maintain precise harvest locations in logbooks (Jamieson 1999a). The true size and aerial extent of a healthy abalone population is therefore not known. Breen (1986) and Sloan and Breen (1988) suggested that abalone population size probably fluctuated even in the absence of commercial fishing. Exploratory surveys conducted in south-eastern Queen Charlotte Islands (QCI) during 1955 by Quayle (1962) suggested that northern abalone were less abundant in 1955 than both 1914 (Thompson 1914) and in the late 1970's (Sloan and Breen 1988).

The northern abalone has been declining in numbers and distributions in surveyed areas of British Columbia since the late 1970's (Abalone Recovery Team 2002). The surveys showed continued declines in densities and as a result, the northern abalone fishery was closed in 1990.

Since 1978, the surveys of index sites using standard survey design (Breen and Adkins 1979) have been conducted in areas along the southeast QCI and the central coast of BC (Winther et al. 1995; Harbo 1997; Campbell et al. 1998; Campbell et al. 2000). Most surveys were conducted in areas with significant historical commercial harvests, where northern abalone were most abundant (Sloan and

Breen 1988). Surveys at index sites in southeast QCI and the central coast of BC have indicated that the abundance of northern abalone has declined more than 75% between the period of 1978-84 and remained low and or continued to decrease through 1998 (Winther et al. 1995; Thomas and Campbell 1996; Campbell et al. 1998; Campbell et al. 2000; Campbell 2000). The mean total northern abalone density at comparable index sites changed from 2.4 to 0.2 abalone per m^2 for the central coast, during 1979-97 and from 2.9 to 0.5 abalone per m^2 for southeast QCI during 1978-98. The similarity in northern abalone density between new random sites and index sites indicated that the mean densities from all index sites were reasonably representative of adult northern abalone sampled in areas of the central coast of BC in 1997 and southeast QCI in 1998 (Campbell et al. 1998; Campbell et al. 2000).

Surveys during the 1990's in southern BC even in the absence of legal fishing, have also indicated low densities of northern abalone with the exception of an abalone population near William's Head Penitentiary near Victoria, BC. Wallace (1999) reported a high population northern abalone abundance (number/minute of diving) of 0.77 near a prison, as a result of penitentiary guards discouraging poachers from near shore access, compared to 0.05 for 'non-protected' sites.

Several species of abalone around the world have shown a decline including in countries such as Japan, South Africa, New Zealand, Australia and the United States. While many countries have taken steps to limit abalone harvest, populations continue to decline (Abalone Recovery Team 2002). The causes of the continued decline in abalone populations are not known (Jamieson 1999a), but several threats exist.

2.4 Threats

2.4.1 Illegal Harvest

Illegal harvest is considered to be the most significant threat from humans to northern abalone. The northern abalone is especially vulnerable to over-exploitation because this species has a patchy distribution, a short larval period, and is slow growing, relatively long-lived, has low sporadic recruitment, and with mature individuals that occur in shallow water, is readably accessible to divers (Abalone Recovery Team 2002). The high market value of northern abalone, and the difficulty in enforcing the fisheries closures in a large, mostly uninhabited coastal area has facilitated illegal harvesting of northern abalone. Illegal harvesting not only depletes already depressed northern abalone populations, but also reduces their reproductive potential by removing the largest, most highly fecund mature individuals (Abalone Recovery Team 2002). Samples from northern abalone illegally harvested during 1995-98 suggested that harvesters removed mostly large mature northern abalone (Campbell 2000).

2.4.2 Future Developments

It is important to consider the impacts of future developments (e.g. fish farms, offshore oil and gas development, etc.) on, in and under water that may pose a threat to northern abalone habitat. Such works will need to be monitored and regulated in order to maintain an ecosystem in which the northern abalone can be recovered and to prevent losses to important spawning aggregations (Abalone Recovery Team 2002). The potential problem is not just direct habitat alienation, but also the establishment of new human populations in remote areas and thereby increasing the likelihood of illegal harvests. The potential benefit is that if the conservation ethic is strong in such communities, then these communities can provide additional monitoring to ensure no illegal harvesting does occur. Identifying critical habitat now would mean that while efforts everywhere would be made to protect abalone from impacts, the most rigorous regulation of human activities would be at relatively discrete locations, thus maximizing opportunities for both species conservation and human economic usage of the environment.

3 Population Model and Viability Analysis

At present, very little is known about abalone recruitment characteristics except that recruitment to the juvenile stage has been below expectations in recent decades. Given our poor understanding of factors determining abalone spatial distribution and fertilization success, there is no known process whereby an optimal adult population size at any locality can be assessed. Assuming that all age classes of abalone are appropriately represented, i.e., as in an unharvested population, there are two components that need to be considered to evaluate population reproductive potential:

1. optimal microdistribution - average abalone density per square metre, which influences fertilization success in broadcast spawners; and
2. minimum desirable total concentration size – the overall number of adults, which influences population fecundity, appropriate genetic diversity, and so on, to support a sustainable population. This size is perhaps most meaningfully described as the total number of adults present, assuming that their juveniles would be present as in an undisturbed population. This also assumes that this is a source site, i.e, that recruitment is sustainable from within this population.

In more recent years, population viability analysis (PVA) has been performed on various species and has proven useful in estimating population trends. Unfortunately very little PVA has been performed on broadcast spawners such as abalone. One of the biggest challenges to modelling abalone populations is determining appropriate values for parameters such as those listed in Table 1. Most parameter values listed have been estimated during past field and laboratory studies with the exception of the research of Babcock and Keesing (1999) and Shepherd and Partington (1992), who used models. During the research of Babcock and Keesing (1999), sperm release rate, water depth and release height parameter values were held constant.

4 Habitat Availability and Utilisation

We adopted a mechanistic approach to evaluate the location of critical habitat for northern abalone:

1. determine potential habitat suitable for northern abalone over selected areas of the BC coast,
2. in one of the latter locations, model potential abalone larval dispersal to determine if source and sink populations may exist
3. identify subsequent studies to evaluate predictions and refine determination of a critical habitat assessment procedure for abalone.

Abalone occur widely over coastal BC, but they nevertheless have specific habitat requirements: hard, stable bottom, with refuges from sea otter and human predators; close proximity to kelp, a major food source; and moderate wave exposure, since they feed on drift kelp.

Prior to European settlements, native communities were widely distributed along the coast. Native peoples both exploited abalone intertidally and hunted sea otters. This is assumed to have resulted in *de facto* marine protected areas for subtidal abalone on suitable substrate, since sea otters would have avoided human settlement areas (suggested by Russ Jones, Haida Fisheries program, Skidegate, pers. comm.). Most historic native village sites are protected as Indian Reserves, so mapping the locations of coastal Indian Reserves in areas of suitable abalone habitat may roughly correlate with historic larger populations of abalone. Areas where such reserves are clustered may thus represent particularly important historic sites of abalone abundance, from which the recent pre-fishery population established after sea otter disappearance.

Present abalone concentrations are relatively small and cryptic in areas where sea otters occur. To build up larger abalone populations than occurs now, areas where sea otters occur should be excluded from consideration, as should areas that have no effective enforcement capability. In this context, the presence of DFO fishery officers in the general vicinity is not deemed sufficient protection, as Fishery

Officers are often tasked to manage other species (particularly herring or salmon) at specific times, leaving abalone temporally vulnerable to potential poaching.

The beginnings of a “coast watch” program started around 2000 and now has growing participation in several communities (e.g., Bamfield community and local First Nations (FN), Haida FN, Kitasoo FN, and Heiltsuk FN). This program is starting to provide education around the need for abalone conservation, a sense of ownership for abalone conservation and coordinated joint patrols of the coastline. Some individuals in some of these communities have been caught poaching abalone through the coast watch program and are being prosecuted, which may reinforce the benefits of the coast watch program to local communities.

In BC, only national parks among marine protected areas have on-site dedicated enforcement officers (park wardens) in addition to the coast-wide presence of fishery officers, and so for the purposes of this exploratory analysis of critical habitat for northern abalone, only appropriate habitat in national parks is considered as potential high–ranked critical habitat (Jamieson and Lessard 2000). Fortunately, both Pacific Rim and Gwai Haanas National Park Reserves are relatively large in area and each contain considerable known abalone habitat. However, problems re providing adequate regulation enforcement in these areas (especially Gwai Haanas) are that (1) they are large and fishing in remote areas is not always possible to enforce effectively, (2) fishing of several other species (e.g. sympatric sea urchins) is allowed and it is hard for park wardens to monitor for fishing compliance ,and (3) because parks have relatively high numbers of people, parks may ironically be more prone to some impacts than is the case in other remote areas.

For the purpose of this case study, analyses of predicted abalone larval dispersal and abalone source and sink populations has been conducted in the Broken Islands Section of Pacific Rim National Park in Barkley Sound on the west coast of Vancouver Island. Another reason for focusing on this location was that both DFO and Parks Canada have undertaken much study of abalone in this group of islands, and so it is possible to build on studies by both these organizations. In the models described below, much of the baseline modeling was funded by Cliff Robinson of Parks Canada.

4.1 Evaluation of Abalone Habitat Availability Model

The methods used to develop the predictive model of suitable abalone habitat and to predict the distribution of this habitat in British Columbia waters are described below. Preliminary results are presented for the Vancouver Island biogeographic region, which was used for model development, and for the Queen Charlotte Islands biogeographic region to which the methods were subsequently applied.

The degree of spatial overlap between predicted abalone habitat and historic and present-day human communities was also explored to determine how the presence of humans might influence the spatial distribution of sea otters in abalone habitat, assuming that sea otters avoid humans.

The approach developed here, and the underlying data sets, are believed to be applicable to similar studies of any shallow dwelling, low-mobility organisms.

Illustrative figures of Barkley Sound demonstrate the methods. Detailed maps of suitable abalone habitat in Barkley Sound are not presented due to conservation concerns. . Publishing locations where we believe abalone are likely to occur in abundance may facilitate abalone poaching. However area calculations are tabulated and presented for each of the two biogeographic regions analysed.

4.1.1 Data Assessment

We assessed a number of comprehensive coastal data sets available for British Columbia coastal waters for their suitability to modeling abalone habitat. Since abalone are found primarily in a relatively narrow depth range (low intertidal to 10 m depth), the resolution of the data was important. Also, since the analysis was intended for all British Columbia waters, the registration (i.e., alignment) of the different data sets was also important. The data were therefore assessed for their spatial resolution and relative accuracy.

Some potentially useful data sets (i.e., the provincial ecoregion classification) were rejected because of their low resolution. Of the various shoreline and bathymetric data sets assessed, none overlaid each other accurately or consistently across the entire province. In some areas, the various coastline data overlaid very well; in others there are discrepancies of hundreds of metres.

We ultimately selected DFO's shellfish baseline data, the provincial shoreline classification, and a kelp coverage (provided by Jeff Ardron, Living Oceans Society, Salt Sprin Island, BC,) for use in the predictive habitat model.

4.1.2 Data Sources

DFO's Pacific Region Shellfish Section's province-wide land and tidal coverage was the most suitable measure of the province-wide nearshore depth range because identifying this marine region was the objective for developing their coverage. The area defined as being between the lower intertidal (i.e., Chart Datum) and 10 m depth was used to define the extent of abalone habitat, and formed the basis of the spatial analysis. Chart Datum was also used as the barrier for fetch calculations when defining wave exposure. Consequently, despite the potentially lower resolution in some regions, it is likely to be the most consistent data of its kind for the entire province. The shoreline classification, despite some irregularities, provides a high resolution analysis of coastline characteristics both physically and biologically.

BC's shoreline unit designations (1:10,000) were used to assign a physical characterization to areas near shore. The substrate component of the BC Ecoregions analysis (1:250,000) was used to assign physical characteristics away from shore.

The spatial discrepancies between the two coastline data sets (as noted above) resulted in some unmeasurable degree of error. Misalignment in these data sets resulted in a loss (through necessary geographic clipping) of nearshore areas that could potentially support abalone. The only solution to this issue is a careful, manual alignment of the data sets for the entire coast.

The Living Oceans Society kelp coverage, while assembled from several different sources, provided a general indication of where kelp concentrations might be found (Jeff Ardron, Living Oceans Society, Salt Spring Island, pers. comm.) and was used as a proxy for estimations of spatial food availability for abalone.

We combined a relatively coarse resolution tidal model data (provided by Mike Foreman, DFO, IOS, Sidney, BC) with a higher resolution analysis of fetch to estimate the degree of water mass movement over potential abalone habitat. Fetch was calculated to estimate wave exposure due to wind driven water movements.

Indian reserve boundaries (polygons), intended as a proxy for historic human community distribution, were based on data from BC Ministry of Water, Land and Air protection (MWLAP), Survey General Branch.

Present day human community locations (points) were obtained from BC Ministry of Sustainable Resource Management (MSRM).

4.1.3 Methods

Analyses were conducted using the BC Albers projection on a 50 m grid. To facilitate computation, analysis used the five biogeographic regions identified in the Abalone Recovery Strategy (Fig. 1). Currently the methods discussed have only been applied to the VI and QCI regions.

Methods were developed using the VI region as the model area with a focus on Barkley Sound for model validation. Methods developed were then applied to the QCI region. The model for Barkley Sound used a habitat suitability approach, where rules were defined to maximize the correspondence of predictions with available survey information. Rules were used to define the influence of five factors (depth availability, physical habitat characterization, kelp availability, tidal currents, and wind-driven currents) on abalone habitat suitability, and to combine these influences according to hypothesized effects on abalone distribution. Expert opinion from DFO's abalone researchers (A. Campbell and J. Lessard, Nanaimo, BC) was used to assist in rule definition and analyses calibrations.

4.1.4 Estimating parameters influencing abalone spatial distribution

4.1.4.1 Habitat depth

Abalone habitat extends from the low water line to a depth of about 10 m. This area was best characterized and determined from DFO's Pacific Region Shellfish Section's shoreline data. These data were projected to align with the BC shoreline data. The polygon feature for the low water line to 10 m (LWLto10m) was extracted for subsequent GIS operations, and was applied as a mask to the combined influence of the remaining four influencing factors.

4.1.4.2 Physical substrate characterisation

BC shoreline features data were converted to a grid, and the associated classifications were assigned to 4 classes [0, 1, 2, 3], representing the degree of association with abalone (none, low, medium, or high) (Table 2). The ranges of the reclassified features were then expanded using a 150 m (three pixels) neighborhood maximum filter (moving window).

To classify subtidal areas, we used the 1:250,000 substrate coverage from the BC Marine Ecounit classification project (http://srmwww.gov.bc.ca/risc/pubs/coastal/marine/index.htm). This coverage has low resolution both spatially and in terms of its substrate categories – defined as Hard, Sand, or Mud. However it is the best available comprehensive representation of substrate presently available for BC.

The values from the subtidal substrate coverage were reclassified as Hard=3, Sand=1, Mud = 0, and Unknown = 0. This reclassification was based on the assumption that hard substrate is the most suitable for abalone, while sand may provide marginal habitat, if interspersed with patches of harder substrate. While it could be argued that the areas defined as "Hard" likely contains patches of less suitable habitat (i.e., mud), this issue cannot be addressed without better resolution data.

The reclassified substrate data were mapped to a raster with the same resolution and extent as the available habitat depth. Any grid cell not assigned a value from the shoreline data was assigned a value from the lower resolution substrate data.

The combined result (Fig. 2) is a comprehensive physical characterisation of substrate suitability for abalone. Figure 3 shows the two components (shoreline and substrate) separately, while Fig. 4 shows a portion of Fig. 3 in more detail.

4.1.4.3 Kelp distribution

The kelp coverage database consisted of points identifying the approximate locations of kelp concentrations. The influence of these areas was defined using a triangular distribution, attenuated from 1.0 at the point site to 0 at a distance of 1500 m (Fig. 5), representing the assumed potential for the dispersal of drifting kelp (Fig. 6).

4.1.4.4 Tidal currents

Annual, root mean square tidal current speeds for the study area were obtained from a tidal model developed by Mike Foreman (Institute of Ocean Sciences, DFO, Sidney, BC). These data were provided as irregularly spaced point values, characterized by a positively skewed distribution (i.e., a small number of very high values). A 250 m grid was interpolated using inverse distance weighting.

While the influence of water currents, i.e., tidal flow on abalone, is not well studied, it was assumed that higher flows are more likely than lower flows to favour both kelp growth by circulating nutrients and drift kelp presence ,thereby increasing abalone habitat quality. The highest tidal flows may be strong enough to reduce habitat quality because of more energy spent clinging to the bottom or the drift kelp drifting by too fast for the abalone to capture it.

Tidal flow was therefore reclassified into the suitability classes shown in the following table. Only moderate and high suitability classes were assigned because the non-normal distribution of tidal flow values. Extreme (low and high) values were deemed unsuitable since low values provide no exchange, while the high values are representative of tidal rapids (e.g., Skookumchuck Narrows). Moderate and high suitability were assigned based on the distribution of the tidal speeds. The lack of knowledge about how tides affect abalone habitat suitability made it difficult to be more specific about the functional relationship. The resulting surface is shown in Fig 7.

Suitability	Suitability Code	Tidal flow (rms*)
None	0	0-10; 500-783
Moderate	2	10-25
High	3	25-500

*average of the x and y components, i.e. sqrt(x^2 + y^2).

4.1.4.5 Wave Exposure

We calculated potential wave exposure using an ArcView extension provided by Ian Murfitt (DFO, Nanaimo, BC, pers. comm.) and based on work by Ekebom et al. (2002). For a particular point in space, exposure was defined as the sum of the distances for 24, 100 km radial lines (Jenness 2001), drawn from the point to a defined barrier (Chart Datum on adjacent land) (Fig. 8). Exposure was calculated for a set of points spaced at 1000 m intervals along the 10 m depth contour of the Shellfish Section's baseline data. By calculating the potential wave exposure at these points, the exposures at potential abalone locations could be estimated.

A natural log transform was applied to calculated exposures because the range of values spanned several orders of magnitude. The point values were then interpolated to create a 50 m grid for each biogeographic region. The exposure grids were converted to a continuous suitability surface [0,1] using a triangular distribution with a minimum ln(exposure) value of 10, and maximum suitability at ln(exposure) = 12, attenuated linearly to 0 at the maximum exposure value (Fig. 5). The resulting surface for Barkley Sound is shown in Figure 9.

4.1.5 Estimating total abalone habitat

Each of the influence surfaces above were transformed onto the range [0,1] and combined with equal weighting into a prediction of the spatial distribution of abalone habitat (Fig. 10 top). This equal weighting represents the simplest method for combining the influence surfaces. However the methodology supports any ecologically justifiable method of combining these layers.

Finally, the continuous suitability was reclassified using equal intervals to the 4 qualitative suitability ranking of None, Low, Moderate and High, and clipped with the LWLto10m coverage (for each biogeographic region) to generate the final abalone habitat suitability prediction (Fig. 10 bottom). Again, the equal interval reclassification is the simplest approach. More sophisticated reclassifications could be applied if ecologically justified.

The predicted availability of suitable abalone habitat in the VI and QCI regions are shown in Fig. 11 and Table 3. In Fig. 11, the VI predictions show much better resolution (i.e., appear less “blocky”) due to the resolution of the underlying bathymetric data sets.

4.1.6 Abalone habitat in relation to historic and existing communities

The extent to which the predicted habitat was within the range of existing and historic communities was explored. Indian reserve boundaries were assumed to have a 500 m influence zone, while three different influence zones (500, 1000, 1500 m) were used around map points (the only data available to us at this time) of existing community locations (Fig. 12). Three influence values were used because we had no data on community size and range of potential influence, so providing a range allowed different assumptions to be evaluated. The abalone habitat area contained within each of these influence zones is shown in Table 4.

4.1.7 Abalone Habitat Prediction Summary

The analysis presented here demonstrates that the approach to quantify and map the suitability of sublittoral benthic habit for abalone has merit, and represents an important step in the quantification of both important and “critical” (SARA context) abalone habitat. Field verification of the predicted abalone habitat suitability was beyond the resources of this study, but would be the next logical step. Nevertheless, the results agree to a large extent with field observations, and what is known about abalone occurrence in the study areas (J. Lessard, DFO, PBS, pers. comm.). Survey results, such as those from Atkin and Lessard (2004) and Campbell et al. (1998), can ultimately be compared to results, when a more complete analysis is undertaken.

It is interesting to note that for the WCVI, clusters of optimal (moderate and high suitability) abalone habitat are predicted at relatively discrete locations, which hadn’t before been recognized, since field studies had mostly been concentrated in Barkley Sound. If these sites contain abalone, this would have implications for the evaluation of sites most appropriate for the focus of long-term abalone conservation efforts, and the identification of potential locations where substantial viable populations of abalone might be established, i.e., critical habitat for this species.

Not all predicted locations of abalone abundance need necessarily be designated as critical habitat, which has to be considered in the context of both the retention of abalone within a location and the causes of population decline that resulted in abalone to be listed as “threatened’ by COSEWIC. However, a number of locations coast-wide should be so designated, so that possible catastrophic destruction of some by unpredictable events such as an oil spill will be less likely to affect the overall abalone recovery effort.

4.1.8 Prediction sensitivity to assumptions

There is a lack of empirical evidence for both the nature of the associations between abalone and the resources modeled, and for the interactions between the resources themselves. A key part of validating this work would therefore be to explore the effects of alternative assumptions on a final prediction.

As an example, the results of combining resource influences if exposure and kelp influence were considered twice as important as the influences of tidal and physical characteristics are shown in Fig. 13 and Table 3. The effects are relatively subtle, but are locally significant. For example, predictions of high quality habitat have been reduced around Cape Beale, and have increased in the Deer Group and in some more sheltered areas of the Broken Group. Some areas predicted as high value in Fig. 10 are now reduced in value, while some other areas have had their suitability values increased.

Exploring the effects of changing the combination rules, as well as the association rules of the resources themselves is a potentially complex and time consuming task. However this type of activity could be undertaken in a workshop environment with abalone biologists and other relevant experts present, if an interactive version of the model was developed.

Consideration of uncertainties in the spatial scales of the different environmental data and abalone required would also be relevant in an assessment of available data utility.

4.1.9 Future work

The approach presented here could be relatively easily applied to other wide-ranging, relatively sedentary coastal benthic species. Additionally, the analytical framework and specific data presented here could be applied to species that make use of similar nearshore and intertidal habitat to abalone, including goose barnacles, some crabs, and urchins. Predictive habitat models for these species could be developed using the same data sets underlying this analysis, but with perhaps different decision rules regarding how these data were applied and weighted. Such an integrated model could subsequently be used for a range of ecosystem level analyses on species interactions, and even including key predators of these species, such as sea otters and sea stars.

Prior to extending this approach to management, however, several issues need to be addressed. The highest priority should be assigned to data validation and rectification. The effective application of this approach requires spatially accurate data. The two main data sets used – the BC shoreline classification and the nearshore representation from DFO’s shellfish group – align very poorly in some regions of the province, while in others the alignment appears to be adequate for the scale of this study. This variable resolution presents a significant data gap at high (<50 m) resolution in the province-wide assessment of species.

The second major issue is the lack of empirical data on how these species respond to the physical influences modelled in this analysis. However this should not impede the further development of this and similar models, since the modeling exercise itself is extremely useful for exploring the consequences of what we think we know, and for generating testable hypotheses. However it is important that the underlying assumptions be 1) sound (which can be tested using sensitivity analyses); 2) based on the latest knowledge of habitat use by these species, 3) well documented, and 4) calibrated in cooperation with the relevant species’ biologists.

The development of a common, transparent and readily available coastal physical parameter database and an interactive modeling system providing a simple, dynamic method of implementing and modifying rules in a workshop-type setting would greatly facilitate this task.

4.2 Larval Abalone Dispersal

4.2.1 General life history dispersal model assumptions

Male and female abalone likely peak spawn in the spring (April to July) in Barkley sound and may be related to water temperature (Sloan and Breen 1988). Mass fertilization occurs in the water column, and fertilized eggs hatch within one day into free-swimming larvae. The larvae may remain in the plankton for 3-14 days before settling (Sloan and Breen 1988). The duration in the plankton is again likely related to both water temperature (development rate) and the chance encounter of a suitable substrate for settlement, i.e., metamorphosis to a benthic form. The planktonic larvae are passively dispersed by ocean currents, both horizontally and vertically; the model has the option of eliminating vertical movement. Metamorphosis modelled was assumed to occur after three days (recognisied as probably too short a time period – seven to 10 days would have been a better initial assumption) of planktonic dispersal if a larvae drifts to within one metre of the bottom, and if no available rocky bottom is reached after 14 days, larvae are assumed to die.

4.2.2 Dispersal Modelling

The approach used in this case study consisted of three parts: 1) field assessment of ocean currents, 2) development of an oceanographic model, and 3) preliminary simulated larvae simulations. The first two parts were done by Parks Canada (Robinson et al. 2003). Each section is now briefly discussed.

4.2.2.1 Field assessment of ocean currents (Robinson et al. 2003).

Field assessments of oceanic currents were conducted over important abalone spawning sites (determined from relative existing population sizes) identified by Fisheries and Oceans Canada in the Barkley Sound region. From May to June 2002, 12 ocean current trackers (Figure 14) were deployed, each containing a GPS and radio-transmitter.

At each of the abalone sites, ocean currents were assessed (Figure 15) by deploying current trackers that contained a GPS and radio transmitter. Trackers were released randomly and simultaneously at as many as 8 locations at each abalone site in varying depths of water (5-20m) and varying distance from land (10-100m). Ocean trackers were also deployed in the major inter-island channels on four occasions. All trackers were recovered before nightfall (maximum time in water of 12 hours).

The first field season (July/August 2002) provided sufficient data to verify that output from the ocean current simulation model was capturing general daily movements in tidal flows. Additional field work in August 2003 was conducted to specifically confirm model predictions at different tidal and wind conditions.

4.2.2.2 Development of an oceanographic model for Barkley Sound (Robinson et al. 2003).

The 3-d model combines information on water density properties (temperature and salinity), tides, and coastal wind data to predict surface and subsurface water currents. The numeric model used for this project is the ELCIRC (5v01) model under development at Oregon Health & Science University, Oregon, USA. ELCIRC is based on the solution of the shallow water equations for continuity, momentum, and salt and heat balances, using an Eulerian-Lagrangian finite volume method. The ELCIRC FVM solves 3-d hydrodynamic equations for velocity and surface elevation and 3-d transport / diffusion equations for temperature and salinity at each time step at a series of grid points.

The triangular grid for the BGI model domain was derived from digitized costal data and soundings supplied by Fisheries and Oceans Canada (Institute of Ocean Sciences; IOS). The large-scale sounding data from IOS were augmented with small-scale sounding data of Barkley Sound provided by Parks Canada. This bathymetric data was processed with GridGen, a Grid Generation and Visualization software package to produce the horizontal model grid. Forty-two vertical layers were created with fine resolution (sub meter) at the surface and coarse resolution in the deep layers that occur offshore.

Definition of the grid domain is one of the most labour intensive processes in oceanographic model building. Shoreline and bathymetry data have to be acquired and then reconfigured into a format suitable for a griding tool. The digitized data has to be edited (generally to reduce the number of shoreline points) so that the shoreline has points separated by distances suitable for the required grid density. In the situation described here, the shoreline point density varied from high density (10s of meters) in the Broken Group to low density (kilometers) on the coast of Washington. With the shoreline established at the required density, the griding tool was used to generate a bottom profile and then to produce a trial grid where the grid density varied with depth. The trial grid was then edited to resolve problems with generated depths and element shapes.

The topography and bathymetry of Barkley Sound are very complex in ocean modeling terms. Physical features being modelled are relatively small (e.g., Hankin Island) which meant that in order to represent them in a model, the grid size had to be even smaller (less than 75 m). Also, even though interest was limited to the Broken Group Islands, a large domain (200 km X 200 km) was needed in order to properly represent the tides and density properties of the surrounding ocean. With a rectilinear grid, over seven million grid points would have been needed and the model run times would be prohibitive. By using a triangular grid system, it was possible to vary the grid density over the domain. We used a high density of points in Barkley Sound with a low density offshore, where the grid separation approached 10 km. The use of the triangular system allowed representation of the domain with only 10600 points (Figure 16).

The oceanographic model is forced by observed winds and tides. Wind data were initially obtained from Environment Canada's weather station at Tofino airport (Robinson et al. 2003) but our model runs were forced with a wind field that was derived from wind observations at the La Perouse buoy, and Capes Beale and Amphitrite lighthouse weather data. Observation of the winds at Tofino during the summer of 2002 revealed that the predominant wind characteristic was an onshore wind that peaked in the early afternoon, alternating with offshore winds over night. Model runs utilized wind data from dates specified in 1998, 2000 and 2003.

One aspect of this study was to understand the potential variability in larval abalone transport in relation to temporal variability in wind forcing. Figure 18 demonstrates how variable winds can be at the same time of year (e.g., July) among years. Winds in July 2001 were almost twice as strong, on average, than winds in 2000 and 2002 (12.5, 21.0, and 11.8 km per hour for 2000, 2001, and 2002, respectively). In this study, wind data is WX Data collected at IOS via Anik Satellite, i.e., it is Environment Canada data that is reformatted and stored on a public disk at IOS. Specifically, data from the La Perouse Bank Buoy 46206, Amphitrite Pont lighthouse and Cape Beale lighthouse were used.

The second major model forcing function, tides, was implemented at the open boundaries using the Q1, O1, P1, K1, M2, N2, S2 and K2, tidal components. Tidal forcing is accomplished by setting the elevations at the open boundaries to the heights calculated for the tides at each time step. Amplitudes and phases of the tidal components can be calculated at any location along the open boundaries. Within three model days, elevations will have propagated through the domain such that the model is able to reproduce realistic tides in areas of interest such as Barkley Sound. Tides are important because from current moorings deployed in the area, it is known that tides were the major component of currents in the area. This is especially true at the shallow depths in the Broken Island Group where the model's abalone were seeded.

4.2.2.3 Model particle transport experiments: the seeding of abalone larvae into the oceanographic model

The oceanographic model for Barkley Sound was used to conduct a series of larval abalone particle transport experiments. Parameterization software to facilitate seeding was developed as a supplement to the model (Robinson et al. 2003). For the trials, the scenario considered was the seeding of 1000 larvae at each of five general island groupings (Figure 18), with seeding restricted to areas that had been identified as habitat that was potentially suitable (rocky less than 10 m depth) for abalone. However, the settling data was not partitioned into settlement on either suitable (rocky) or non-rocky bottom, as only depth was considered. The lat/long data obtained as output for larval settlement positions was not matchable with that used for the input substrate data, and this issue could not be resolved with available resources at this time.

To address the relative importance of egg hatching at different stages of the tidal cycle, in case this was an important variable, larvae were released at three-day intervals during a tidal cycle, i.e., at 0, 3, 6, 9 and 12 days, starting on June 1 each study year. A tidal cycle is about 15 days duration. Twenty percent of the larvae released at each depth at each location were released at each time interval. The model is run for a couple of days prior to seeding. Winds start on day 1 and seeding starts on day 3. The tide is a generic tide, i.e., it is not synchronized with the wind. The objective was not to try to reproduce a specific set of conditions but rather to capture a range of conditions that could occur in late spring. With only three years of wind data, it was impossible to capture the full range of variability that one would expect to encounter. For example, Environment Canada uses 30 years to define its weather normals. The first release of larvae during their simulated 14-day larval period would thus be from June 3-17, while the last release would be from June 15-29. The video clip presented with this paper showed a scenario output for

June 1998, with wind direction and strength shown by the arrows in the upper left (Amphitrite Point) and lower right (Cape Beale).

As indicated above, islands in the Broken Group were grouped into five complexes (Figure 18). The questions we wanted to address were where would abalone larvae from different parts of the island complex in general be transported to, and were there suggested source and sink locations (source is defined here as locations that are self-sustaining and which may contribute larvae to sink locations, which are generally not self-sustaining and that do not contribute many larvae to other locations) in the complex. Particles representing abalone larvae were seeded randomly in appropriate abalone habitat areas in each complex. Four layers of particles were seeded at each random site at 1 3, 5 and 9 meters below the surface. Particle seeding locations by depth were selected to mimic the approximate absolute distribution of adult northern abalone (e.g., maximum benthic vertical distribution of 0-10 m below Chart Datum). Particle movements in the simulated model were tracked for 14 days following release. No "settlement" could occur within the first three of simulation, but after this time period, if a simulated larvae came within one metre of the bottom at a depth of < 10 m, it was assumed to settle at that location. If after 14 days it had not come within one metre of the bottom, it was assumed to die. Larval movement was assumed to be totally determined by water movements, i.e., there was no vertical larval migration assumed.

For each larvae, data was recorded for each hour and summarized for the start and end points of larval drift, the total distance it travelled before it "settled" or 14 days had passed, its furthest straight line travel, its duration of travel, its average speed of travel, the areas it started and ended in, its depth at settlement (if it settled) and whether it settled or not.

4.2.2.4 Simulation results

Caution should be used when analysing and interpreting results provided at this time, as all of the model results provided here have large error bounds. At this stage of model development, we are only comfortable in saying things like "particles seeded at 'x' will travel to 'y' and 'z' with 'z' likely to receive 'n'. times as many particles as 'y'." In part this is a result of the size of the polygons used in the oceanographic model, which restrict the horizontal (along shore) accuracy to about 50 m or so. As a result, we have not considered the output in terms of depth of settlement as being too relevant at this time, since there we are dealing with values of less than 10 m.

A second issue concerns the accurate prediction of larval settlement by 1 m depth intervals. The version of ElCIRC used has an occasional problem with model elements on the water side of the boundary drying out, and the drying elements can cause the model to become unstable. The initial fix was to set the minimum sounding to 5 m so that no matter what the tide state, model elements would remain wet. Hence, we cannot separate settling depths on a meter basis for depths of less than 5 m. The data were binned to represent the cumulative settling in the 0-5 m zone. We understand that these sublittoral "drying" problems have recently been resolved in ElCIRC, such that it should be possible to restore the shallow soundings in future dispersal simulations. Unfortunately, though, we did not have the financial resources to contract out our rerunning of the model scenarios investigated here.

Below we present the results of our early runs to demonstrate the type of data the model is producing, and some of our preliminary observations re larval dispersal and settlement patterns. As mentioned previously, our initial assumption of a three day larval period is probably too short, so results presented here may not be realistic (insufficient funds were available to run new analyses at this time). Nevertheless, results are discussed, to show how results from new analyses might be considered in future simulations.

The spatial patterns of settlement differ slightly across the three years investigated (Fig. 19), but the patterns shown have some consistencies. Most settlement seems to happen almost as soon as the larvae become competent to settle (Fig. 20), and larvae that remain in the water column longer than a day or so after this period have a relatively low settlement probability, although their subsequent dispersal may be substantial (Fig 21). This seems to explain why most modeled larvae settled relatively close to their release site (Figure 22, Table 5). Developing a better understanding of when larvae become competent to settle, and their ability to influence their vertical position in the water column, thus seem to be two research areas where additional data might be particularly useful for modelling. The low level but substantial dispersal observed may suggest why abalone concentrations that are exploited too heavily may disappear, as local recruitment would largely cease and immigration of larvae form other sites would be inadequate. However, the level of immigration than does seem to occur may be sufficient to maintain genetic homogeneity among adjacent populations, which has been observed to be the case, even over distances of hundreds of kilometers (Withler et al. 2003). As discussed by Robinson et al. (Submitted), this type of exchange may be analogous to the stepping-stone genetic model whereby populations exchange propagules only with relatively close adjacent populations, and these adjacent populations subsequently link with other populations even further away (Palumbi 2003). If the time period before settlement can occur is longer, as suggested by Pearce et al. (2003), then results would likely be quite different and dispersal range before settlement more extensive.

Settlement opportunity, i.e., passive transport of larvae to within one metre of the se floor, seems to vary between years (Figure 23), although whether this is meaningful in terms of the real situation is unknown. We have assumed that mortality within the water column was constant among years, which is obviously not true, so it is only proportions across years that are relevant, not absolute numbers. Within the Broken Islands, highest settlement occurred in Areas 4 and 5 (southeast side of the archipelago), with Area 4 also receiving substantial settlement from Area 3 (Figure 22, Table 5). This may in part reflect the larger geographical areas of sites 3-5.

Among the five sites studied, most settled larvae settled at their release sites, suggesting self-sustainability, but it appears that sites 2 and 3 contributed relative more larvae proportionally to other sites. There were no obvious “sink sites”, which received larvae from other sites but which were not self-sustaining on their own and that contributed little to other locations. All five sites identified within the Broken Islands archipelago of Barkley Sound are thus suggested to be source sites in that they appear to be self-sustaining and can contribute larvae, even if relatively few in some cases, to other sites. It should be noted, though, that in the data presented, there has been no standardizing of results as settlement per unit area, and we know that among the five island groupings, suitable sublittoral habitat are of different areal size.

5 Discussion

The purpose of this case study was to investigate approaches relevant to the identification of critical habitat in the SARA context for northern abalone in British Columbia. To repeat the SARA definition of critical habitat, it refers here to habitat that is necessary for the survival or recovery of a listed wildlife species and that is identified as the species’ critical habitat in the recovery strategy or in an action plan for the species. At present, there are no vetted approaches to the identification of critical habitat for marine or aquatic species, and so this report should be considered part of a process to develop guidelines for this task.

Abalone are widely distributed in nearshore BC coastal waters, but at generally unknown locations and at densities that are believed to be largely below a level that will sustain local populations. Evidence for this is the general decline in abalone abundance and densities at monitored sites over the past 25 years. The overall approach taken here was thus to develop a process to cost-effectively and accurately predict coastal areas with suitable abalone habitat, and as a pilot analysis in an area already know to have such habitat, i.e., Barkley Sound, to investigate the utility of circulation models to allow evaluation of whether abalone larvae are retained in areas supporting parent populations. In both cases, the approach taken was generic in that it should be applicable to other nearshore benthic species as well, as suitable habitat and dispersal characteristics should in theory be calculatable for any nearshore benthic species using appropriate decision rules based on each species’ biology. As examples, in habitat suitability analyses for different species, depth ranges and substrate preference may vary, while in the dispersal model, competency period may differ and seed source locations may be over a different depth range.

With respect to the habitat suitability approach, refinement of the assumptions utilized will be necessary, and this can best be done through field verification of predictions in pilot areas, and subsequent modification of assumptions to produce analytical predictions that match as closely as possible field observations. However, as a first effort, results here seem to be realistic enough that concern has already been expressed by regional abalone biologists that data produced may be accurate enough to help focus poaching efforts and as such, should perhaps be kept confidential. In our model, we assumed that all influence parameters were weighted equally, which may in fact not be the case. In Table 3, we show how results would differ if kelp and exposure influences were weighted both twice as important as tidal and physical characteristic influences, as an initial sensitivity analysis of some of the assumptions considered. Further sensitivity analyses need to be undertaken, and predictions compared with field observations to determine what the most appropriate assumptions might be.

The accuracy of dispersal model results is likely impossible to test through field observation, since abalone larvae are extremely small. There is no known way to cost-effectively monitor their occurrence in field sampling, particularly at a scale that would be useful. Even if abalone larvae can be shown to be present at a location, their sources will be unknown except through hindsight model prediction. This does not mean that better analyses in some areas may not be possible, though. Specifically, improvements in the model with respect to its ability to function in shallow water appear possible, and this should be done. Also, better knowledge about larval abalone behaviour is desirable to improve model values used, such as how soon after fertilization can larvae successfully settle (competency period) and can larvae influence their depth distribution in the water column, or is location solely passively determined by water currents.

If it is assumed that the approach adopted here can sufficiently identify abalone habitat (model results will need to be field verified), and that we can evaluate whether identified areas of suitable habitat are likely to be self-sustaining, then the next challenges in determining abalone critical habitat are to determine the optimal numerical size for each abalone population, its specific habitat requirements, the number of such populations desirable for the BC coast as a whole to address possible catastrophic population extinctions, and finally, what should the optimal spatial distribution of such populations be to minimize the risk of local catastrophic extinction, such as from an oil spill. At present, we:

1) do not know the micro-distributions of abalone within predicted suitable abalone habitat (likely to be dependent on local substrate characteristics),), although Parks Canada is conducting night time SCUBA surveys and radio tagging studies on abalone in the Broken Group of islands;

2) have no effective quantitative population assessment methodology (abalone are very cryptic and often live within crevices in boulder fields); and

3) do not know the optimal number of abalone that would comprise a self-sustaining population, as because abalone have to congregate to spawn successfully, micro-spatial distribution is likely very important.

The estimation of optimal critical habitat size for any local population will thus need to be based on common sense, i.e., to err on the side of overprotection. Figure 13 suggests that areas of suitable habitat may be to a large extent discrete, and so with current data, this suggests that entire discrete areas, regardless of size, be identified as critical habitat. It also would seem logical to try and protect at least two to five discrete, geographically separated areas in each of the five abalone recovery regions (Figure 1) to address the possibility of catastrophic event occurrence. Since human poaching appears to be a major factor causing low abalone abundance, discrete critical habitat areas identified should be located where human activity restriction can be most effectively enforced. National parks are unique in BC in that they have both park wardens and fishery officers available for enforcement, and parks also provide public education of the need for protection or renewable resources, including abalone. Thus, at the least, suitable abalone habitat within national parks is suggested to be the minimum critical habitat for abalone identifiable at this time.

Also, it is presently impossible to undertake larval dispersal studies for most identified discrete areas of high abalone habitat suitability, as circulation models presently only exist for a few inshore locations, notably Barkley and Quatsino Sounds and some parts of the Strait of Georgia. While abalone dispersal may be limited at all sites, the Broken Islands example does show that some locations are more likely to support sustainable populations than others. However, the microdistribution of abalone is not known at any site, which argues against identifying areas of critical habitat as relatively small. It seems better to err on making them too large rather than too small, which was whole discrete areas of identified suitable abalone habitat are suggested as critical habitat, rather than just a portion of one.

We have attempted to determine for the Barkley Sound area the spatial proportion and relation of suitable abalone habitat adjacent to both historic and present human communities (Table 4, Fig. 11). Increased effectiveness in enforcement could be achievable through increased public awareness and the involvement of local people in the monitoring process, by trying to encourage local communities to assist in the reporting of possible abalone poaching. If there is agreement within a community that individuals will report any possible poaching in the vicinity of their community, i.e., where people are likely always present, then having more eyes monitoring should reduce poaching and functionally, help protect abalone that might occur in the vicinity of the community. However, the spatial correlation of today's coastal communities, which are generally in sheltered harbours, with abalone, which prefer more exposed sites, is not good, so this approach in Barkley Sound at least would not seem worthwhile. Thus, while the assumption that sea otters avoid humans may still hold, and that areas around communities could offer protection for abalone from both poachers and sea otters, the fact that most communities today are not in suitable abalone habitat areas makes consideration of this possibility a mute point.

Finally, present and future sea otter distributions need to be considered. As can be seen from Fig. 24, sea otters presently occur over the northern part of the west coast of Vancouver Island, and their range is expanding southwards. It can be expected that sea otters will consume most non-cryptic abalone, which may resolve the abalone poaching problem. Since both abalone and sea otters historically occurred together, this may not affect the overall survival of abalone in BC waters, although it may reduce the suitability of some areas we predict as abalone habitat now as suitable in the future. Flat bedrock areas, with little crevices or boulders, was predicted to be suitable abalone habitat, but for visual predators such as humans and sea otters, these areas in fact likely have high adult mortality, making them unsuitable over the long-term as locations to support viable populations. Additional substrate characteristics, notably the availability of crevices or large boulders, thus need to be incorporated into future predictions of suitable abalone habitat. Such detailed sublittoral substrate data is not now available for most areas, and can only likely be obtained through field surveys. Our analyses to date at least narrow down the areas that would have to be surveyed in this regard, as we have already eliminated much of the coast as poor abalone habitat on the basis of the other necessary parameters modeled.

While it has been suggested that marine reserves could assist in the recovery and management of abalone populations (Tegner et al. 1992; Tegner 1993), Jamieson (1999b) and Wallace (1999) suggest that only closed areas that completely and effectively restrict abalone harvest will result in significant changes to local abalone populations. This can be achieved by a total ban on SCUBA diving, or sites that receive unintentional protection from illegal harvest, such as those adjacent to land owned by the Department of National Defense and William's Head Penitentiary near Victoria, BC, support larger and more abundant abalone. Because large abalone are relatively numerous, and larger animals have an exponentially higher reproductive capacity (Campbell et al. 2003), reproductive output is highest in areas with a relatively large proportion of large adults. Since critical habitat is that area where a species' population is sustainable, critical habitat for northern abalone is best located in areas where effective enforcement, even perhaps including a ban on diving, can occur.

6 Knowledge Gaps

The biology of northern abalone has been difficult to study to date due to their slow growth rate, sporadic recruitment, small larval size and cryptic juvenile stage. Information gaps and the need for further research from the published literature have been identified as follows:

- Little is known about the relationship between northern abalone adult concentrations, breeding success and subsequent dispersal of larvae and settlement of juveniles, all factors required to provide effective reproduction and subsequent sufficient recruitment (Abalone Recovery Team 2002).

- The frequency and size of patches and size composition of northern abalone required to maintain sufficient egg production and recruitment for a healthy population [is likely site specific and] needs investigation (Abalone Recovery Team 2002).
- Almost nothing is known about the early juvenile stages of northern abalone in BC (1-3 years) (Abalone Recovery Team 2002).
- Causes of poor recruitment in northern abalone are not well understood (Sloan and Breen 1988).
- Little is known about short-term movement patterns. The issue of how abalone forage and how that behaviour is influenced by abalone size, presence of predators and abundance of food is a potentially rewarding question for study (Sloan and Breen 1988).
- The influences on mortality of early life stages are unknown (Abalone Recovery Team 2002).
- No direct estimates of size-specific fecundity has yet to be made (Abalone Recovery Team 2002).
- A better understanding of the ecological interactions between northern abalone and abalone food sources (e.g. kelp beds), predators (e.g. sea otters) and competitors (e.g. sea urchins) is required (Abalone Recovery Team 2002), i.e., the empirical relationships between environmental factors and abalone populations properties

Finally, we could not specifically address the high-level question of what abalone biomass might be needed to delist the species by COSEWIC, as this involves a spatial distribution component which we did not have the resources to address at this time. We suggested above that at least 2-5 discrete, geographically separated areas in each of the five abalone recovery regions might be needed, but we did not review the basis for identifying five recover regions, as opposed to simply specifying the whole coastal zone as one region.

Also, while the main threat at the present may be human poaching, as the range of sea otters expands, if it is permitted to do so, then the human threat will likely largely be eliminated, since sea otters will keep abundances below that which would permit substantial poaching. The hypothesis here is that because sea otters and abalone coexisted together before there were industrial harvests of either species, they can coexist together again in the future. However, this suggests that the “immediate recovery plan goal of halting the decline of existing wild northern abalone population in order to reduce the risk of northern abalone becoming listed as “endangered” in BC” may not be feasible in areas where sea otters occur, and in areas where their range expands in to. There has been and is presently no monitoring of abalone populations in areas where sea otters occur, so we do not know what average densities or recruitment is in areas where abalone can occur in the presence of sea otters. The long-term recovery goal of “increasing the number and densities of wild northern abalone to levels where the population become self-sustainable in BC” also appears to be poorly stated, and it is not clear, to us at least, if this is meant as sustainable for a fishery or simply as an existing species in a kelp-rocky ecosystem, where abalone would persist as a cryptic, low abundance species in the presence of sea otters. The number and densities of wild northern abalone may not have to be increased too substantially to achieve self-sustainability for naturally self-sustainable populations, and the latter may just have to be identified. Much of the abalone population monitoring that has and is being conducted may not be in appropriate areas to assess overall abalone stock viability, either because 1) areas samples are not complex enough topographically to provide cover for the long-term presence of this cryptic species in the presence of sea otters, assuming sea otters are likely to occur there eventually, or 2) the areas being surveyed are not in naturally self-sustaining abalone population locations because of physical environmental features. Current population assessment locations need to now be assessed for their actual suitability as significant areas of suggested abalone habitat suitability, and be adjusted if justified as necessary.

7 Recommendations

1) Conduct more extensive sensitivity analyses of the weighting of influence parameters (e.g., Monte Carlo assessment) in an effort to determine the most robust prediction of abalone habitat suitability.
2) Conduct on-site verification of abalone presence in predicted suitable and unsuitable abalone habitat in the Broken Islands pilot study area of Pacific Rim National Park Reserve, and describe abalone population characteristics and relationships to environmental factors in suitable abalone habitat.
3) If model predictions of suitable abalone habitat are verified, consider concentrating abalone population recovery activities in locations of suitable abalone habitat both within and outside the present sea otter distribution range.
4) Assess current abalone population assessment locations for their actual significance as suitable areas of suitable abalone habitat, and adjust these locations, if deemed necessary.
5) An optimal, practical number of discrete, geographically-separated abalone populations that address the issue of potential catastrophic loss of a few populations needs to be determined. We suggested somewhat arbitrarily that this number should be in the range of 5, but could not address (because of lack of understanding of the real distribution of suitable abalone habitat at this time) whether this number should be for the whole coast or for each of the five identified abalone recovery regions. However, a final recommendation could base the number of areas, etc on model estimates of total area of suitable habitat in a given management region with and without sea otters. In other words, the model could/should be used to guide us as to how many areas are required, and how big the areas need to be, to protect from potential catastrophe.
6) When actual critical habitat for abalone is determined (this study evaluated a process but was not planned to be conclusive in the determination of abalone critical habitat), it should be considered in an adaptive management context, with extensive subsequent monitoring to ensure that abalone population sustainability expectations are being met. Our understanding of abalone recruitment dynamics is weak, and will likely remain so for many years to come because of the generation time frames involved and difficulties in assessing population characteristics for this cryptic species.

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10 Tables

Table 1: Parameter sources and estimation for *Haliotis spp.*. Species origin: [1] Australia, [2] New Zealand, [3] US/Mexico, [4] France, [5] Canada.

Parameter	Estimate	Method	Species	Source
Distance between adults for fertilization success	< 1.6 m	calculated	*H. laevigata*[1]	Babcock and Keesing 1999
	< 1.0 – 2.0 m	estimate	*H. kamtschatkana*[5]	Rothaus and Friedman 2003
	1 – 4 m	calculated	*H. laevigata*[1]	Babcock and Keesing 1999
Minimum adult population needed for fertilization success	$> 0.3\ m^{-2}$	estimate	*H. laevigata*[1]	Babcock and Keesing 1999
	$> 0.15\ m^{-2}$	calculated	H. laevigata[1]	Shepherd and Partington 1992
	> 800 individuals	estimate	*H. laevigata*[1]	Shepherd and Brown 1993
Mortality rate	0.1 to 0.2	estimate	*H. iris*[2]	Sainsbury 1982
	0.21 to 0.36	estimate	*H. laevigata, H. ruber*	Shepherd et al. 1982
Maximum growth rate (juveniles)	$29.2\ mm\ y^{-1}$	estimate	*H. sorenseni*[3]	Hobday et al. 2000
Maximum growth rate (adults)	$10\ mm\ y^{-1}$	estimate	*H. sorenseni*[3]	Hobday et al. 2000
Optimal sperm densities for > 90% fertilization success	10^7 to $10^9\ L^{-1}$	estimate	*H. tuberculata*[4]	Mill and McCormick 1992
Sperm release rates	$5 \times 10^7\ s^{-1}$	model input	*H. kamtschtkana*[5]	Babcock and Keesing 1999
Fecundity	1.56×10^5 to 12.56×10^6 eggs	estimate	*H. kamtschtkana*[5]	Campbell et. al 1992
Ambient water current speed	$5.5\ cm\cdot s^{-1}$	mean	*H. laevigata*[1]	Babcock and Keesing 1999
Water depth	5 m	model input	*H. laevigata*[1]	Babcock and Keesing 1999
Release height	0.1 m	model input	*H. laevigata*[1]	Babcock and Keesing 1999
Mobility	$125\ m\ y^{-1}$	calculated	*H. kamtschtkana*[5]	Emmett and Jamieson 1988

Table 2: British Columbia shoreline physical classification units and their potential suitability (none, low moderate, high) for abalone habitat.

Shoreline classification	Abalone suitability
Rock Platform - Near horizontal rocky intertidal areas >30m in width. A thin sediment veneer may be associated with the ramps but the veneer is typically patchy and there are no organized beach features. Most commonly associated with sedimentary bedrock outcrops.	High
Rock Cliff - Steep sloped (>20o) rock coasts. Small pockets of sediment occur sporadically within the indentations along the coast.	High
Rock with Gravel Beach - Rock and pockets of clastic sediments (rubble, boulder, cobble or pebble beach). Sediments can occur on well- developed beach forms, such as berms or beach terraces, or as large patches of sediment in an otherwise rocky shoreline. Beaches typically occur in the middle to upper intertidal zones and often include log deposits in the supra-tidal zone.	High
Rock, Sand and Gravel Beach - Rock with pockets of clastic sediments including sand beaches; they typically occur in the middle to upper intertidal zones and often include log deposits in the supra-tidal zone. The gravel in the lower and middle intertidal zones frequently occurs as an armor over the sand gravel mixture. Distributions may be intermittent and patchy along the coast within small indentations.	Moderate
Rock with Sand Beach - This type has similar characteristics to a rock platform but it has a sand beach, with the sand content >90%. The beaches typically occur in the middle to upper intertidal zones and often include log deposits in the supra-tidal zone. Distributions may be patchy, occurring intermittently along the coast within small indentations.	Low
Gravel Beach - Sediments are usually comprised of a boulder, cobble, pebble mixture with < 10% sand content. Beach slopes are in the range of 5o to 20o with the berm the steepest part of the intertidal zone. Lower to middle intertidal zones are commonly armored. Because of the low sand content, these beaches are highly permeable.	Moderate
Gravel Flat - Sediments are usually comprised of a boulder, cobble, pebble mixture this sand content < 10%. Beach slopes are low, < 5o with the berm the steepest part of the intertidal zone. Lower to middle intertidal zones are commonly armored. Because of the low sand content these beaches are highly permeable.	Moderate
Channel - A current dominated region in the intertidal area as opposed to a wave dominated area in the intertidal area composed of either bedrock or sediment substrate.	Moderate
Sand and Gravel Beach - Sediments are a mixture of boulders, cobbles, pebbles and sand (>10% sand content and > 10% gravel content). Beach slopes are in the range of 5o to 20o with the berm the steepest part of the intertidal zone. Lower to middle intertidal zones are commonly armored by cobbles with the sand layer in the subsurface. These beaches usually have similar permeabilities to sand beaches.	Low

Table 2: (Continued)

Sand Beach - Sediments are < 10% gravel and > 50% sand. Beach slopes are in the range of 5o to 20o with the berm the steepest part of the intertidal zone. Sediments are highly mobile in moderate to high energy exposured areas. Beach permeability may range from high to low depending on the mud content of the beach. Ridge and runnels or swash bars may occur in the lower or middle intertidal zones.	None
Sand and Gravel Flat - Sediments are a mixture of boulders, cobbles, pebbles and sand (>10% sand content and >10% gravel content). Beach slopes are low, < 5o with the berm the steepest part of the intertidal zone. Lower to middle intertidal zones are commonly armored by cobbles with the sand layer in the subsurface. These beaches usually have similar permeabilities to sand beaches.	Low
Sand Flat - Sediments are <10% gravel and > 50% sand in content. Beach slopes are low, < 5o with the berm the steepest part of the intertidal zone. Beach permeabilities may range from high to low depending on the mud content of the beach. Multiple ridge and runnels or swash bars are common in the lower or middle intertidal zones.	None
Mud Flat – Sediments are < 10% gravel and > 50% mud. Beach slopes are low, < 5o to 20o with the berm the steepest part of the intertidal zone. Berm sediments, located near the high-tide mark are usually coarser than those of the beach flat. Beach permeability is low due to the high mud content.	None
Estuary, Marsh or Lagoon - Estuaries are characterized by high variable distributions in texture although, muds and organics are common. Marshes frequently rim the estuary at the high water mark. Brackish water conditions are common due to freshwater input to the estuary from stream runoff. Exclusively confined to low wave exposure environments.	None
Man-made - These are man-made features or structures within the intertidal zone such as wharfs, seawalls, breakwaters, log dumps, boat ramps, marinas, piers, etc. Common construction materials are; concrete, timber, pilings, rubble and rock. Intertidal zone widths are often narrow due to the vertical nature of most structures.	None
High Tide Lagoons - Lagoons that have a tidal influence.	None

Table 3: Area (ha) by abalone habitat suitability and region from the low water line to 10 m depth range, assuming all influence parameters are weighted equally. With “Vancouver Island - Alt 1”, the assumption was that kelp and exposure influences were both twice as important as tidal and physical characteristic influences, as an initial sensitivity analysis of some of the assumptions considered.

Region	None	Low	Moderate	High	Total
Vancouver Island	10,882	20,222	19,766	7,597	58,467
Vancouver Island - Alt 1	12,717	19,912	21,347	4,503	58,479
Queen Charlotte Islands	5,657	146,517	98,768	16,262	267,205

Table 4: Total potential abalone habitat by region contained within the assumed community influence zones: 500, 1000 and 1500 m zones were applied to current communities noted on NTS map sheets (1:250,000). A 500 m influence zone (IR 500) was applied to Indian Reserves (IR) locations, which represent both current and historic native communities. Results are shown as hectares of each habitat type in each influence zone, and as the proportion (%) of each habitat type that occurred within each influence zone.

A. Vancouver Island

	Habitat Area (ha) by habitat type				
Influence Zone	**None**	**Low**	**Moderate**	**High**	**Total**
500	95	152	100	20	368
1000	414	583	405	135	1,536
1500	738	1,295	845	233	3,111
IR 500	909	1,207	1,668	839	4,623
			% of each zone		
500	26	41	27	5	
1000	27	38	26	8	
1500	24	42	27	7	
IR 500	20	26	36	18	

B. Queen Charlotte Islands

	Habitat Area (ha) by habitat type				
Influence Zone	**None**	**Low**	**Moderate**	**High**	**Total**
500	11	63	3	0	77
1000	53	316	157	31	556
1500	84	822	569	71	1,546
IR 500	87	491	194	138	910
			% of each zone		
500	14	82	4	0	
1000	10	57	28	6	
1500	5	53	37	5	
IR 500	10	54	21	15	

Table 5: Sample model output: settled proportion by site, with a minimum three, maximum 14 day dispersal. A, B and C: 1998, 2000 and 2003 winds respectively. Bold = > 5% settlement. D. Mean proportion for all years for all depths where there was a significant settlement. Vertical axis is the start location, horizontal axis is the destination location. The four sets of results for each year are for depths of 0, 3, 5 and 9 m seeding respectively.

A.

Area Group	**1**	**2**	**3**	**4**	**5**
1	0.000	0.000	0.004	0.004	0.040
2	0.004	0.004	0.000	0.024	0.020
3	0.004	0.004	0.008	0.060	0.004
4	0.000	0.012	0.016	0.048	0.012
5	0.000	0.000	0.000	0.004	0.024
1	0.020	0.004	0.000	0.000	0.036
2	0.000	0.012	0.004	0.008	0.008
3	0.004	0.012	0.020	**0.068**	0.016
4	0.000	0.004	0.020	**0.072**	0.004
5	0.000	0.000	0.000	0.008	**0.084**
1	0.044	0.000	0.000	0.008	0.016
2	0.008	0.048	0.000	0.036	0.024
3	0.000	0.020	0.024	**0.060**	0.012
4	0.000	0.016	0.000	**0.136**	0.008
5	0.000	0.000	0.000	0.000	**0.124**
1	**0.120**	0.000	0.000	0.008	0.036
2	0.004	**0.140**	0.008	0.012	0.024
3	0.000	0.028	0.040	0.048	0.012
4	0.004	0.000	0.028	**0.188**	0.000
5	0.000	0.000	0.004	0.004	**0.196**

B.

	1	2	3	4	5
1	0.004	0.000	0.004	0.008	0.008
2	0.004	0.004	0.000	0.036	0.048
3	0.000	0.012	0.000	0.032	0.012
4	0.000	0.004	0.012	**0.072**	0.016
5	0.004	0.012	0.008	0.028	**0.068**
1	0.012	0.000	0.000	0.012	0.020
2	0.000	0.004	0.008	0.044	0.012
3	0.000	0.040	0.008	0.036	0.024
4	0.000	0.008	0.020	**0.100**	0.008
5	0.000	0.004	0.004	0.032	**0.068**
1	0.036	0.004	0.000	0.012	0.044
2	0.000	0.012	0.016	0.032	0.020
3	0.004	0.024	0.016	0.044	0.012
4	0.000	0.004	0.004	**0.152**	0.004
5	0.000	0.008	0.000	0.028	**0.100**
1	**0.136**	0.000	0.000	0.004	0.028
2	0.004	**0.056**	0.008	0.040	0.004
3	0.000	0.024	**0.052**	0.020	0.016
4	0.004	0.000	0.012	**0.184**	0.000
5	0.000	0.004	0.000	0.024	**0.196**

Table 5: (Continued)

C.

	_1	2	3	4	5
1	0.012	0.000	0.000	0.000	0.008
2	0.004	0.004	0.008	0.000	0.004
3	0.004	0.004	0.008	0.028	0.004
4	0.004	0.000	0.012	0.040	0.008
5	0.004	0.004	0.000	0.004	0.032
1	0.032	0.004	0.004	0.000	0.004
2	0.004	0.032	0.020	0.016	0.012
3	0.004	0.008	0.020	0.012	0.004
4	0.004	0.020	0.016	0.044	0.000
5	0.012	0.004	0.008	0.008	**0.056**
1	**0.064**	0.000	0.000	0.000	0.016
2	0.004	**0.052**	0.016	0.020	0.020
3	0.016	0.004	0.016	0.008	0.012
4	0.000	0.004	0.012	**0.120**	0.004
5	0.000	0.000	0.000	0.016	**0.132**
1	**0.196**	0.004	0.000	0.000	0.004
2	0.004	**0.076**	0.000	0.020	0.020
3	0.008	0.020	**0.072**	0.016	0.012
4	0.000	0.004	0.020	**0.156**	0.004
5	0.000	0.004	0.008	0.008	**0.180**

D.

	1	**2**	**3**	**4**	**5**
1	0.06				
2		0.04			
3			0.02	0.04	
4				0.11	
5					0.11

11 Figures

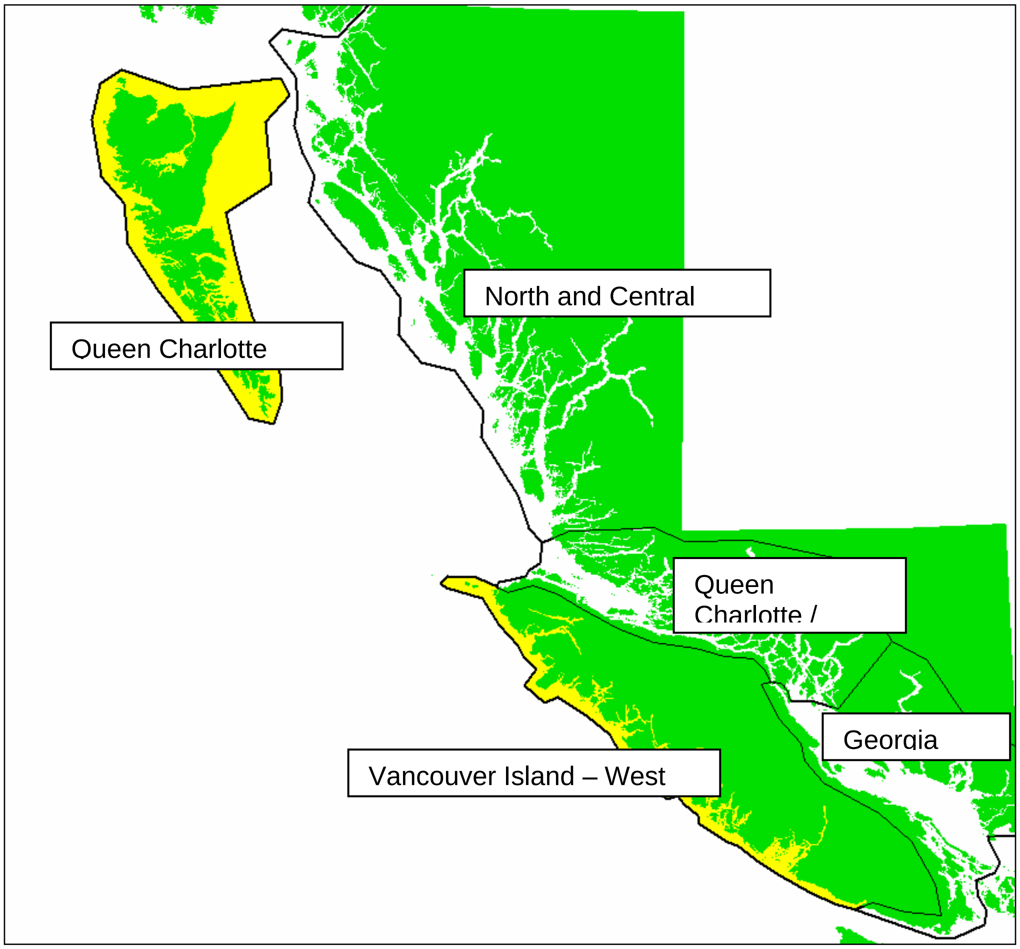


Figure 1: Abalone biogeographic zones in B.C., based on environmental, management and/or biological considerations for northern abalone. They include intertidal and sub-tidal waters surrounding the following land areas: **Haida Gwaii (Queen Charlotte Islands):** Queen Charlotte Islands, **Queen Charlotte and Johnstone Straits:** Quadra Island (Seymour Narrows) north to Cape Caution, **North and Central Coast:** Cape Caution north to and including Prince Rupert, **Georgia Basin:** San Juan Point to Seymour Narrows near Quadra Island, and **West Coast of Vancouver Island:** the west coast of Vancouver Island from San Juan Point north to the Scott Islands. The highlighted yellow areas were analysed in this study.

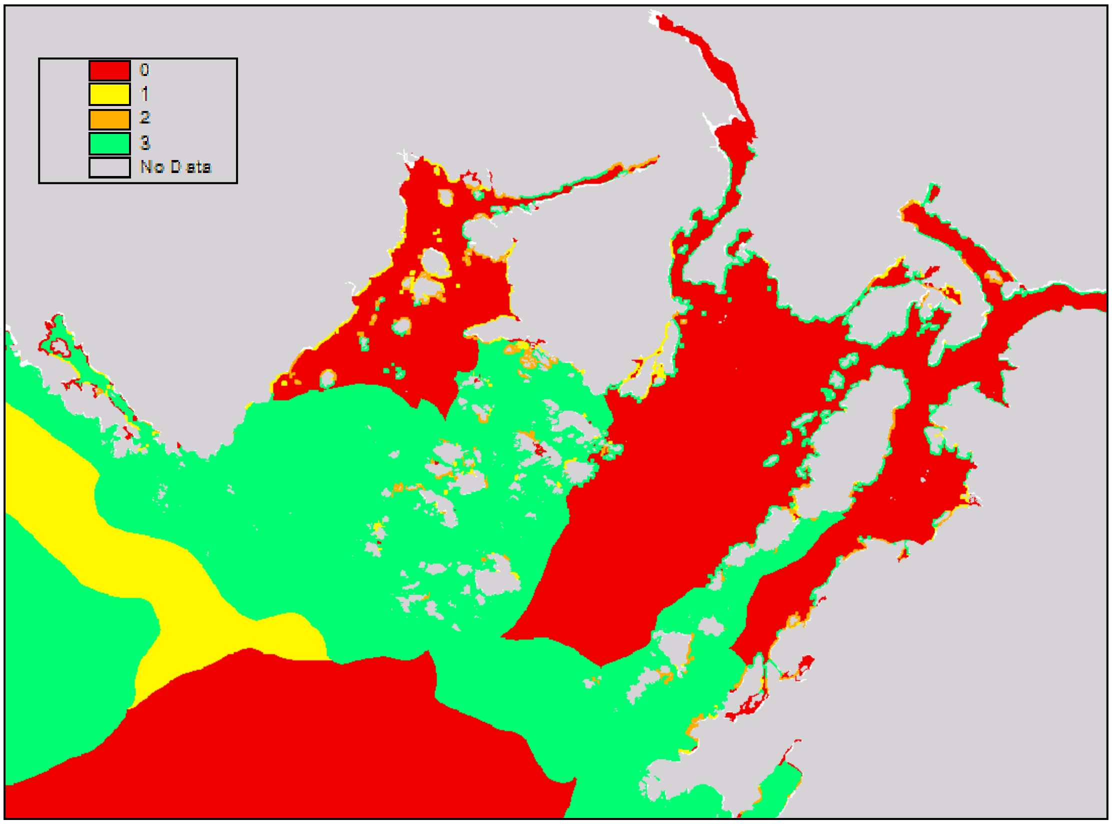


Figure 2: Physical Influence– BC MEC substrate combined with BC shoreline values.

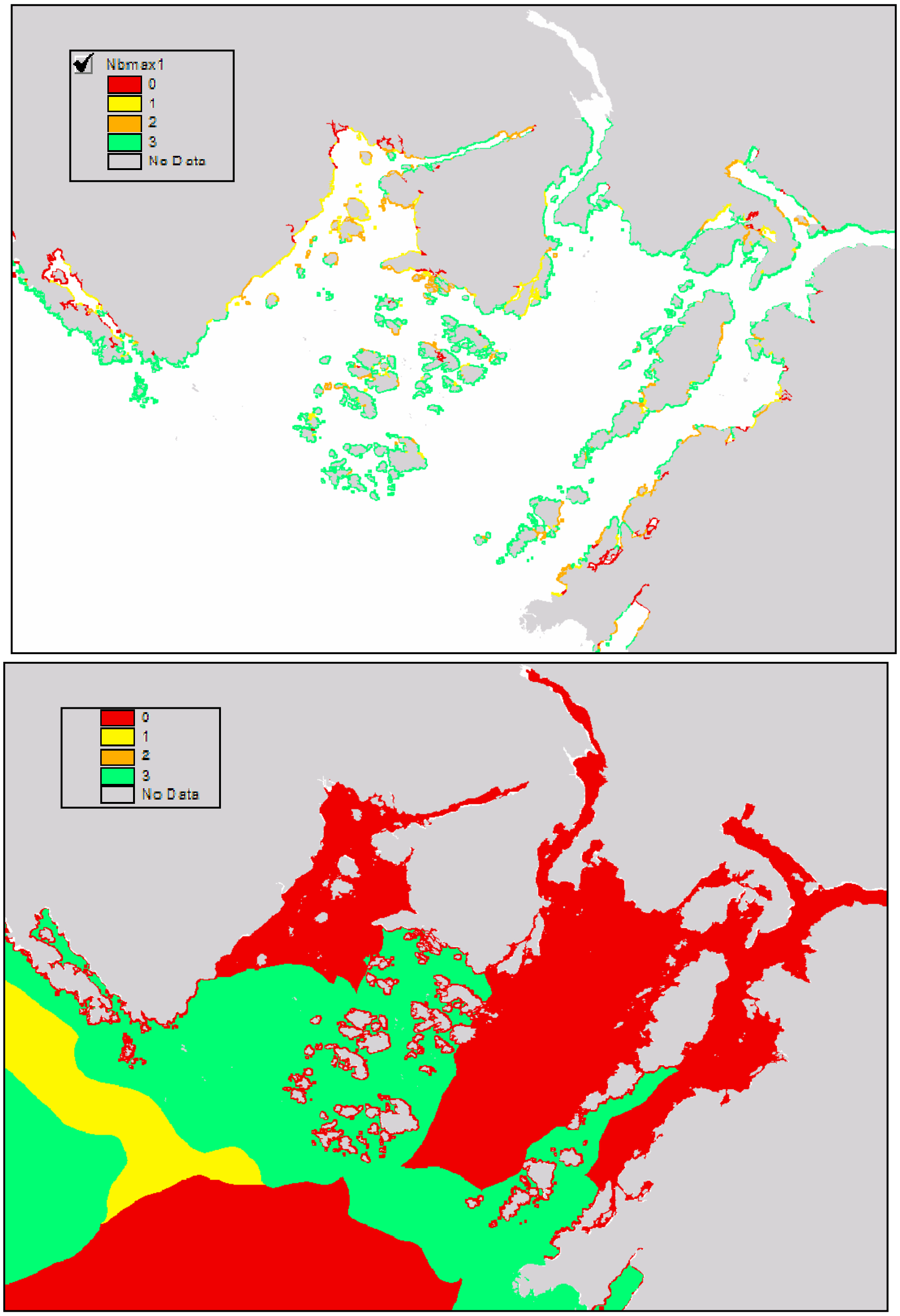


Figure 3: Example of the two components that contributed to the physical influence surface. **Top**: part 1 - BC Shoreline units with 150 m maximum window applied. **Bottom:** part 2 – BC MEC substrate with 0 values where shoreline values will be placed.

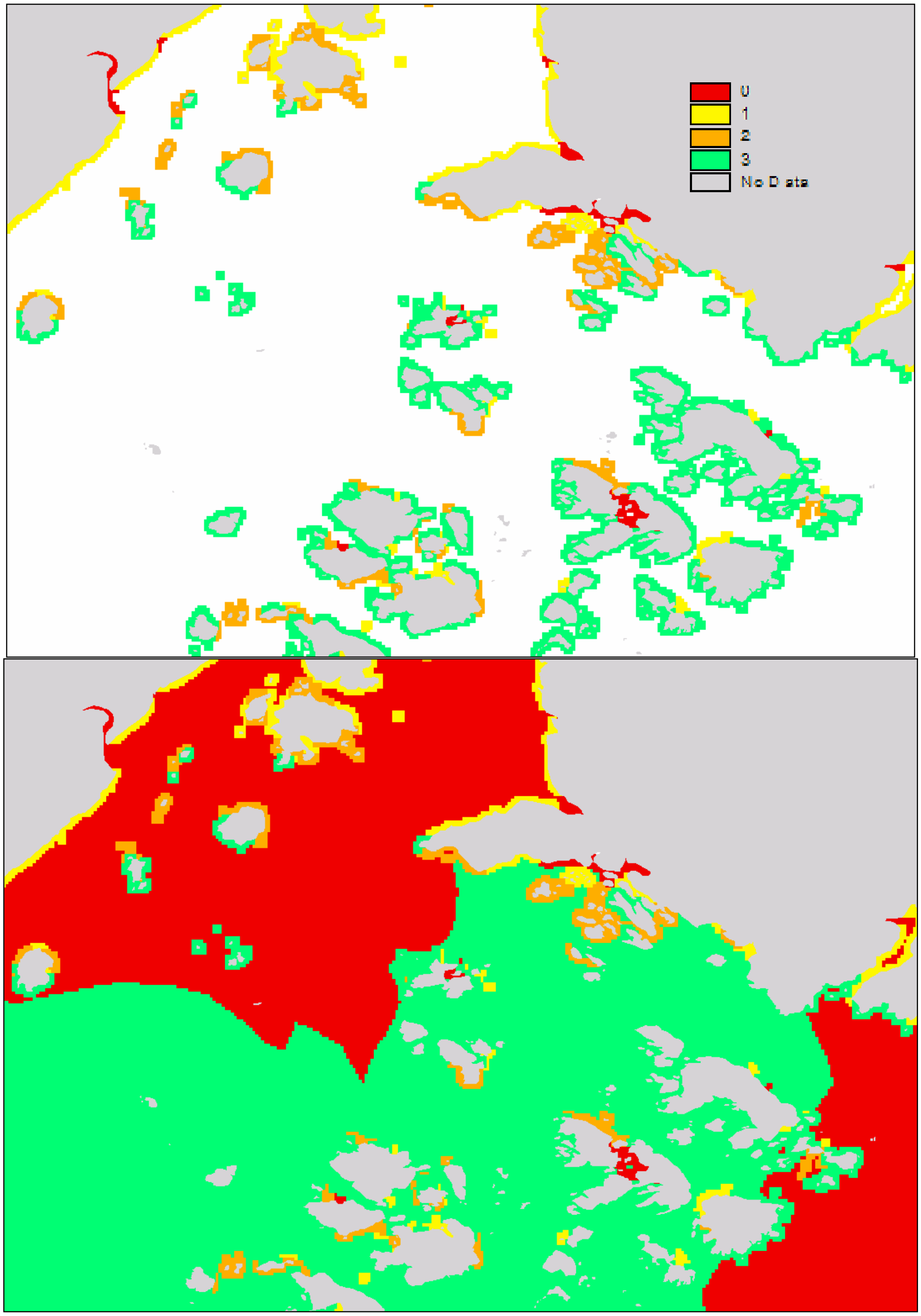


Figure 4: Top: Close up of shoreline classification at the head of Barkley Sound, Bottom: shoreline classification combined with substrate type, forming the physical influence surface.

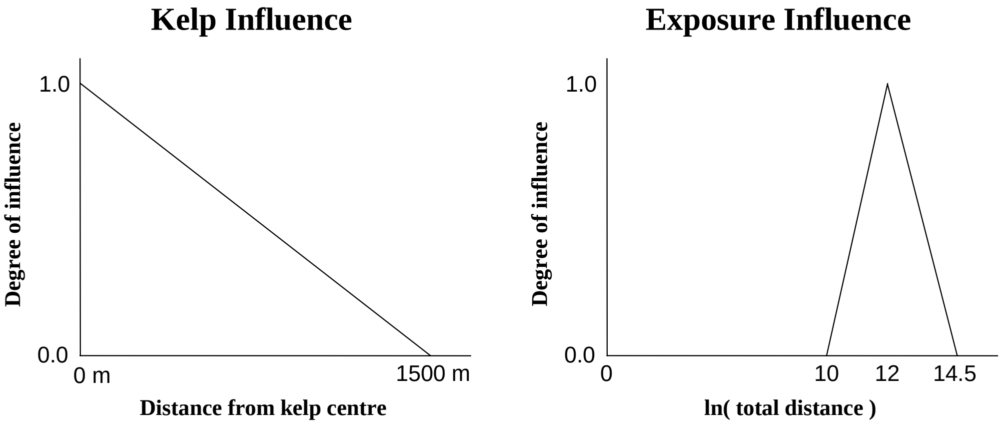


Figure 5: The triangular distributions used to define the influence of kelp (Fig. 6) and exposure on abalone habitat (Fig. 9).

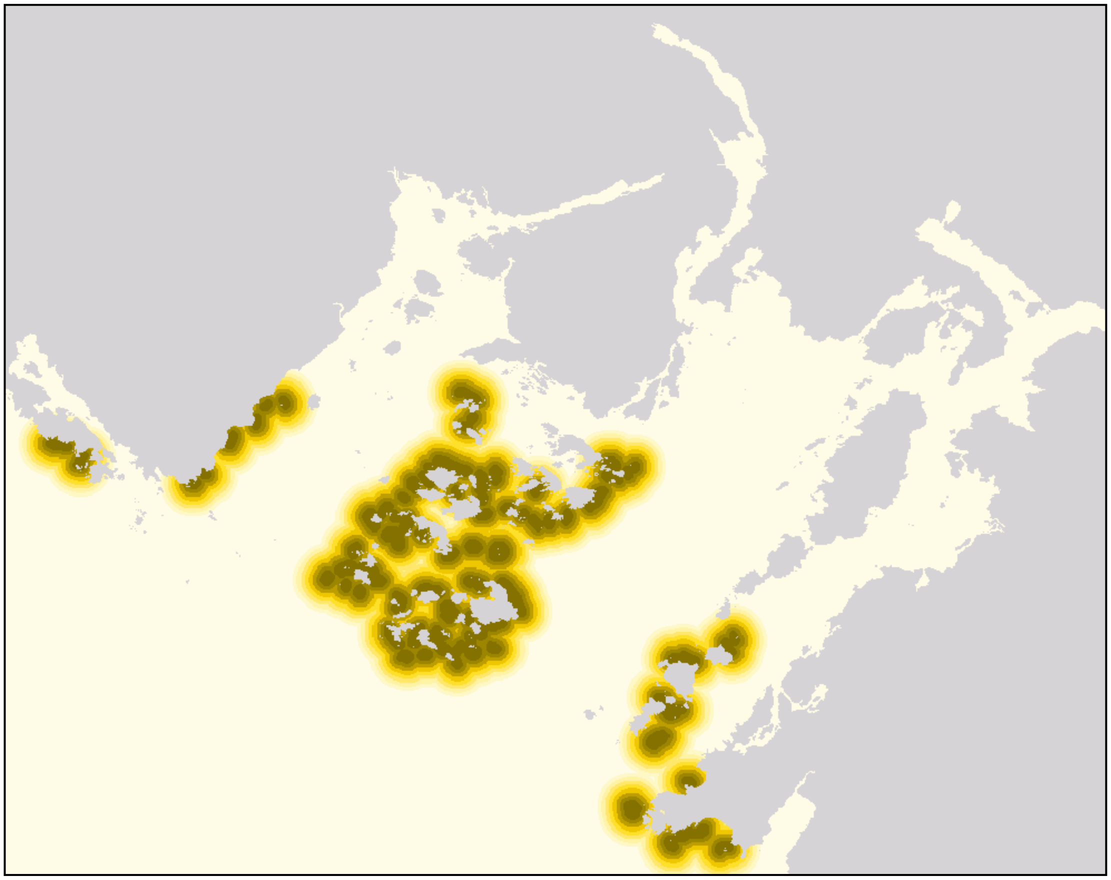


Figure 6: The assumed drift distances of kelp, defined using a triangular distribution, attenuated from 1.0 at the point site to 0 at a distance of 1500 m (Fig. 5), representing the assumed potential for the dispersal of drifting kelp.

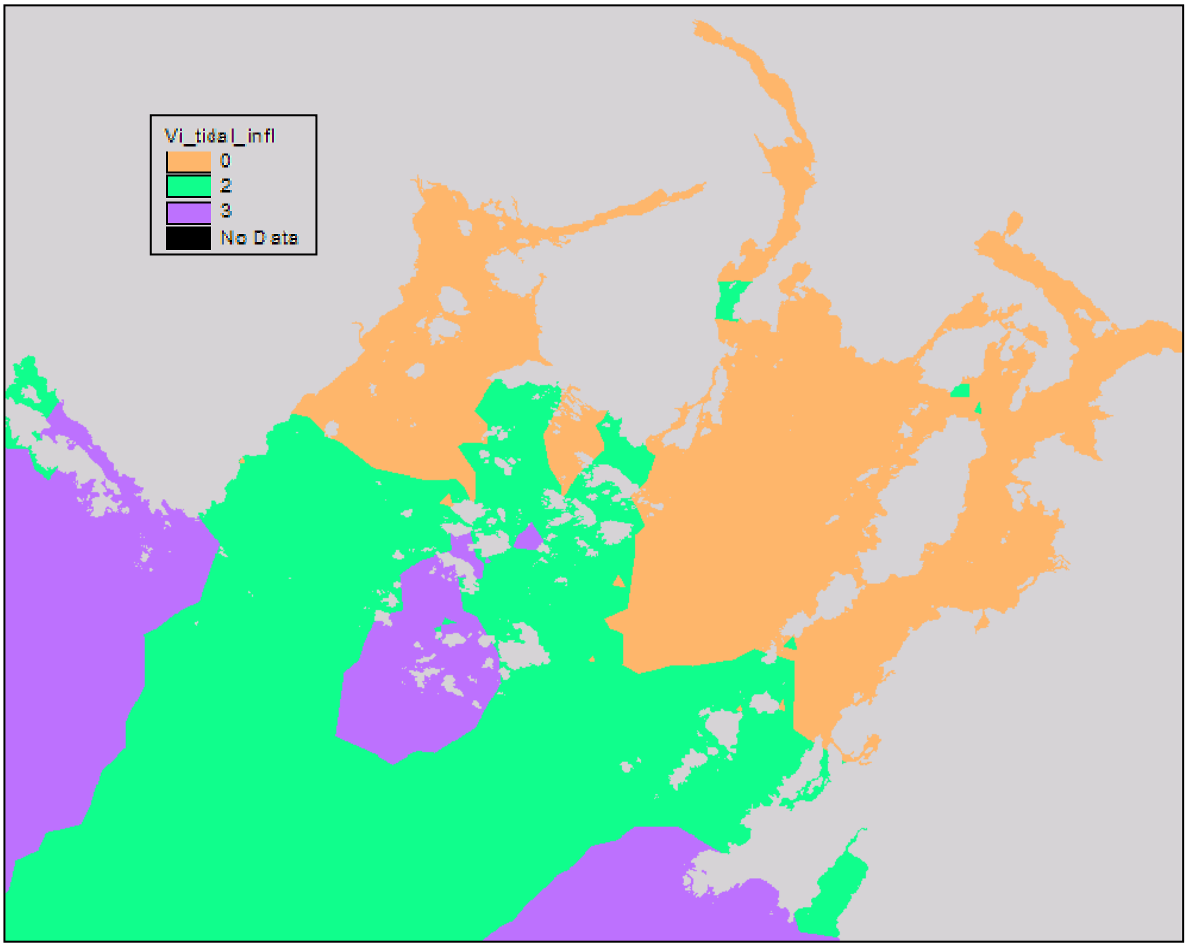


Figure 7: Tidal influence showing the suitability of the reclassified root mean square tidal speed (average of the x and y components, i.e. sqrt(x^2 + y^2).

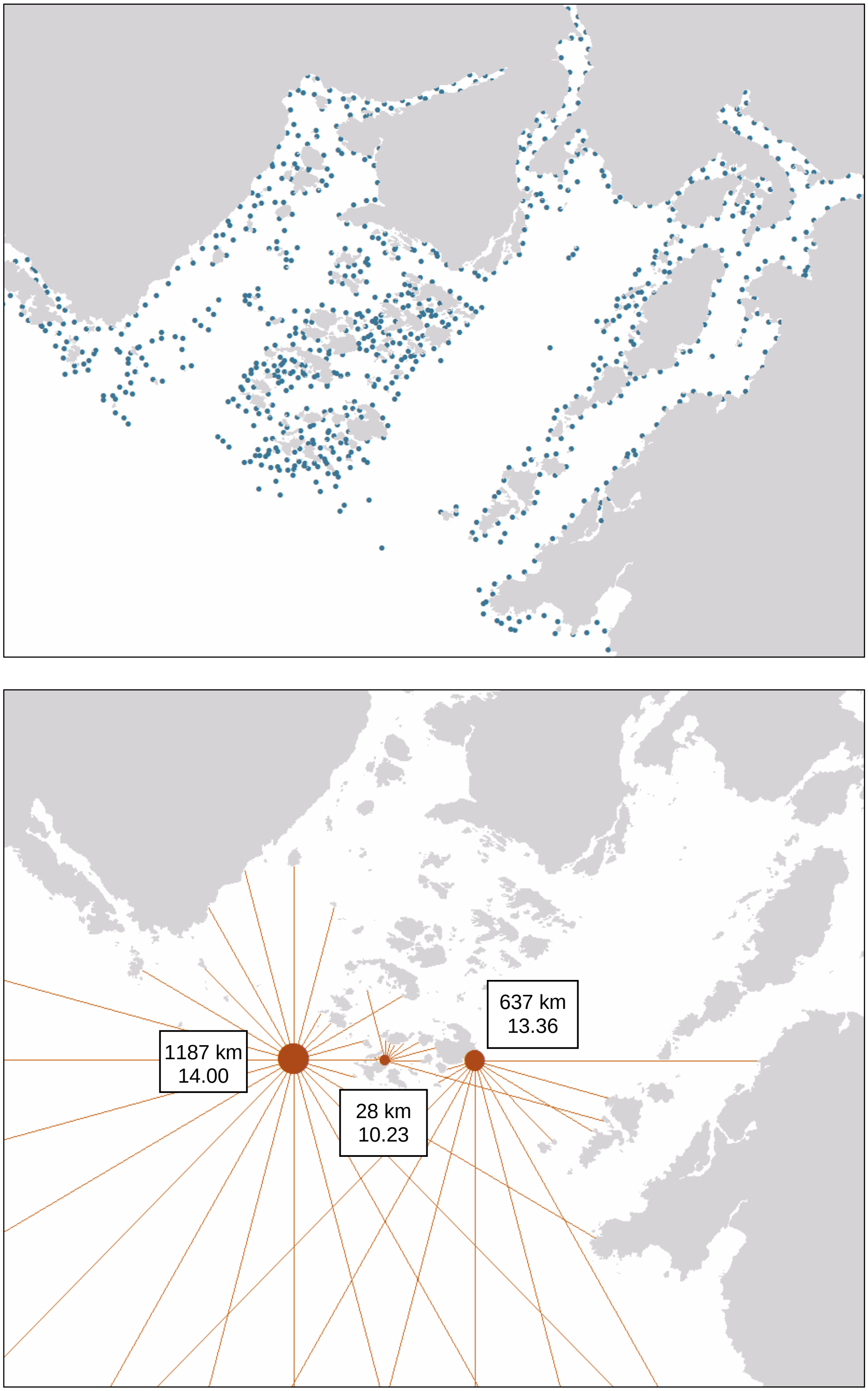


Figure 8: Examples of an exposure calculation. **Top:** The point density used to calculate the exposure. **Bottom:** A comparison of the results for three points showing the radial lines, the total distance (km), and the associated ln() value.

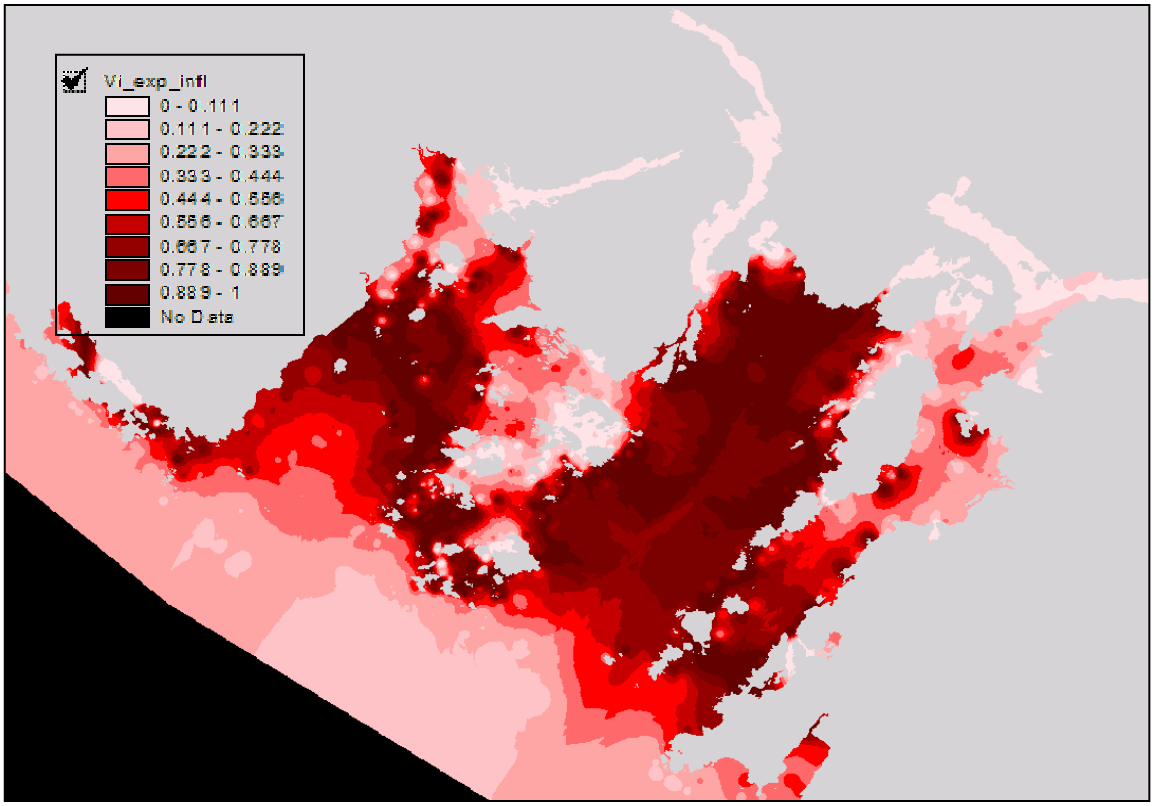


Figure 9: Exposure influence based on reclassification according to triangular distribution shown in Figure 5.

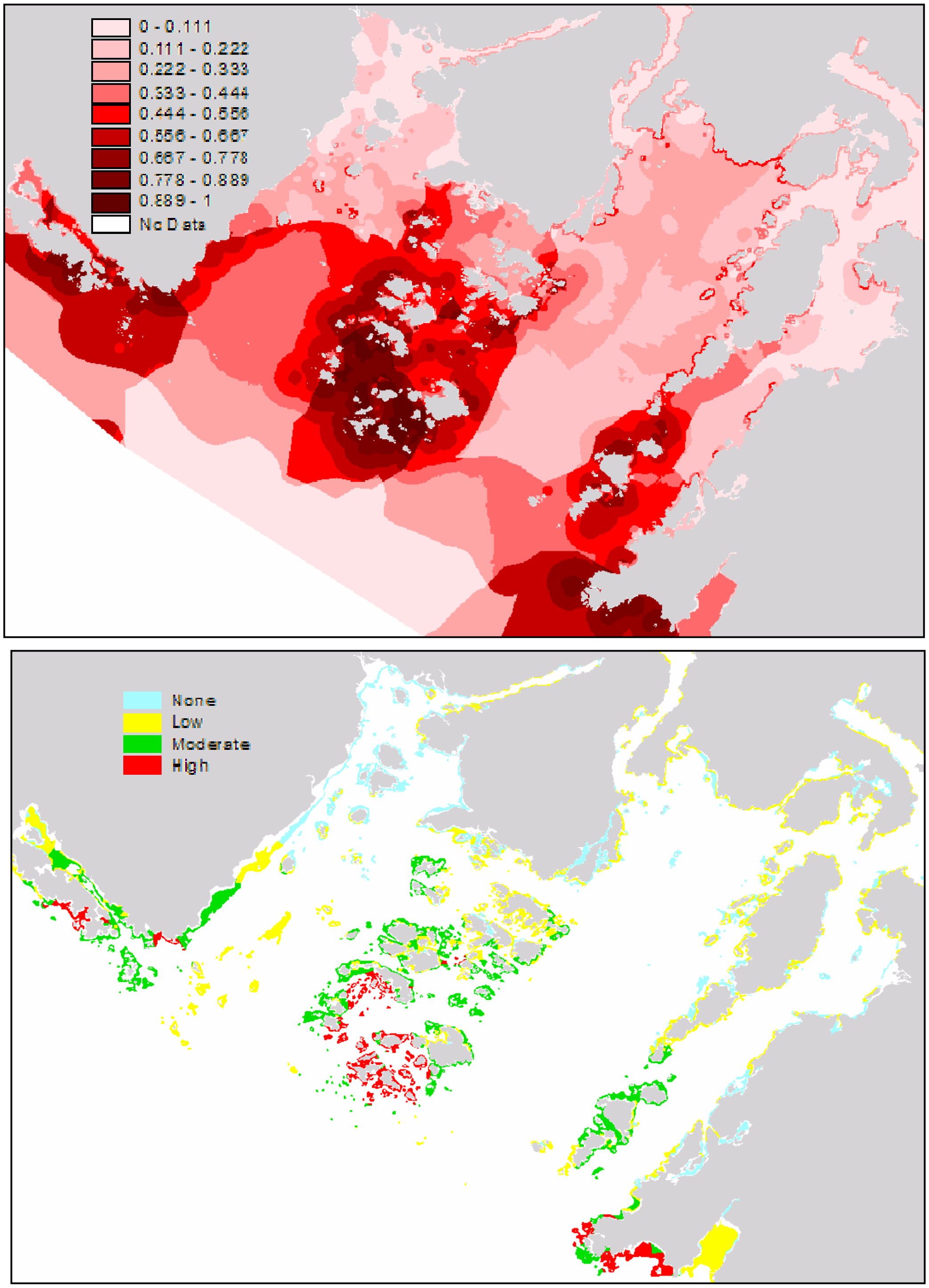


Figure 10: The combined influence surfaces, under the assumption that all four influence parameters (kelp, exposure, tidal and physical characteristics) are weighted equally. **Top**: before reclassification; **Bottom**: Final habitat suitability prediction after reclassification to none, low, moderate, and high; and clipping to the available habitat (i.e., low water line to 10 m habitat range).

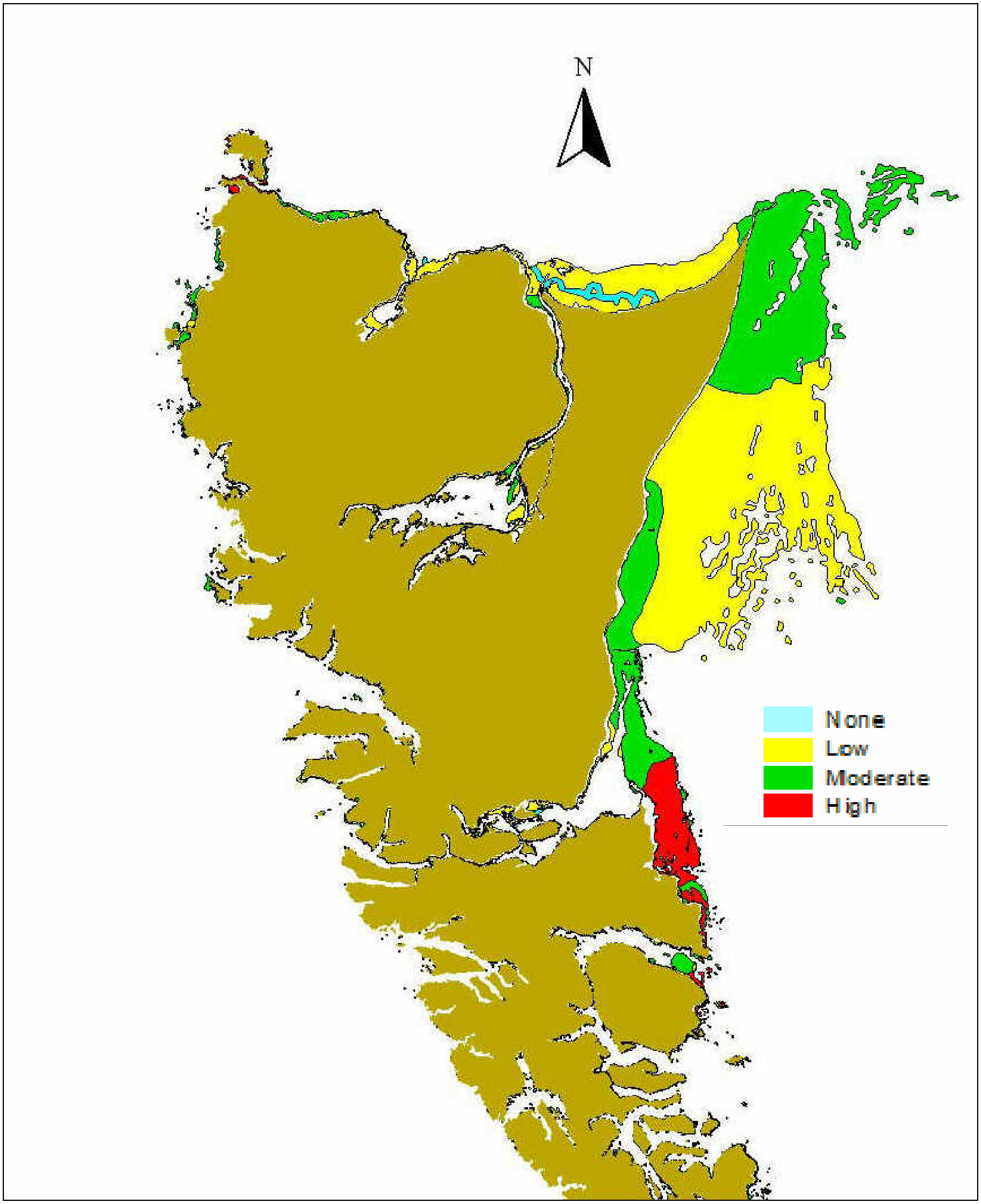


Figure 11A: Predicted abalone habitat values for northern Haida Gwaii (Queen Charlotte Islands). Note: poor substrate surveys may have resulted in more suitable habitat prediction than likely exists.

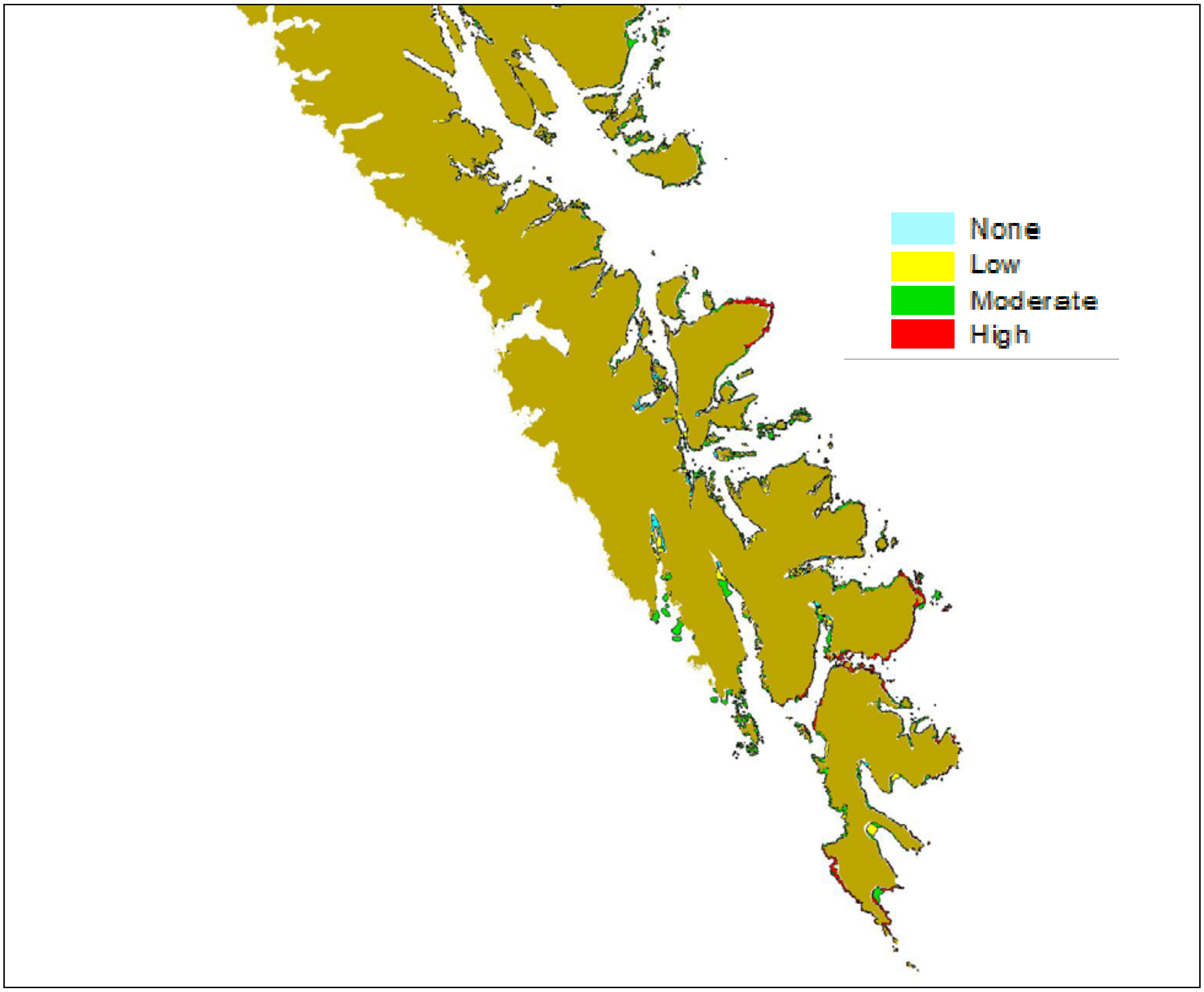


Figure 11B: Predicted abalone habitat values for southern Haida Gwaii (Queen Charlotte Islands).

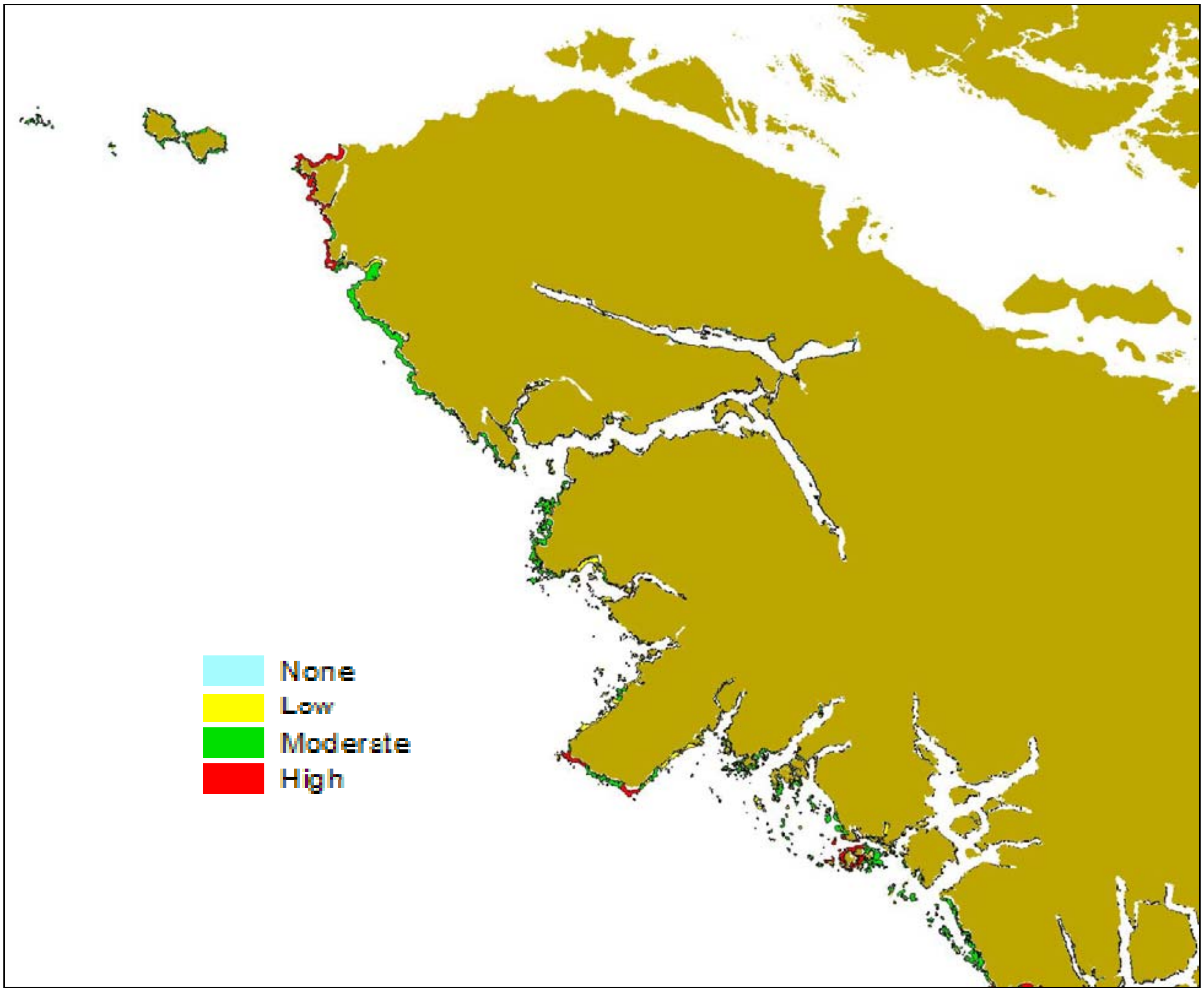


Figure 11C: Predicted abalone habitat values for northwestern Vancouver Island.

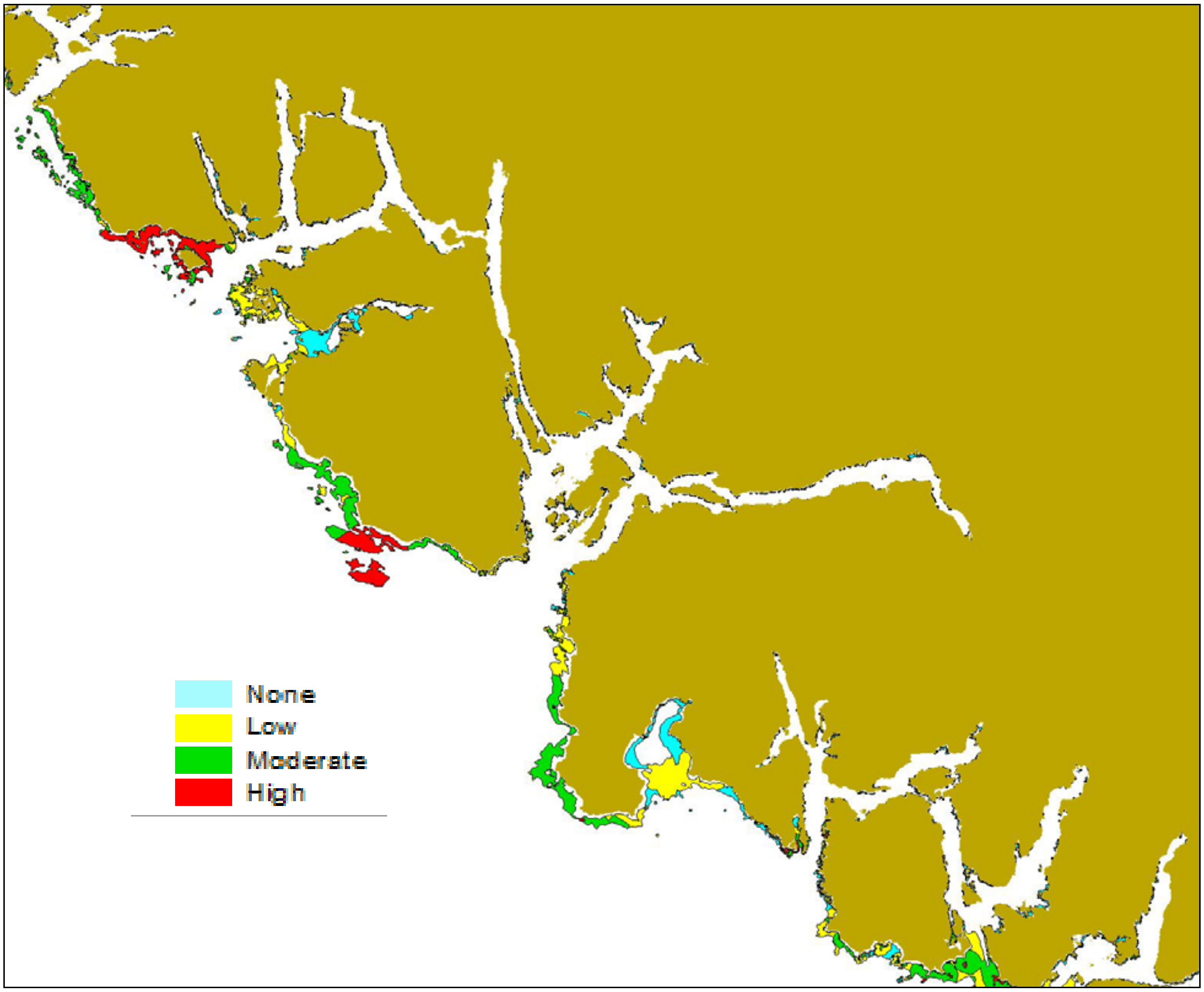


Figure 11D: Predicted abalone habitat values for north-central western Vancouver Island (centred around Nootka Sound). Note: poor substrate surveys may have resulted in more suitable habitat prediction than likely exists.

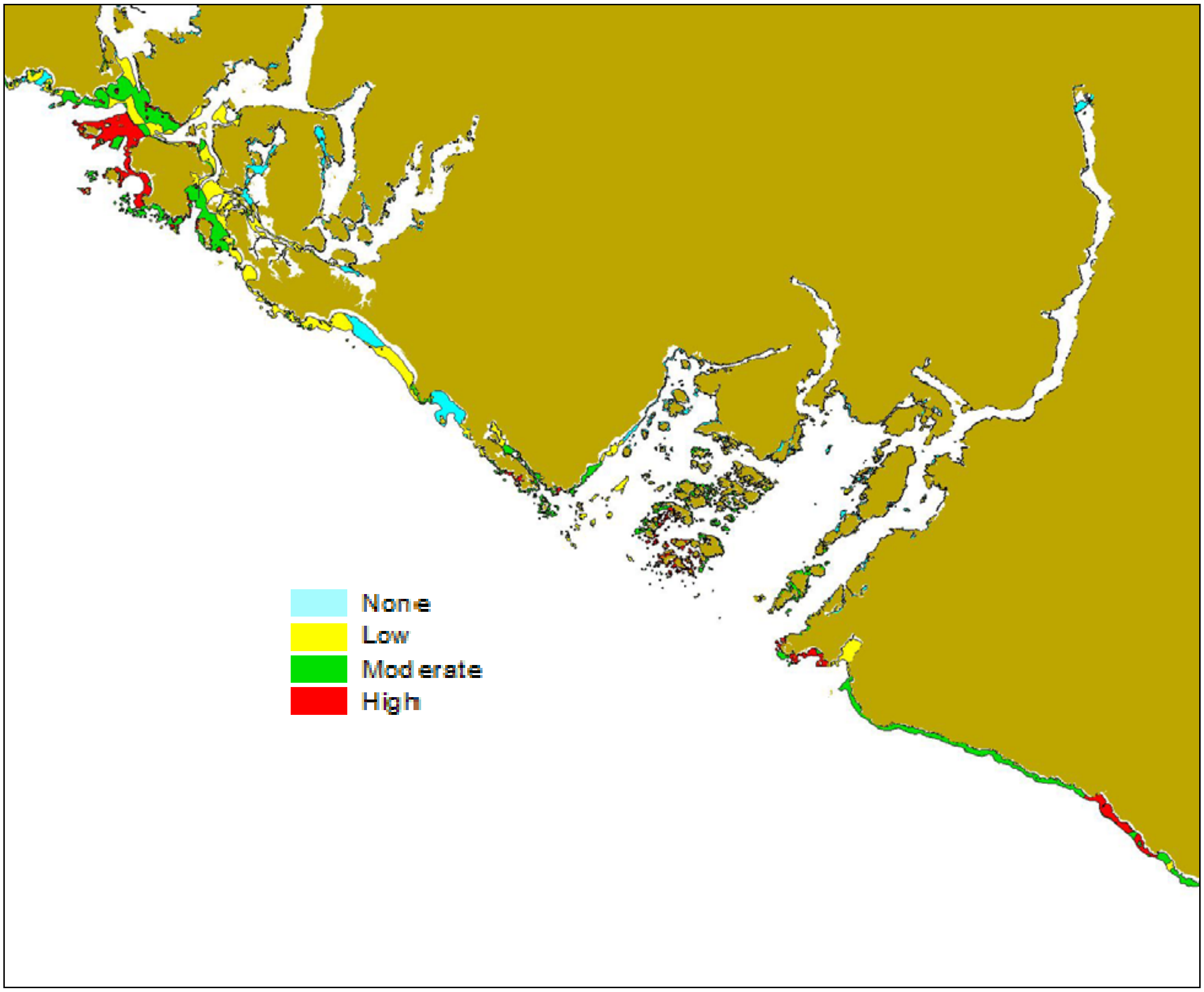


Figure 11E: Predicted abalone habitat values for south-central western Vancouver Island (centred around Barkley Sound). Note: poor substrate surveys may have resulted in more suitable habitat prediction than likely exists.

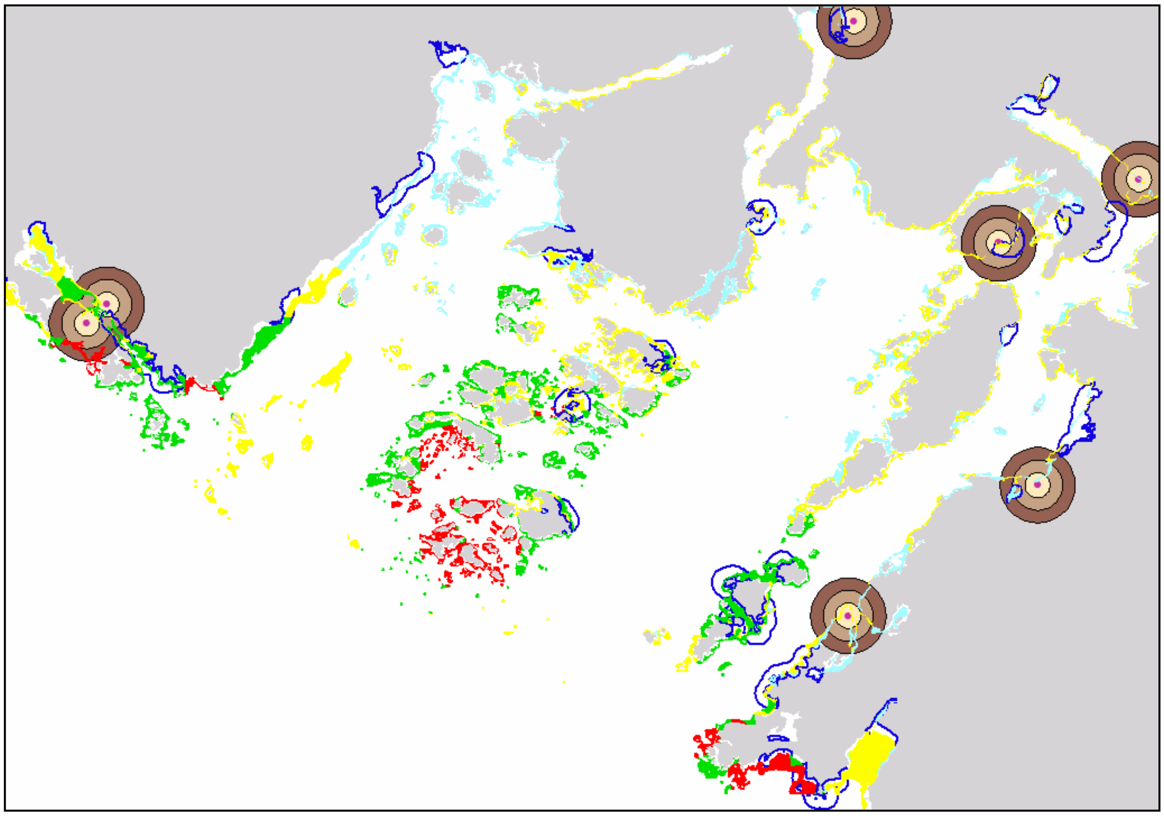


Figure 12: Historic (Indian Reserve's, blue lines, 500 m) and present day (brown circles: 500, 1000, 1500 m) communities in relation to predicted abalone habitat. There is no scaling for estimated community population size.

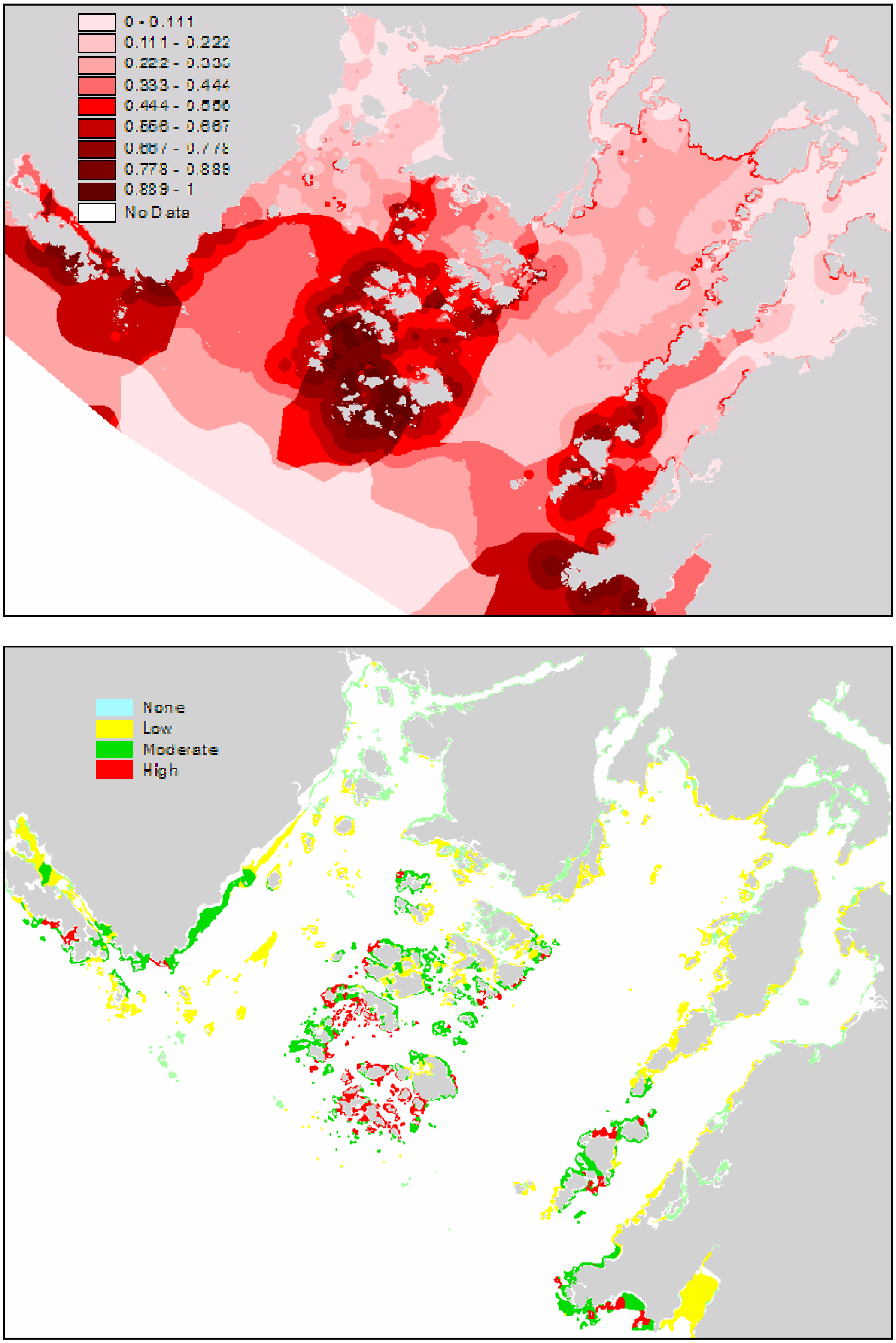


Figure 13: To show the effect of a parameter influence weighting change, the influence surfaces combined (top) and reclassified as none, low, moderate, high (bottom) under the assumption that kelp and exposure are now both twice as important as tidal and physical characteristics. In Figure 10, all four parameters are weighted equally.

Figure 14: Ocean current drifters.

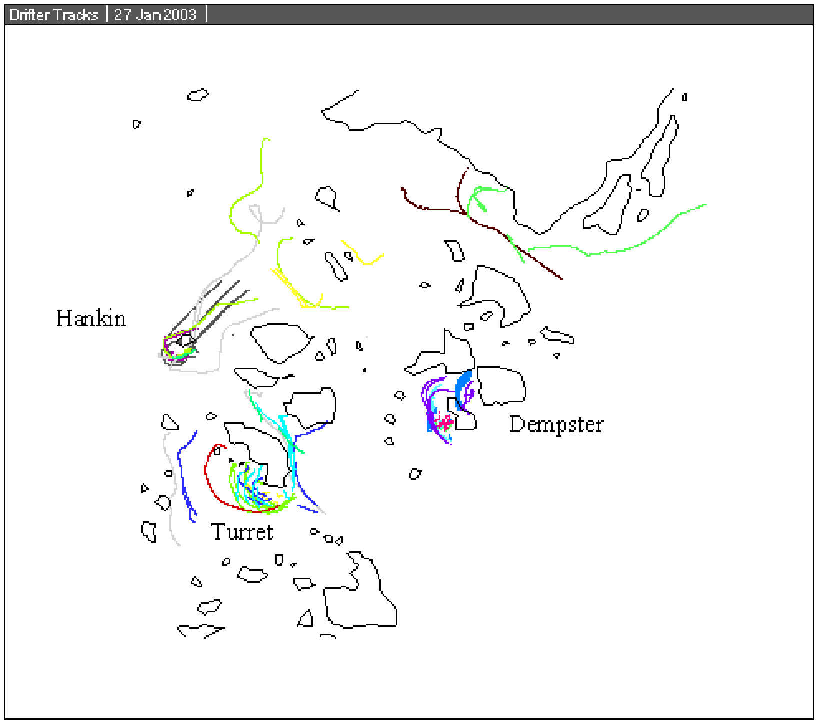


Figure 15: The movement of all trackers over the summer. Colors represent releases; however, a given color may have been used for more than one release.

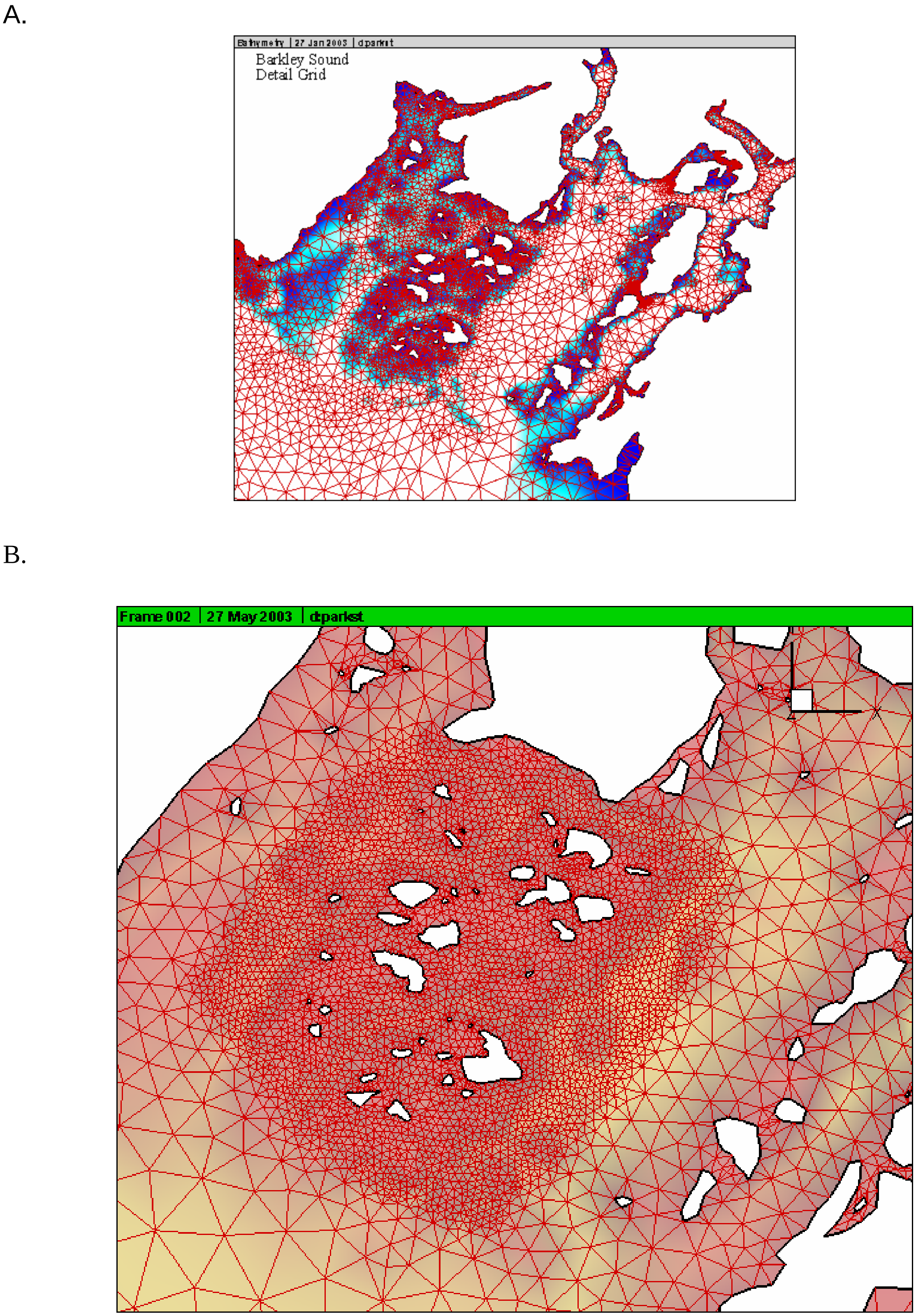


Figure 16: The map of the final triangular grid used to cover A. Barkley Sound and B. the Broken Islands on the west coast of Vancouver Island.

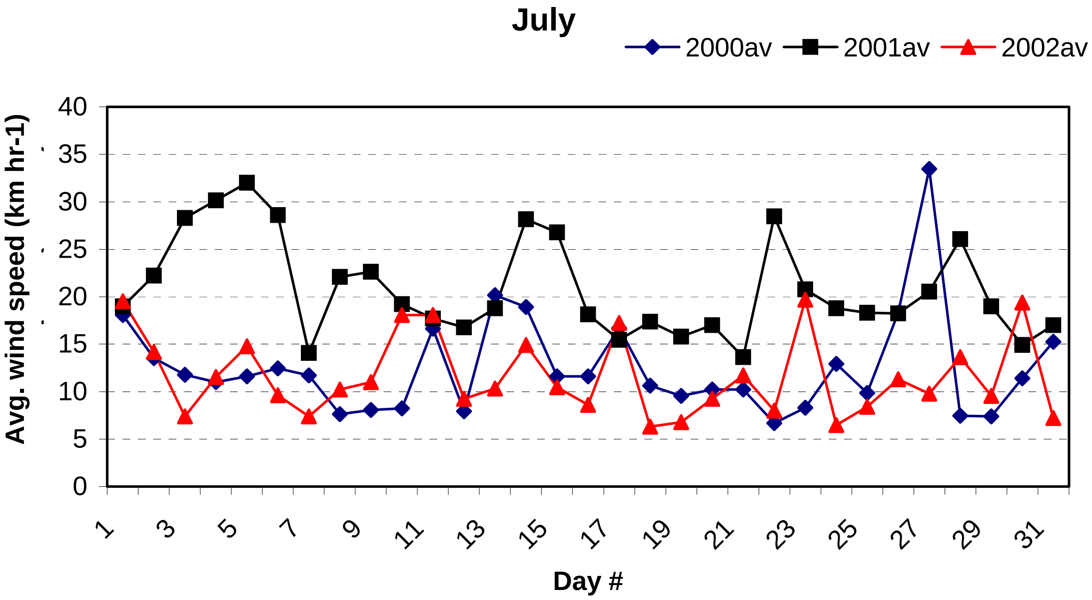


Figure 17: Daily annual average wind speeds by year during July at the Tofino airport.

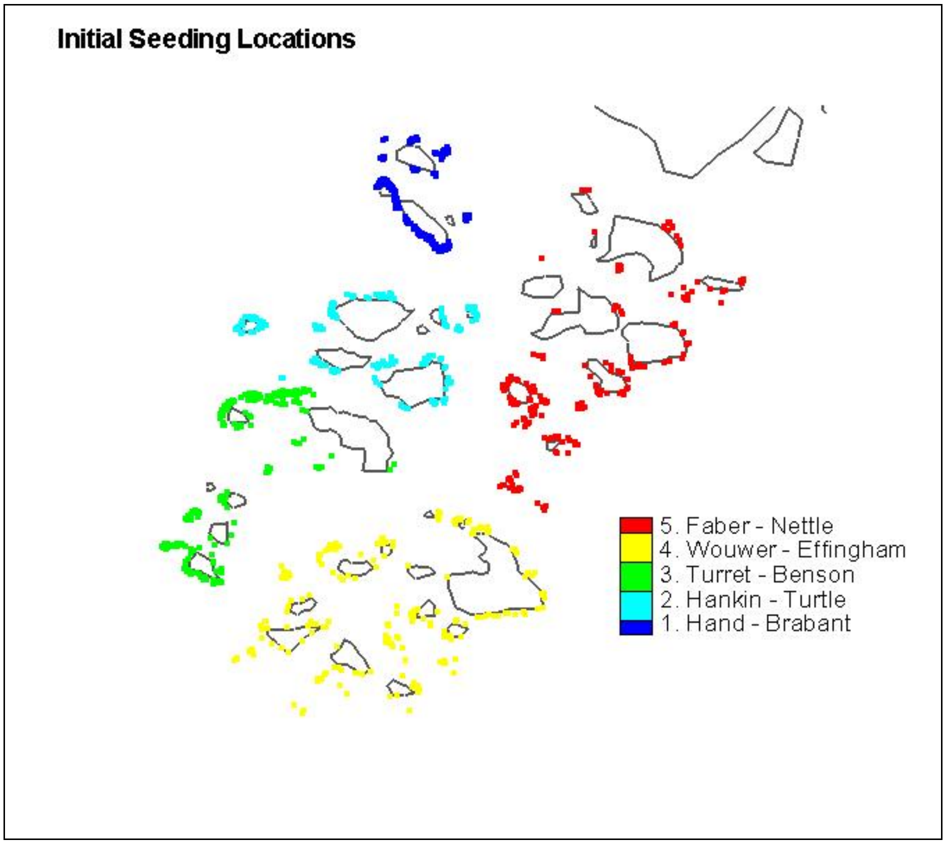
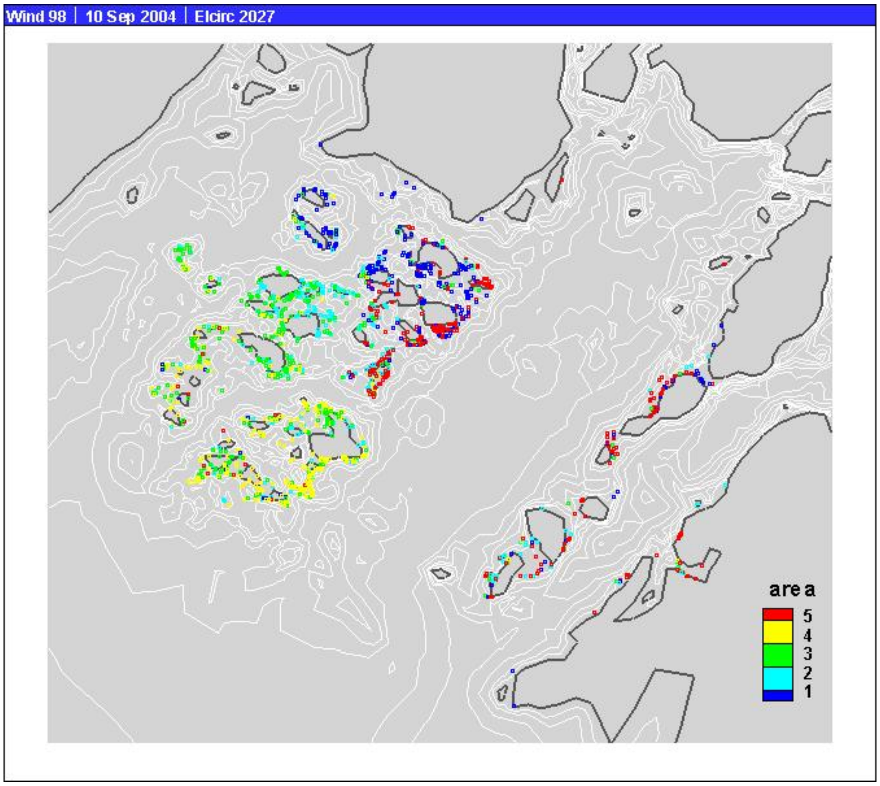
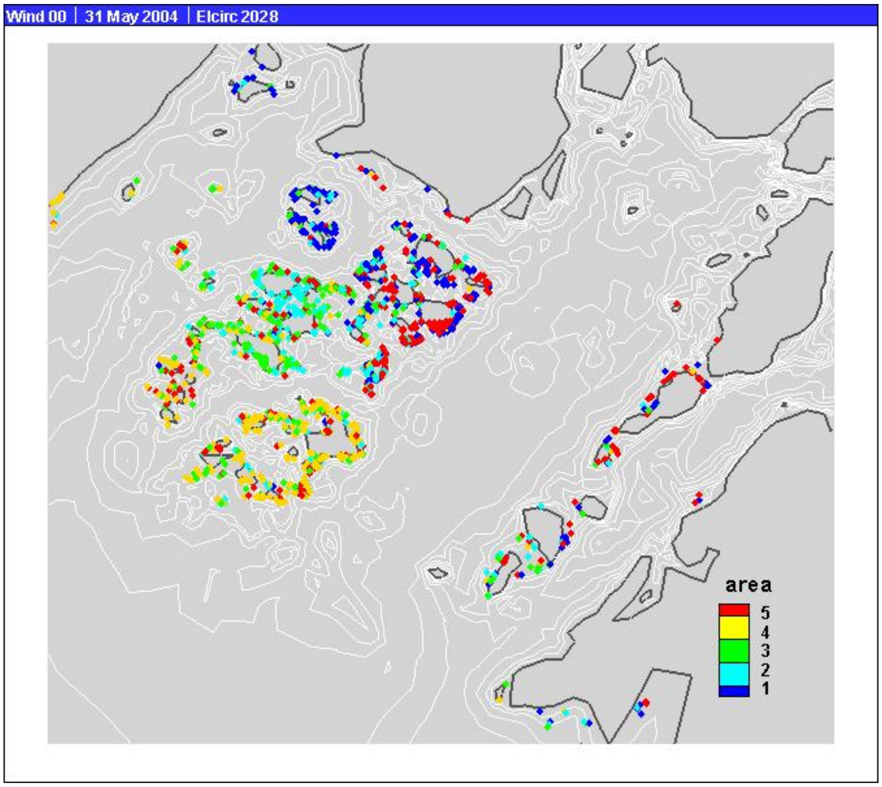


Figure 18: The five complexes of islands (each colour) in the Broken Islands, and their numeric and colour codes.

A.


Wind 98 | 10 Sep 2004 | Elcirc 2027
area
5
4
3
2
1

B.


Wind 00 | 31 May 2004 | Elcirc 2028
area
5
4
3
2
1

C.

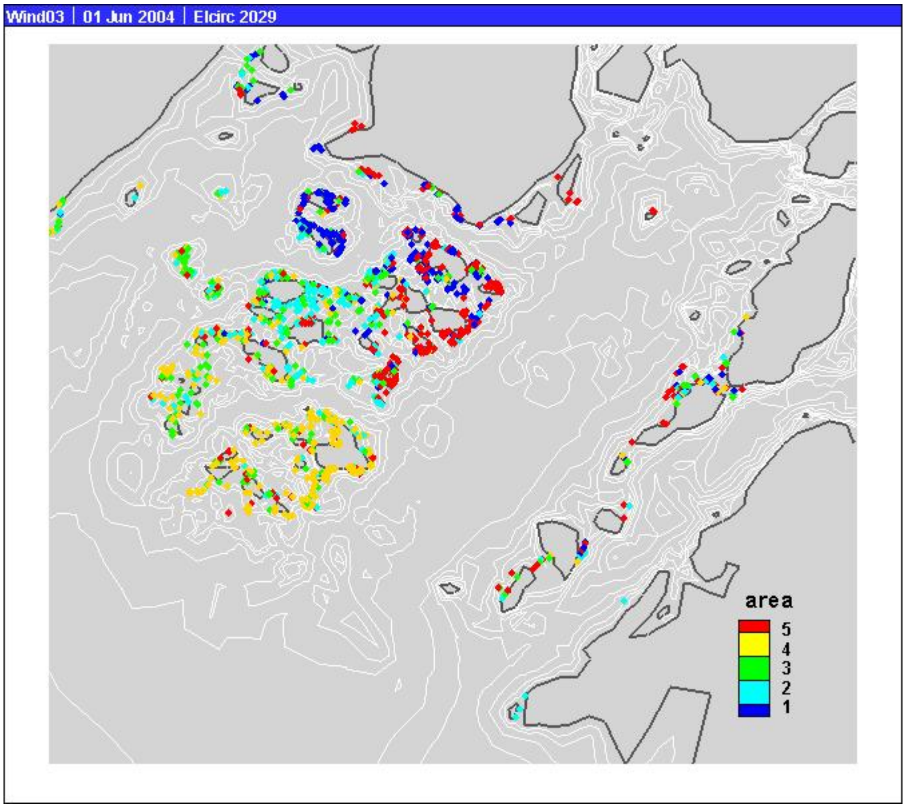
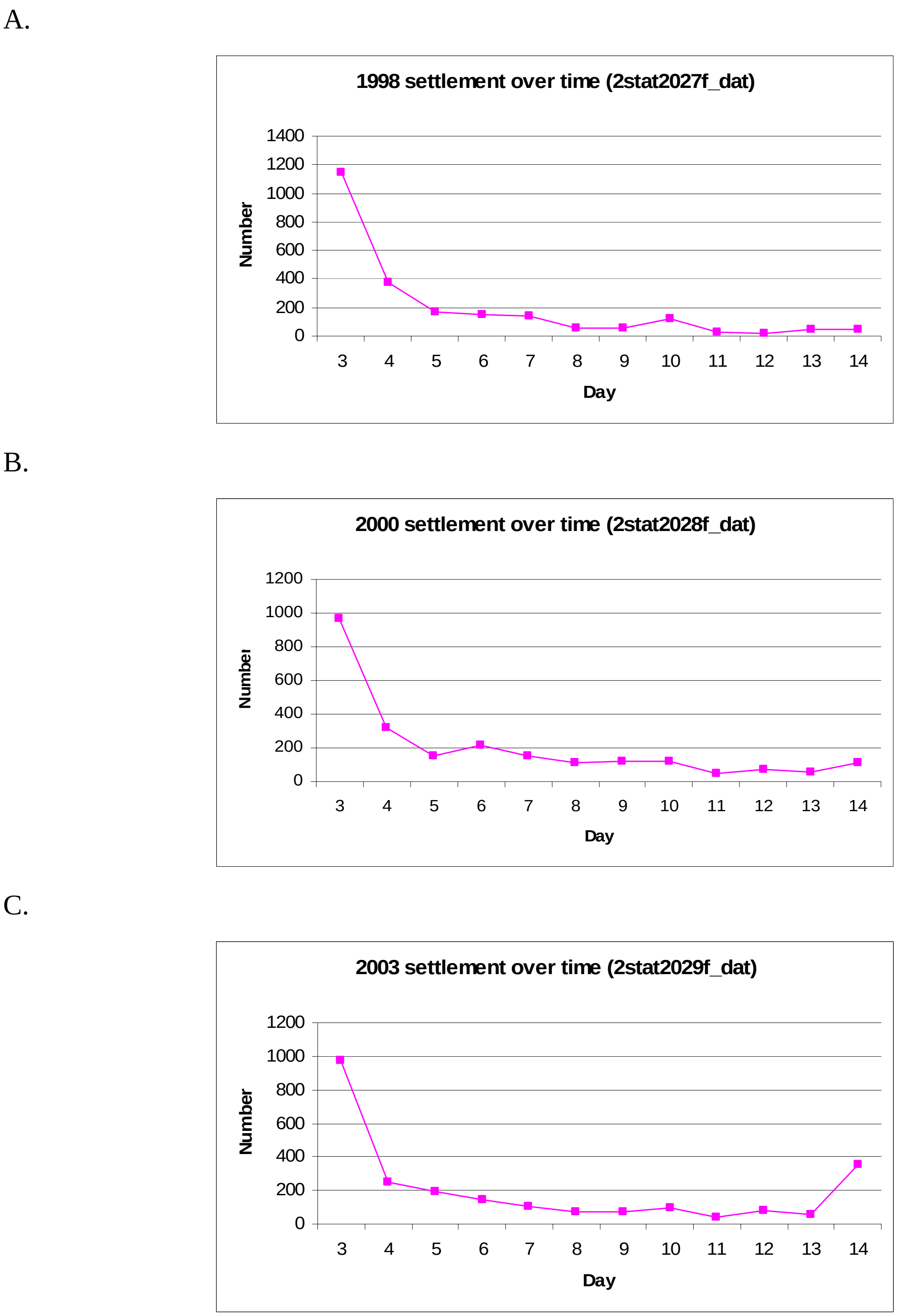


Figure 19: Model simulation results showing the predicted settlement of abalone larvae randomly seeded at the five sites (Figure 19), with larvae from each source site coded by colour as indicated in the figure. There appears to be a modest clock-wise rotation among the sites, although most larvae settle at their release sites, consistent with the limited dispersal suggested for abalone. Data from A. 1999, B. 2000 and C. 2003.



A.

1998 settlement over time (2stat2027f_dat)

B.

2000 settlement over time (2stat2028f_dat)

C.

2003 settlement over time (2stat2029f_dat)

Figure 20: Predicted settlement over time by year, with a three-day competency period before which larvae cannot settle.

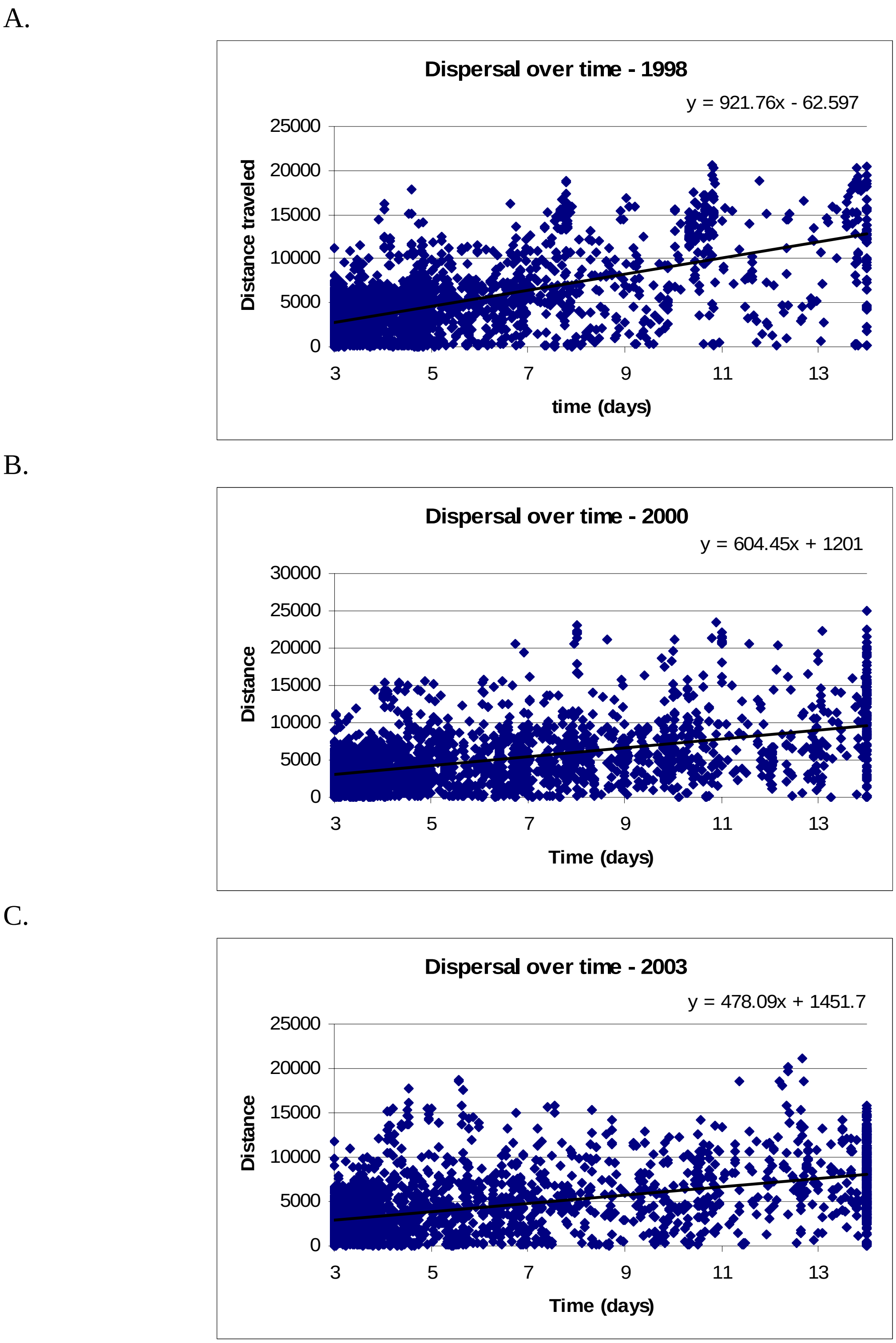


Figure 21: Predicted dispersal distances (m) over time for each of the three years studied. Regression slopes are significantly different among years.

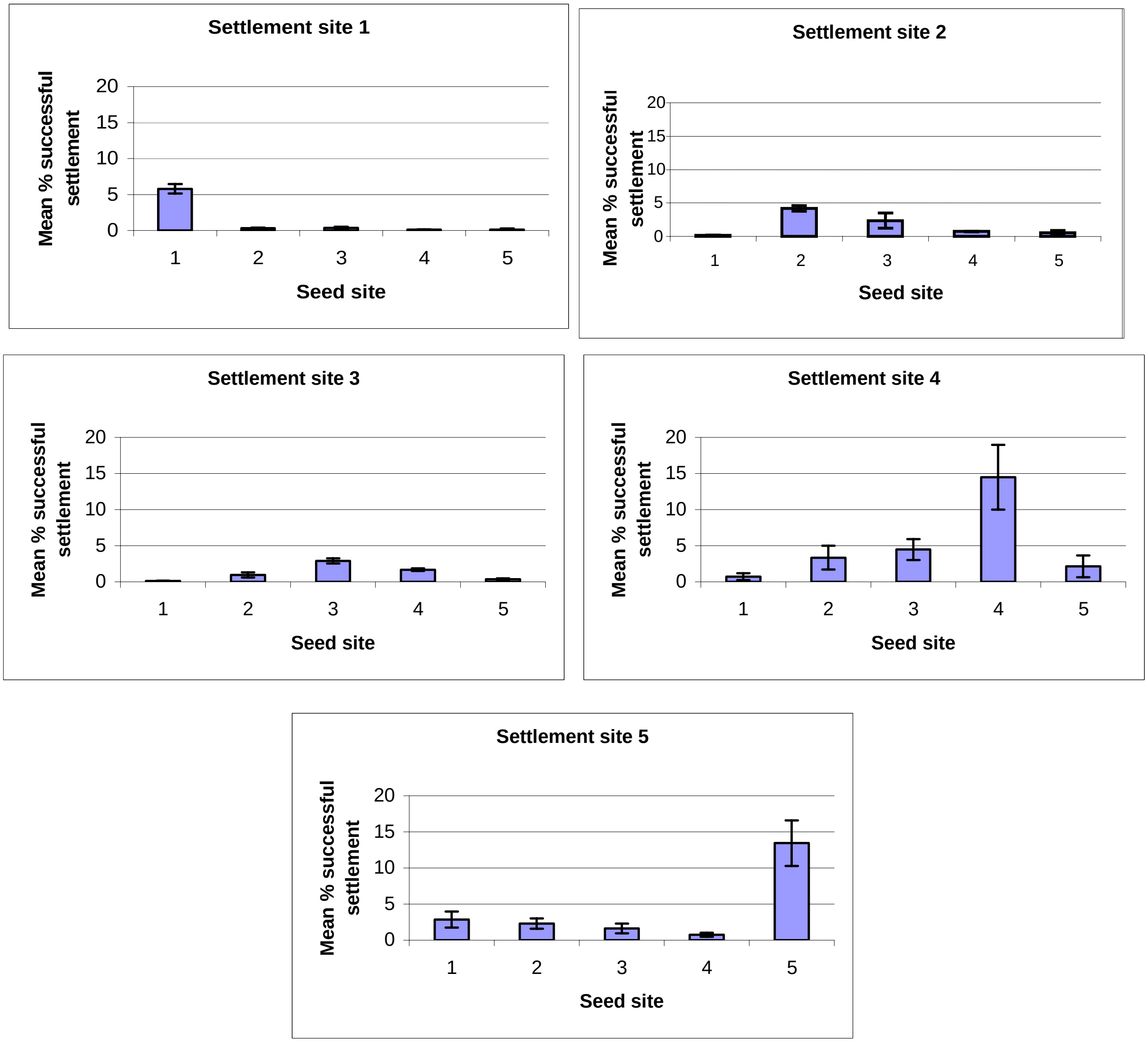
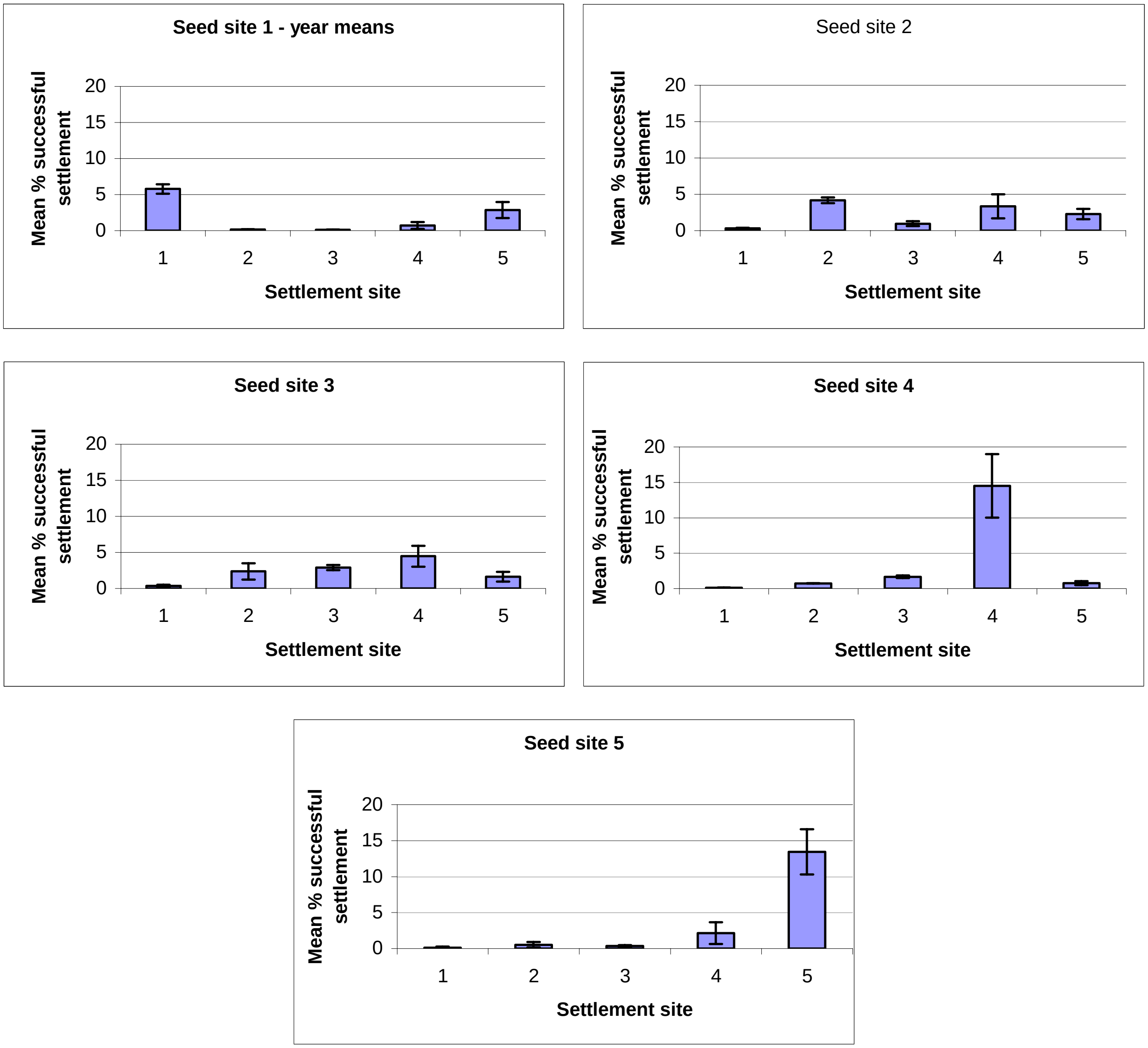


Figure 22A: Site sources of larvae (from year means) that settled in sites 1 through 5.


Seed site 1 - year means

Seed site 2

Seed site 3

Seed site 4

Seed site 5

Figure 22B: Destinations of larvae (from year means) from sites 1 through 5.

Figure 23: Percent of larvae that settled in each year, assuming no mortality while in the water column, i.e. these are the proportions of larvae each year that came close enough to the bottom to permit settlement.

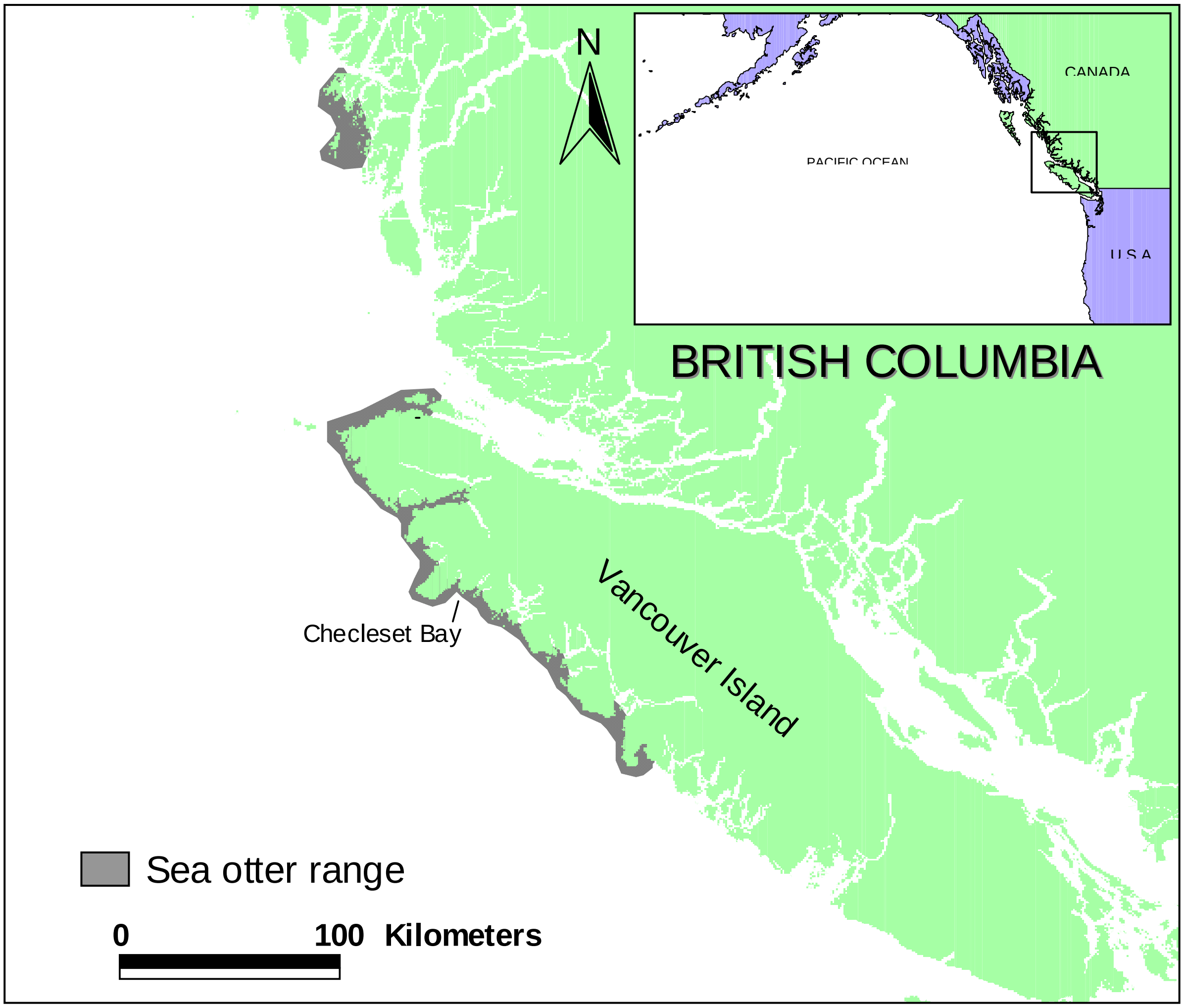


Figure 24: Sea otter range (shaded area) in BC in June, 2004 (Linda Nichol, DFO, Nanaimo, BC, pers. comm.).