J Coast Conserv
DOI 10.1007/s11852-010-0101-8

Application of aerial photography in combination with GIS for coastal management at small spatial scales: a case study of shellfish aquaculture

Leah I. Bendell · Peter C. Y. Wan

Received: 3 October 2009 / Accepted: 29 March 2010

Abstract Coastal zones are among the planets most threatened ecosystems and effective management of these systems requires spatial tools at appropriate spatial scales. Here we apply aerial photography with Geographic Information Systems (GIS), to map the cumulative anthropogenic footprint of an industry in a spatially defined ecologically important region of the British Columbian coast. Resolution required for such an analysis was made possible through highly detailed aerial photography of the region taken at an elevation of 305 m, at a 1:3000 scale. The approach applied here was successful in accurately detailing the cumulative extent of the anthropogenic activity on the foreshore which could have not been achieved at a coarser resolution. Such information was then effectively applied to visualize and assess the potential impact of an industrial development of the foreshore on bird distribution within the spatially identified region. The degree of overlap between the anthropogenic footprint and small estuaries within the region was also successfully assessed. For ecologically important regions such as Marine Protected Areas, and other such designated sensitive coastal regions, detailed mapping through aerial photography and GIS can aid in first identifying the true extent of an anthropogenic activity and then secondly used to link to possible ecological consequences. This in turn greatly enhances our ability to best manage the region of interest such that conservation priorities can be met.

Keywords Aerial photography · GIS · Spatial analysis · Cumulative affects · Anthropogenic footprint

L. I. Bendell (✉) · P. C. Y. Wan
Department of Biological Sciences, Centre of Coastal Studies,
Simon Fraser University,
8888 University Drive,
Burnaby, BC, Canada V5A 1S6
e-mail: bendell@sfu.ca

Introduction

Coastal zones, the interface between land and ocean, are among the planets most threatened ecosystems. Ever increasing pressures from human population growth represents one of the greatest threats as this pressure can manifest itself in various cumulative ways including; increased inputs of pollution, urbanization, and, rates of erosion due to extreme weather events as a consequence of climatic warming. A recent report of Sale et al. (2008) noted that by 2050, 91% of the world's coastlines will have been impacted by development with this development poorly planned if planned at all. Coastal zones aside from their recreational and aesthetic value provide key ecosystem roles such as supporting various fisheries of economic importance, serving as habitat for wildlife, as well as have an important role in the cycling of essential nutrients such as nitrogen (Jickells and Rae 1997). Proper management of these critical ecosystems is essential.

Management of coastal regions however, presents unique challenges. Unlike terrestrial systems, the intertidal is a spatially complex, highly dynamic region constantly changing as a consequence of tidal and storm activity. Because of tidal action, and again, unlike terrestrial ecosystems, the intertidal is a region of environmental extremes with a gradient of physio-chemical conditions (e.g., temperature and salinity) which occur over small spatial scales, in some cases less than 100 m. This environmental gradient in turn supports a diverse number of habitat types and intertidal species which occur within this spatially confined region.

An approach for the management of spatially complex regions that has received ever increasing use is the application of Geographical Information Systems (GIS). For terrestrial systems, applications have ranged from predicting spatial aspects of human elephant conflict to predicting suitable rufous bristlebird (*Dasyornis broadbenti*) habitat (Sitati et al. 2003; Gibson et al. 2004). GIS has also been extensively used for coastal zone management to assess the intensity of anthropogenic marine activities. For example Ban and Alder (2008) through a GIS approach determined that 83% of the continental shelf and slope of British Columbia Canada was currently being used by humans. Low resolution photography coupled with GIS has also been used to successfully characterize and quantify habitat types (e.g., Sheppard et al. 2006; Higinbotham et al. 2004). However, as noted by Zharikov et al. (2005) current GIS applications for coastal zone management are designed for large spatial scales (10–1000 km). Management of key coastal habitats require much greater resolution. This is especially true where in some regions of the coast the foreshore region can be less than 100 meters in width, a spatial scale that requires a high resolution analysis. For example, Banks and Skilleter (2007) recently reported the importance of incorporating fine-scale habitat data into the design of an intertidal marine reserve system. These authors noted that surrogate measures most often based on broad-scale (100–1000's of km) bioregional frameworks that define general categories for intertidal systems (e.g., sandy beach, rocky shore) are inadequate when making decisions about conservation priorities at the local level (10–100's of m). To achieve conservation goals Banks and Skilleter (2007) conclude that use of finer-scale physical data is required. Winberg et al. (2007) also note the importance of fine spatial scale for their application in the conservation of tidal flat macrobenthos.

Here we apply high resolution aerial photography coupled with GIS to characterize a key ecological region on coastal British Columbia (BC), Canada, but, rather than habitat mapping (e.g., by Zharikov et al. 2005), our objectives were first to map in detail the cumulative impact of a specific anthropogenic use on a key type of foreshore habitat such that the spatial scale of the footprint could be visually assessed. We then apply this spatial assessment to evaluate the consequences of the anthropogenic activity on other ecological uses within the spatially defined region.

The case study presented here is unique in that the region under study is an Important Bird Area (IBA, defined as a site providing essential habitat for one or more species of breeding or non-breeding birds) of global significance (Booth 2001). The Baynes Sound region supports globally important populations of the Western Grebe (*Aechmophorus occidentalis*), the White-winged (*Melanitta fusca)* and Surf Scoter (*Melanitta perspicillata)* and the Pacific Loon (*Gavia pacifica*) (Booth 2001). It is one of BC's most ecological sensitive and important coastal regions. It also serves as a major centre for the BC shellfish aquaculture industry with half of the industries economies being generated from this region (British Columbia Ministry of Sustainable Resource Management (BCMSRM) 2002)). Bird use of the intertidal directly overlaps with the use of the intertidal for shellfish farming purposes. Hence this case study provides an excellent example of the fine-scale resolution required to spatially and visually access the degree of overlap between two conflicting uses of foreshore. Our objective is to work towards a tool that not only allows detailed characterizing of an impact, but also will aid in assessing the consequences of the impact such that effective conservation management decisions can be made.

Methods

Study area

On the west coast of BC, Canada, there has been attempt by industry and the federal and provincial governments to aggressively expand shellfish aquaculture, with the Manila clam (*Venerupis philippinarum*), and Pacific oyster (*Crassostrea gigas*), the main product farmed. The region of interest for the current case study is Baynes Sound (Fig. 1). Baynes Sound falls within the Regional District of Comox Strathcona and includes the foreshore of the City of Courtenay and the Town of Comox (Jamieson et al. 2001). This area is part of the Gulf Island Archipelago and, as such, forms a unique ecological region of Canada. The sound is approximately 25 km long and is 3.5 km wide at its widest point, with the average width being less than 2 km. Baynes Sound has over 9000 ha of shallow coastal channel fringed by protected bays, open foreshore, tidal estuaries, inshore marshes and adjacent forests (Jamieson et al. 2001). Comox Harbour is one of the largest low gradient deltaic deposits on the east coast of Vancouver Island (Fig. 1). This region has been ranked as the most important wetland complex on Vancouver Island and is internationally recognized as important for migratory water birds as well as providing habitat for at least 6 salmonid species (Jamieson et al. 2001). Birds that occur within this region in numbers that are of global significance include; the Pacific Loon, the Western Grebe, Brant (*Branta bernicla ssp. nigricans*), Black Turnstone (*Arenaria melanocephala*), Surf and White-winged Scoter, Harlequin Duck (*Histrionicus histrionicus*), Mew Gull (*Larus canus*), Glaucous-winged Gull (*Larus glaucescens*) and Thayer's Gull (*Larus thayeri*) (Booth 2001).

Baynes Sound has a long history of shellfish aquaculture dating back to the 1900's (BCMSRM 2002). Prior to 1984 oysters were the primary species farmed. The number of leases and the numbers of approved species for farming on the individual leases has greatly increased since 1984

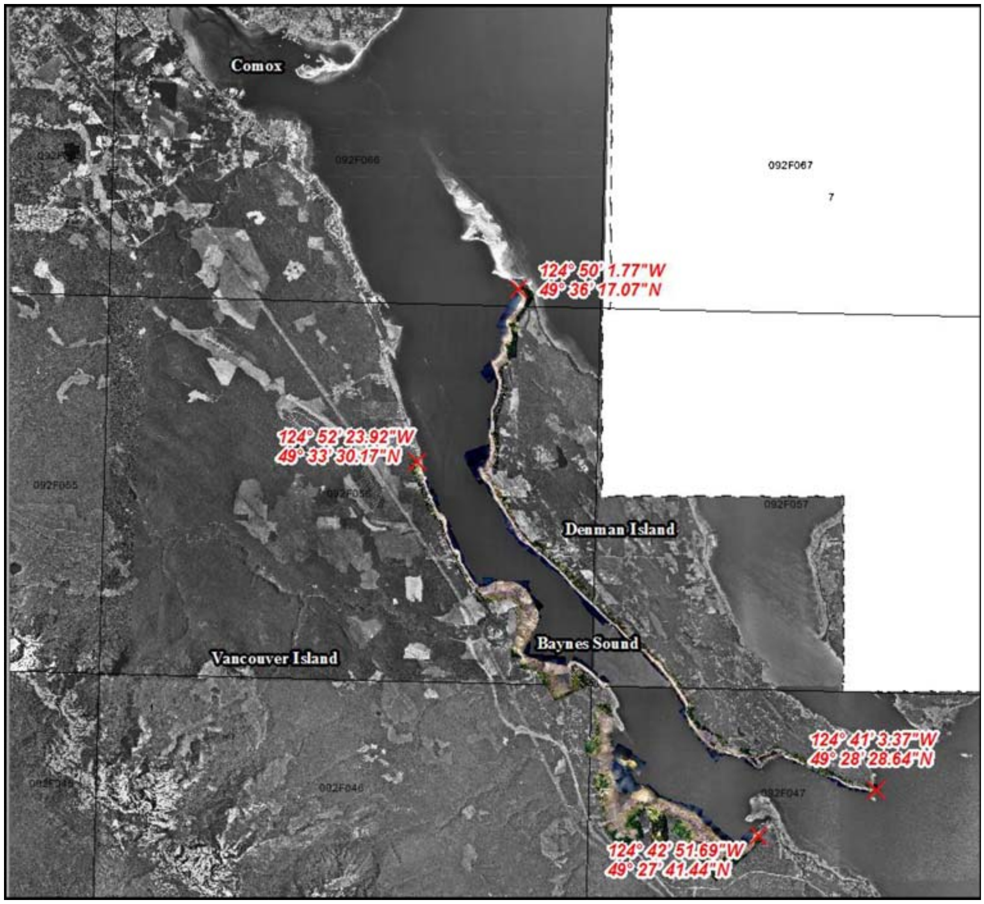


Fig. 1 Baynes Sound intertidal study area between eastern mainland Vancouver Island and Denman Island. Range of coverage of air photo on the Vancouver Island side and Denman Island side

(Fig. 2a and b). Dawe et al. (1998) provides a description of the foreshore of Baynes Sound obtained during their 1980 survey of bird within the Baynes Sound-Comox Habour region. The region at this time was relatively pristine and void of large expanses of shellfish aquaculture leases. In addition to shellfish aquaculture increasing urban development also results in habitat loss within this region. Martell (2008) notes during 1992 to 2002 at least 5% of the sensitive ecosystems were lost and 30% of modified ecosystems such as older second growth forests (60–100 yrs) and seasonally flooded agricultural fields disappeared (BC Ministry of Environment 2005). In addition to habitat loss from urbanization is direct loss of the foreshore due to intertidal shellfish aquaculture. Use of the foreshore exclusively for aquaculture purposes precludes the use of this region for ecologically important roles such as providing key habitat for spawning activities (e.g., the Pacific sand lance (*Ammodytes hexapterus*)), foraging by wildlife and as nurseries.

This stretch of shallow coastline is the most intensely farmed shellfish area in the province accounting for over half of the total production of shellfish in BC (BCMSRM 2002). An interesting aspect of why this region is so intensively farmed as compared to other regions of BC involves the nature of the shellfish tenure system and First Nations land claims. The province of BC owns the seabed and has the mandate under the Land Act through Lands and Water British Columbia Inc. to allocate and administer the use of these lands through tenures for aquaculture (BCMSRM 2002). However, much of First Nations traditional territories lie within provincial Crown Land. The granting of shellfish tenures may adversely impact First Nations interests (Deo 2002), by preventing access to the wild harvest on traditional lands. This in turn has hindered new development and expansion of this industry into other regions of the province. The Baynes Sound region lies within the traditional territories of the Comox and Qualicum First Nations. The Comox Band has identified areas with Baynes Sound for shellfish aquaculture and have also been advise that in the event that shellfish applications by Non-Comox Band proponents are made within Comox Nation Traditional Territories, they will be consulted to ensure that there is no infringements on aboriginal rights. Areas of interest to the Qualicum Band have already been alienated by current foreshore use (BCMSRM 2002). With First Nations aboriginal rights then partially resolved, in contrast to other regions of coastal BC, the province has aggressively expanded the industry within this region through the granting of new leases or the approval of new species to harvest.

Farming of the foreshore involves a number of invasive techniques which includes first clearing the beach of all surface and competing sub-surface species such as the native littleneck clam (*Protothaca staminea*), raking the area to be seeded, seeding, then laying anti-predator netting, a mesh with a net size of ca. 1 cm^2, used primarily to prevent loss of product due to foraging by clam eating sea ducks over the cleared and seeded area. Farming also includes the use of the intertidal for "oyster grow-out". Oysters which have been long-line cultured (suspended in the water column) are placed onto the foreshore and allowed to "harden" off for a period of 2–3 years to make the flesh more suitable for market. Large regions of the foreshore can be used for this purpose. Other industrial uses of the foreshore include the building of berms, equipment storage and the building of roads. All uses result in the loss of this one region of the foreshore with all practices being cumulative in nature. With the ever increasing expansion of this industry, and given the cumulative nature of the impacts and the need for effective management of such impacts, a question that arises is, is it possible to determine the spatial extent of these practices, i.e., the true anthropogenic footprint of the industrial activity, especially given the spatial resolution required (i.e., <50 m), to provide for accurate assessments? Secondly, if cumulative impacts can be assessed, can this information be used to evaluate the extent of ecological consequences such that effective management decisions can be made?

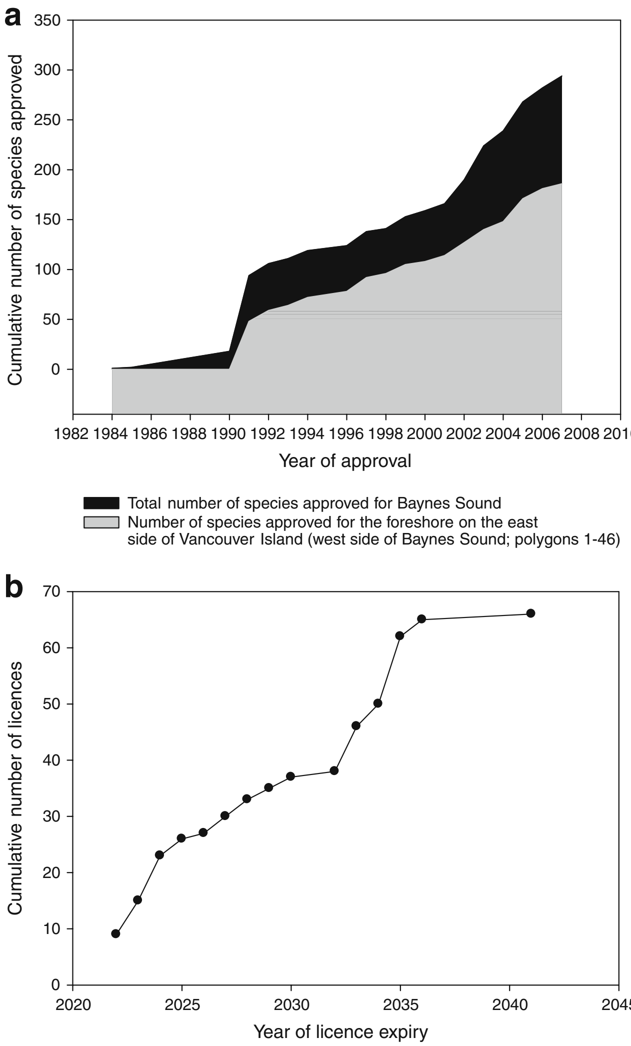


Fig. 2 **a** Cumulative number species approved versus date for the Baynes Sound study area, and the east side of Vancouver Island (polygons 2–46). One licence can have up to at least 7 species approved, hence this measure provides a more accurate estimate of use of the intertidal for shellfish farming. The primary approved species include; Pacific oyster, Manila clam, Varnish clam (*Nutallia obscurata*), Littleneck clam (*Prothacaca staminea*) and Geoducks (*Panope abrupt*). **b** Cumulative number of licences versus licence expiry date. The length of lease can vary to up to 35 years, hence this also provides in addition to farming intensity (2a), the planned duration of the farming intensity. Data from http://www.agf.gov.bc.ca/fisheries/Licences/cabinet/detailed_sf_sites.pdf. Accessed June 20th 2009

Air photo treatment

Three hundred and ten hardcopy air photos of Baynes Sound were purchased from the BC Ministry of Agriculture and Lands. Photos were taken of Baynes Sound at an elevation of 305 m between June 22 and 23, 2001 at a scale of 1:3000. All photos were taken during a series of extreme low-tides such that all intertidal areas were fully exposed. The set of 9″×9″ air photos were scanned by a Canon MP750 photo scanner at 2400×2400 dpi. As the original hardcopies of the photos were not ortho-rectified not all objects were truly vertical resulting in distortions of objects tilting away from vertical with respect to the photographic centre. To improve interpretative accuracy an extra treatment was applied to the photographs to lower the distortion effect. Each photograph had an 60% overlap, therefore each 9″×9″ photograph had 5.4″ also covered by the next adjacent photograph. Hence, any distortion on the edges of the first photograph was compensated by the 5.4″ optimal area of the next photograph. The entire set of scanned photographs was imported into ESRI's ArcGIS 9.0 ArcView software for further GIS analysis. In ArcGIS, each photo was labelled according to the photo number identified in the original hard copy set. Each photo was georeferenced (assigned a physical geographic location) by using the georeferencing tool in the software. The physical location of objects in the air photos were matched to fit the visible features on the 1:20,000 TRIM (Terrain Resource Inventory Maps) orthomosaic photo. The georeferencing tool in ArcGIS uses first order polynomial algorithms to correct for any remaining distortion by stretching and shrinking certain parts of each photo. By georeferencing the photoset one-by-one, the study area was digitally rubber-sheeted to form a photo mosaic along the entire Baynes Sound study area.

Air photo interpretation

Air photo interpretation involved four nested area identifications; 1) maximum intertidal or foreshore, 2) maximum viable habitat 3) region of viable habitat under netting and 4) region of viable habitat under oyster grow-out beds, both within and outside of maximum viable habitat.

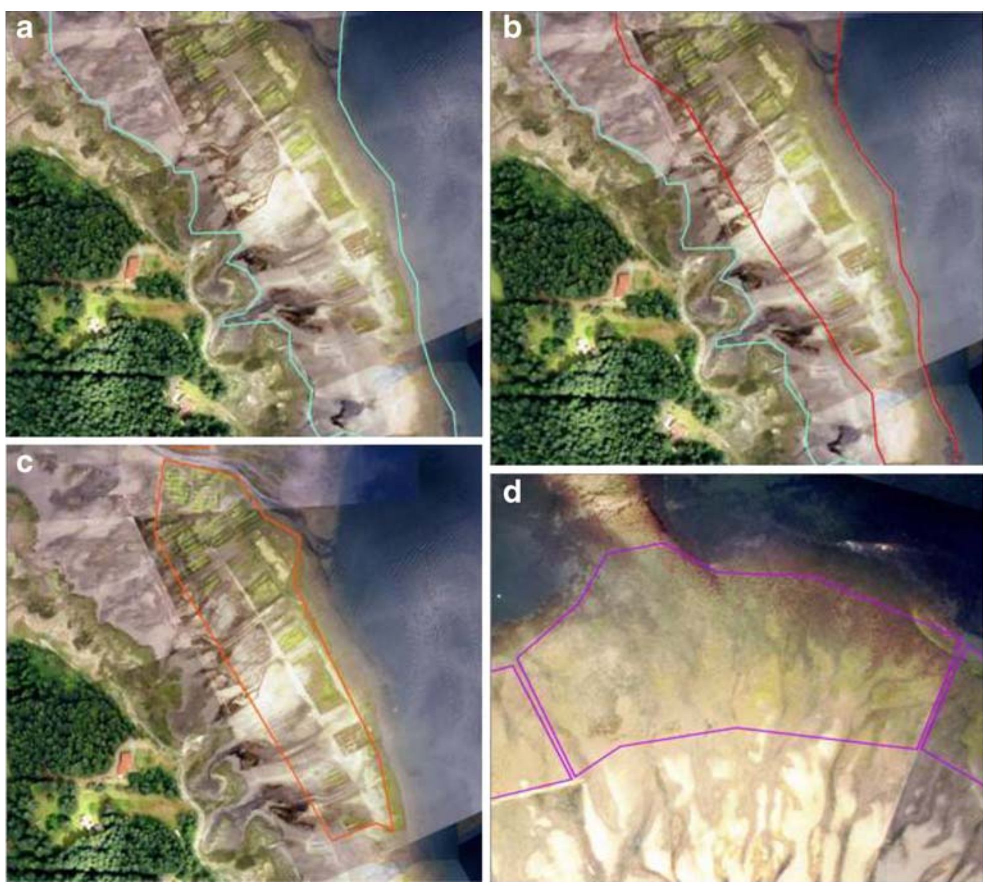
Maximum intertidal

After the photo mosaic (1:3000) of Baynes Sound was formed, the intertidal area was identified. From the aerial imagery (Fig. 3a), approximate locations of the maximum extent on the shore when the tide was high was estimated by the water mark and vegetation-sand interface. The maximum intertidal area was digitized from where substrate (sand, rock, etc.) is first visible from the sea (water) side to the approximate area where the high water mark was. Importantly, estimation of maximum intertidal was done during the period of an extreme low tide, hence this area represents the absolute maximum amount of intertidal at one particular time of year that occurs during the summer solstice.

Viable habitat

In general the foreshore can be comprised of many types of substrates and habitat ranging from rock shelf to mudflats. Of the various types of foreshore habitats, the habitat of interest and of concern in regards to habitat loss is the region of the intertidal that is conducive to shellfish growth and hence is exclusively used by the shellfish farming industry. Bivalves such as the indigenous littleneck clam are found 0.9–2.4 m above the low water mark where high water mark is 5.3 m above the low water mark. This region in Baynes Sound is characterized by small cobble/gravel substrate with high secondary productivity. This region is also key habitat and serves a number of ecological roles such as nutrient cycling, providing habitat for nurseries, supporting numerous other intertidal species, plus serving to provide a primary food source for clam feeding sea ducks (Bendell-Young 2006; Whiteley and Bendell-Young 2007). This region is also important for shore birds such as the Dunlin (*Calidris alpina*) which by contrast forages on polychaetes within the intertidal (Dierschke et al. 1999; Shepherd and Lank 2004). Given these uses, relevant habitat was defined as that region 0.9–2.4 m above the low water mark, approximately two-thirds of the exposed

Fig. 3 **a** Maximum intertidal range at extreme low tide (*blue outline*). Maximum intertidal is identified by the low water mark and vegetation-sand and the high tide-line. **b** Viable intertidal as defined by 2/3 of maximum intertidal region (*red outline*). **c** Digitized anti-predator netting used for shellfish farming (*orange outline*). **d** Digitized oyster grow-out beds (*purple outline*)



intertidal and not the complete foreshore as exposed at extreme low tide. Reference to the maximum area exposed at extreme low tide would over estimate relevant habitat. Subsequently, a new shape file was digitized for the viable intertidal range based on the two-thirds intertidal approximation of viable intertidal habitat (Fig. 3b).

Area of viable intertidal under coverage by anti-predator netting

After the maximum and relevant intertidal were digitized, regions of the intertidal covered by anti-predator netting were determined. Depending on lighting, substrate type, and substrate wetness, netting appears either appears dark in colour over the substrate or light compared to the substrate. The process of digitization was done by tracing the outline of all nettings within the study area (Fig. 3c).

Area of intertidal used for oyster grow-out beds

Oyster grow-out beds include intertidal regions that are spotted anywhere without being covered by protective nettings and are being used for oyster grow-out operations (Fig. 3d).

Ground truthing

Three aspects of the spatial analysis were subject to ground truthing: 1) whether the two-thirds rule of estimating viable intertidal was valid 2) whether the polygons drawn around oyster grow-out beds were indeed oyster beds and 3) whether netting sites that existed in 2001 were still netting sites in 2006. Twenty-seven strategic locations were chosen along both the coast of the Vancouver Island side and the Denman Island side. At each location, Global Positioning Systems (Garmin eTrex and eTrax Venture © with 15 meter accuracy) were used to log the latitude and longitude location, and the site characteristic were recorded (e.g., presence of oyster beds, nettings, or both). Images of the site were also taken and compared to aerial photo interpretation for verification.

Spatial analysis

A multi-step analysis by GIS modelling was applied to the four layers (maximum intertidal, viable intertidal, anti-predator netting, and oyster grow-out beds) to determine that region of the foreshore not compromised by shellfish farming activities. A final additional supporting layer (ArcGIS shapefiles) required for the analysis was that region of the intertidal currently under shellfish lease, (a lease being that region of the foreshore delineated by the provincial government as a shellfish tenure and leased to the farmer for a defined period of time) but not necessarily being actively farmed. Areas of the intertidal under shellfish leases were obtained from Department of Fisheries and Ocean Canada (digitized in 2005). All operations were specific to ESRI's ArcMap-ArcInfo 9.1 software package. Three main overlay operations were used; 1) "Intersect" in which the software simply takes two specified layers of input (e.g. leased areas and viable intertidal areas) identifies their common features and creates a new "intersected" layer with only features that are common. 2) "Symmetrical Difference" which is essentially the opposite of "Intersect". This procedure examines two input layers and determines areas that do not overlap and creates these areas into a new output. 3) "Erase" which treats the first input layer as the base layer and the second as the erase layer.

Spatial analysis model

A schematic flow diagram of the GIS analysis model is presented in Fig. 4 with all steps in the analysis detailed. Application of and model outputs are presented in Fig. 5. The first step (1) in the model involves an intersection of the maximum intertidal range polygons and the lease area polygons. The output of this operation produces a new layer called "leased intertidal" which contains polygons that are leased within the intertidal range. The next step (2), intersects the viable intertidal range with the leased intertidal area to find the size and location of viable habitats within leases. The output of this intersect is "leased viable". By using the viable intertidal area, an operation (3) of symmetrical difference is executed with the shapefile containing the polygons of all netted sites. This is done with the sole purpose of estimating areas that are viable habitat not covered by netting and the output of this operation does not have a continuation within the model. Following this, the leased viable output is intersected (4) with the oyster grow-out beds polygon. This produced the layer "leased viable beds" which are oyster grow-out beds that are currently within viable intertidal leased zones. After this, the leased beds polygons are used to undertake a symmetrical difference operation with the oyster grow-out beds (5). This essentially creates the opposite of (4) and the output shapefile (non-lease viable beds) contains polygons that are not leased and are still oyster grow-out beds. "Non-lease viable beds" is very close to the final product of this model. However, the model so far has been based upon viable intertidal ranges where some lease areas are actually classified out-side of the viable intertidal areas, and some marginal bed areas are also within these non-viable leases. Therefore, as a cleanup and tidying procedure, the model incorporated an "Erase" operation (6) creating the layer

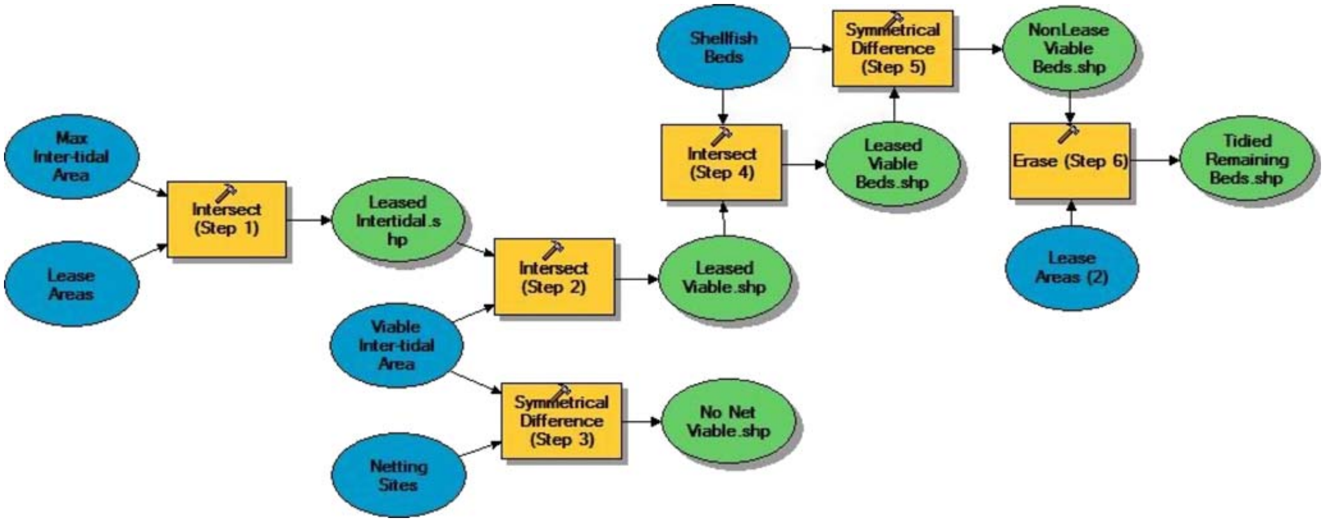


Fig. 4 A full schematic of the spatial analysis model. Blue ovals represent input layers, green ovals represent outputs, and yellow rectangles represent operations

"Tidied Remaining Beds" and is the final output of the model.

Assessment of the potential impact of the anthropogenic footprint on other ecological uses of the foreshore

Overlap of the anthropogenic footprint with sensitive ecosystems

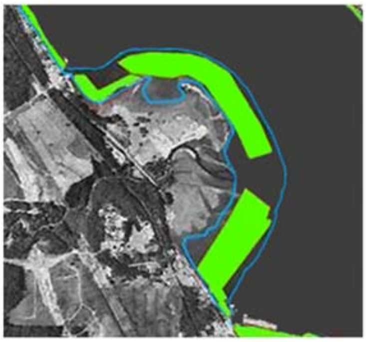
One application of the spatial analysis was to determine overlap of the industry with key habitat types, in this case small estuaries. These regions provide a multitude of ecosystem services such as acting as nurseries for economically important fish species and providing key habitat for a number of semi-aquatic and aquatic species. To complete this analysis we obtained ArcGIS supporting layers from the Pacific Estuary Conservation Programme (PECP) which provided locations of estuaries within the study area. To determine the degree of overlap, the shellfish industry's footprint was overlayed with the presence of estuarine environments on the east side of the study area.

Overlap of the anthropogenic footprint on regions of high bird use and its influence on bird distribution

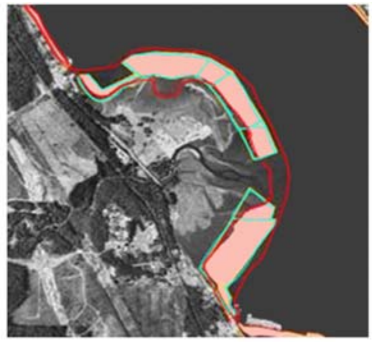
A major advantage of the combined use of high resolution aerial photography with GIS is that it can help visualise the true extent of an anthropogenic activity on a defined region of the foreshore. In this case, cumulative effects include the use of the foreshore for oyster grow-out as well as coverage with anti-predator netting. Both activities result in this region being inaccessible for other ecological roles such as for foraging by birds. Hence, the application; can we use the information obtained by spatially characterizing the anthropogenic footprint to assess its role in influencing the distribution of shore and water birds such as the dunlin, grebe and scoter, within this area?

To address this application, two data sets were accessed. First were historic bird counts in Baynes Sound-Comox Harbour conducted in 1980–1981 (Dawe et al. 1998). Data from these bird counts were used to provide a baseline to compare to recent observations of bird distribution. The second data set was obtained from the Canadian Wildlife Service, Pacific Yukon Region, British Columbia, Canada for birds counts from 2003–2005. For both data sets, survey data was collected spatially with bird observations linked to shoreline units or survey polygons (Fig. 6). For the 1980 bird counts, the study area was divided into 48 shoreline units to determine locations of high bird use. For the 2003–2005 surveys, these original 48 polygons were further subdivided into 73 polygons. For the purposes of comparison, bird counts for the subdivided polygons were totaled to represent total bird counts for one polygon as defined by the 1980 survey. For example, the number of birds counted in the 1980 survey for polygon 27 would be compared to the total number of birds surveyed in polygon 27A, 27B and 27C in the 2003–2005 survey (Fig. 6).

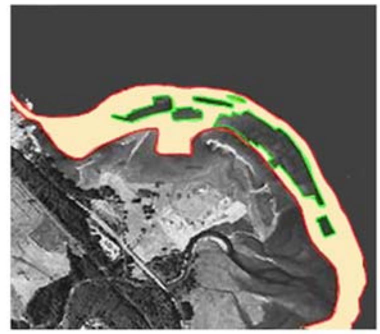
For the 1980 survey, bird counts were made during the year of October 1980–October 1981. For comparative purposes data for the winter (December, January and February) of 1980–1981, that is, the prime overwintering period for these migratory birds was used. Survey teams covered each polygon, and on a weekly basis, counted and recorded all birds observed. For the 2003–2005 survey's, counts were conducted on a biweekly basis from October to April 2002–2003 and 2003–2004 and monthly from



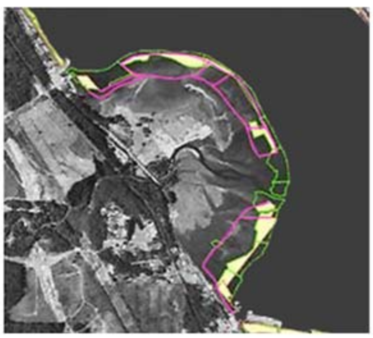
Step 1. Intersection of Max Intertidal area (blue outline) and Lease produces Leased Intertidal (green polygons)



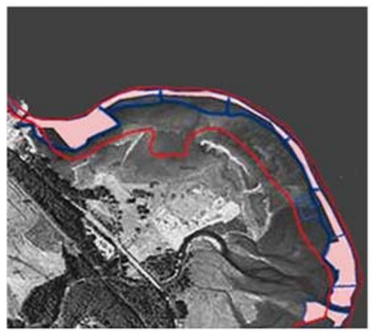
Step 2. Viable Intertidal Area (red outline) intersected with Leased Intertidal (light blue outline) produces Leased Viable (pink polygons).



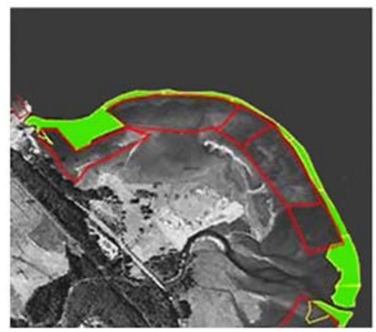
Step 3. Symmetrical difference of Viable Intertidal Area (red outline) and netting (green outline) produces No Net Viable (beige polygons)



Step 4. Leased Viable (pink outline) intersected with shellfish beds (green outline) produces Leased Viable Beds (beige polygons)



Step 5. Symmetrical difference for shellfish beds (red outline) and Leased Viable Beds (blue outline) produces Non-Leased Viable Beds (pink polygons)



Step 6. Erase operation used to clean up Viable Intertidal still within Leased Areas (red outline), but not within "Leased Viable" areas. The result is Tidied Remaining Beds (green polygons) that are not commercially harvested.

Fig. 5 Application of the spatial analysis model as outlined in Fig. 4

October to April 2004–2005. As with the 1980 survey, only data in the core wintering period (November–February, early March) was used for comparative purposes. As noted in (Žydelis et al. 2006) this time period excludes data from migration periods and also from the Pacific herring (*Clupea pallasi*) spawning period when birds can alter their distribution in response to this abundance food source. It is important to note, that given the different survey methods, numbers of birds are not directly comparable between the two data sets. What can be drawn from the two data sets is a comparison of the locations of high bird use in 1980 versus 2003–2005. Baynes Sound in 1980 was mostly in a relatively natural condition (Dawe et al. 1998), by contrast to present day where much of the sound is under intensive aquaculture use with the number of aquaculture leases dramatically increasing post 1990. Areas of high bird use in 1980 versus 2003–2005 were contrasted for 1) White-winged Scoter, 2) Surf Scoter, 3) Bufflehead, 4) Pacific Loon, 5) Western Grebe, and 6) Dunlin. All are dependent on the habitat of the foreshore in someway, e.g., for food such as mussels, clams, small fish, invertebrates and plants.

Results

Extent of the anthropogenic footprint

All 27 locations that were ground truthed were in agreement with aerial photo interpretation. Estimates of viable habitat proved to be accurate, as did areas of intertidal under predator netting and oyster beds. Aerial estimates from the model analysis are presented in Table 1. The maximum intertidal of the Baynes Sound study area is 8.4 km^2 and the viable intertidal area is 4.4 km^2, 52.4% of the maximum intertidal area. In Baynes Sound, netted areas area occupy 1.2 km^2, whereas oyster grow-out beds occupy 1.5 km^2, 27% and 34% of the intertidal area respectively. For just the viable intertidal region these areas are only slightly less; 1.0 km^2 (23%) is covered by anti-predator netting and 1.43 km^2 (33%) used for oyster grow-out. By summing netted areas and the areas used for oyster grow-out operations within the viable intertidal range, the amount of foreshore habitat in Baynes Sound used for shellfish farming is 2.43 km^2 which is 56% of the viable intertidal.

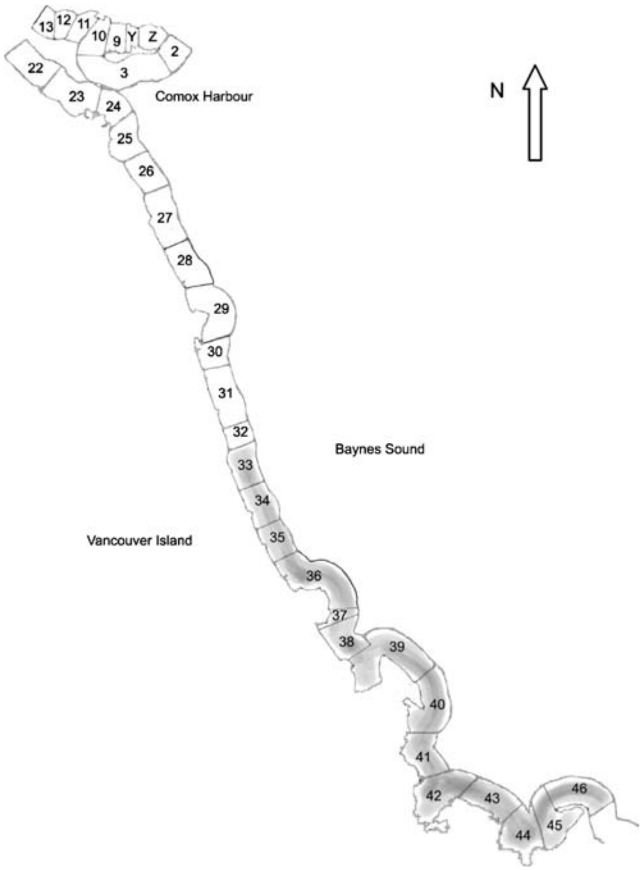


Fig. 6 Polygons used in 1980 and 2003–2005 bird surveys. Shaded regions are intensively farmed (see also Fig. 7)

Spatial overlap of shellfish farming activity with sensitive habitat

Overlaying the extent of the shellfish industry's footprint with the presence of estuarine environments on the east side of the study area indicated that shellfish farming activities occur regardless of the presence of this habitat type (Fig. 7).

Spatial overlap of shellfish farming activity with areas of high bird use

There were distinct differences in the locations of high bird use in 1980 as compared to 2003–2005 (Fig. 8a–f). Although 1980 represents only one sampling period, noteworthy is that regions of high birds use for the eight species were similar, polygons 36–46. Also of note, this region is a sensitive estuarine environment (Fig. 7). During 1980, Surf Scoters were generally distributed from polygons 2–46, with polygon 39 being the region of greatest use; in 2003–2005 polygons 2, 3, Y, 13 and 22 were locations of high use (Fig. 8a). White-winged Scoters were distributed along polygons 30–45 in 1980; in 2003–2005, as with the Surf Scoter, this use shifted to polygons 2–25 (Fig. 8b). Bufflehead were located in polygons 23 and 39–44 in 1980. In 2003–2005 birds were located all along the coastline, with no one particular region of high use (Fig. 8c). In 1980, Pacific Loons used polygons 43–46 exclusively. By contrast, low numbers of loons were

Table 1 Results of area calculations from mapped polygons. (Numbers may not add exactly due to rounding up to one decimal place)

	Area ID	Total Area (km^2)	% of maximum intertidal	% of viable intertidal	% total oyster bed
Maximum intertidal area	A	8.4	100.0	N/A	
Viable intertidal area	B	4.4	52.4	100	
Netted area	C	1.2	14.4	27.4	
Total oyster grow-out beds	D	1.5	17.4	33.1	
Leased intertidal	E	4.4	52.4	N/A	
Netted viable intertidal	F	1.0	11.9	22.7	
Non-netted viable intertidal	G	3.4	40.5	77.3	
Leased viable intertidal	H	3.0	36.1	68.9	
Leased viableoyster grow-out beds	I	0.9	11.2	21.4	60.0 I/D*100
Non-leased viable oyster grow-out beds	J	0.5	6.1	11.7	33.0 J/D*100
Tidied remaining beds	K	0.5	5.8	11.1	33.0 K/D*100
Sum of farming practices overall (C+D)	L	2.7	29.3	55.9	
Sum of all farming practices within viable intertidal (F+I+J))	M	2.4	23.1	44.2	
Area remaining	N	2.0			
% of viable intertidal used for shellfish farming (F+I+J)	O	55.0			
% of viable interdal remaining	P	45.0			

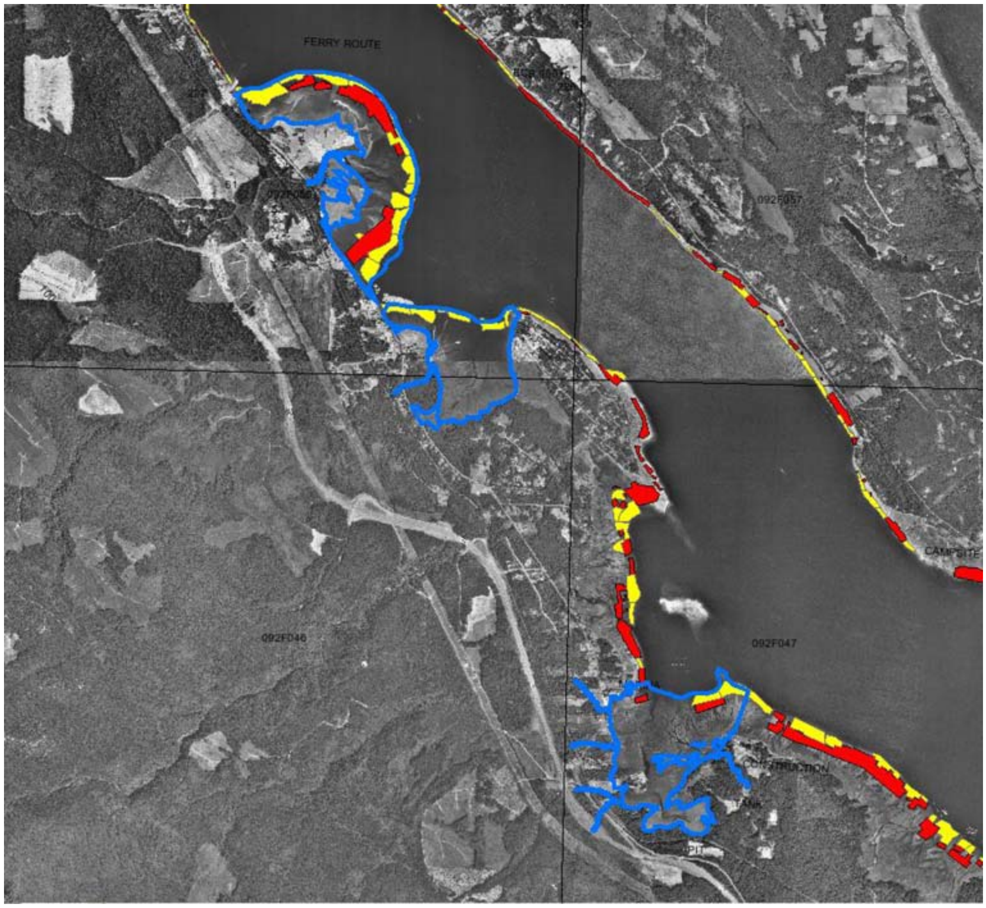


Fig. 7 Overlap of the anthropogenic footprint of the shellfish industry with estuarine habitat (*blue outline*). Red represents coverage due to oyster-grow-out, yellow due to anti-predator netting

distributed in all polygons in 2003–2005 (Fig. 8d). In 1980, the Western Grebe was located exclusively in polygons 40–42. In 2003–2005 only polygon 33 recorded important use by this bird (Fig. 8e). In 1980, Dunlin, a shore bird, was also located in polygons 41–44. In 2003–2005 high areas of bird use were polygons 2–25 and notably 28 (Fig. 8f).

Although numbers cannot be directly compared as counting techniques differed between the two surveys, differences in abundance for the Pacific Loon and Western note comment. For the Pacific Loon, in 1980, maximum counts of 400 were recorded for polygons 45. During 2003–2005 greatest average numbers of 50 were recorded for polygon 25. In 1980, maximum counts of 14000 for the Western Grebe were recorded for polygon 41. For 2003, 2004, 2005 the maximum average of 200 was recorded for polygon 33.

Discussion

Anthropogenic footprint

Based on our model estimate, the anthropogenic footprint of the shellfish industry is approximately 56% of the viable intertidal habitat. Of this, 23% is under anti-predator netting with 33% being used for oyster grow-out purposes; both practices preclude the use of this region for other purposes. Carswell et al. (2006) recently attempted to address the amount of foreshore within this same region that was exclusively under anti-predator netting. Using low-level high-resolution air photos taken during periods of extreme low tides combined with GIS these authors determined clam net coverages for each of Baynes Sound's major substrate types (e.g., coarse beach, mixed beach, rock platform, rock platform with beach veneer, sand beach, tidal flats, rock shelf, sandy beach). These authors concluded that only 3% of the foreshore was under anti-predator netting, a value in contrast to our estimates of close to 25% of the viable intertidal being under netting. There are two primary reasons for this large discrepancy; 1) the approach of Carswell et al. (2006) assumed that all exposed regions of the intertidal were viable habitat from extreme high tide to low tide and 2) all habitat types were included in the spatial analysis. The result of these two assumptions is that the amount of relevant habitat, i.e., that portion of the intertidal or foreshore that is considered viable habitat, is greatly overestimated. This is especially true if areas of available foreshore are based on that amount of intertidal exposed during extreme low and high tides, an event that happens once a year.

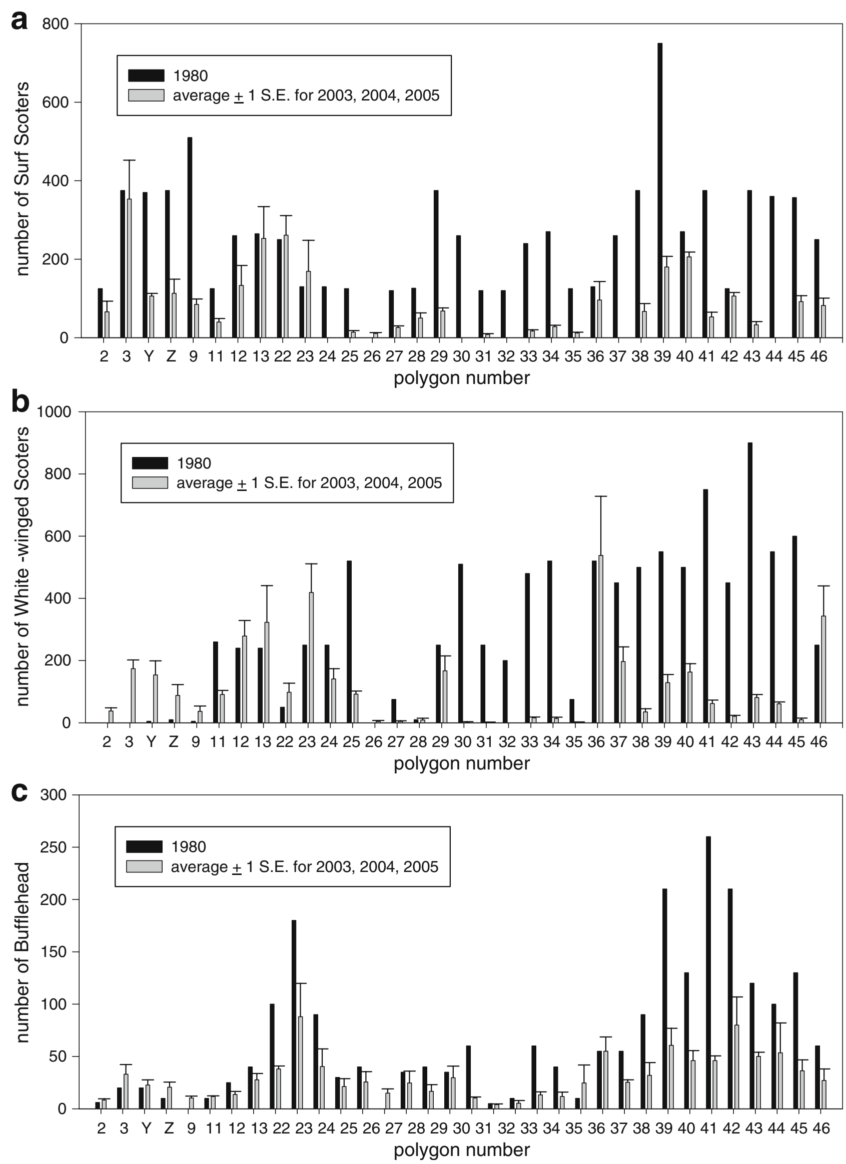


Fig. 8 Number of **a** Surf Scoters, **b** White-winged Scoters, **c** Bufflehead, **d** Pacific Loons, **e** Western Grebes, **f** Dunlin for each polygon as shown in Fig. 6 for 1980 versus 2003–2005

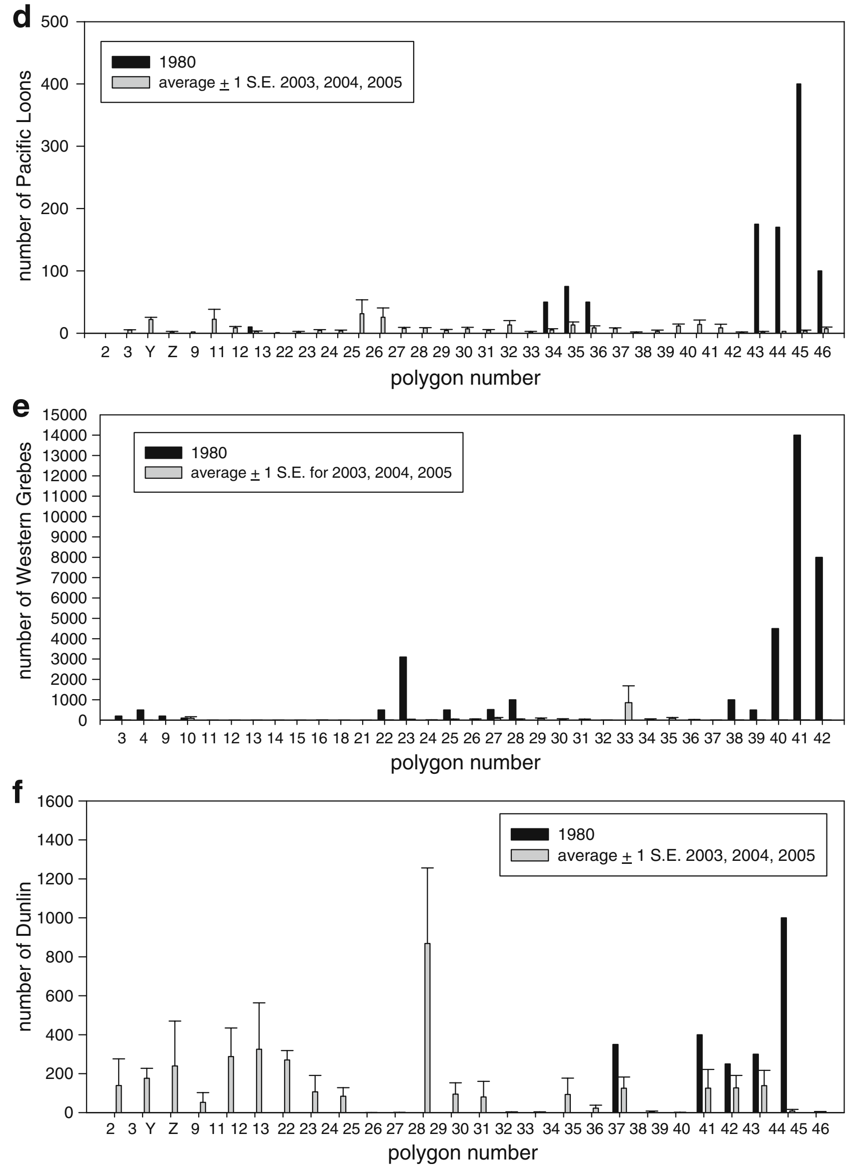
Management applications

In their approach to using aerial photography coupled with GIS, Zharikov et al. (2005) developed a thematic map of various coastal habitats across a gradient of shallow subtidal to terrestrial zones within a large estuarine system. Indeed thematic maps, for terrestrial and marine systems have been successfully applied in conservation biology for studies directed at understanding factors which determine plant and animal distribution and changes in distribution patterns over time (e.g., Sitati et al. 2003; Sheppard et al. 2006; Higinbotham et al. 2004). Application of thematic maps then need corresponding data on the abundance and distribution of the species of interest which would turn would aid in conservation and management decisions (Zharikov et al. 2005 and references therein). In our study, rather than developing a thematic map based on habitat type, we mapped and identified the extent of an anthropogenic footprint. We then applied this spatial data to visually assess the degree of overlap of the anthropogenic footprint with sensitive estuarine habitat as well as to help explain changes in bird distribution within the spatially defined area.

Overlap of the anthropogenic footprint with sensitive habitat

Application of aerial photography with GIS clearly demonstrated the extent of overlap of the anthropogenic footprint with sensitive habitats, in this case, small estuaries. Within the Baynes Sound region, 23 creek/river tidal estuary systems have been identified and their importance reported in Dawe et al. (1998). Nutrients and sediments from the surrounding

Fig. 8 (continued)



watersheds are provided by the rivers/creeks and are deposited onto the tidal flats creating rich environments that support a variety of species. Further, estuaries in combination with farmlands and freshwater wetlands form a wetland complex that supports hundreds of thousands of wintering birds. During periods of freezing when farmlands and freshwater marshes are no longer accessible, these estuaries become critical habitat for overwintering waterbirds (Dawe et al. 1998). With high resolution aerial photography and GIS, the location of these small estuaries and the extent that they have been altered could be visually assessed. This information could then be used for effective management of these regions for example, identification of and the removal of any industrial activity that occurs within keys parts of the estuary. Conversely, recommendations could be made as to where industrial activity could occur such that its impact would be minimized on these spatially small (< 500 m) but ecologically important and sensitive regions.

Bird distribution

Combining historical data on locations of high bird use with current day observations proved to be a powerful means to spatially reveal how sea duck and shore bird distribution within Baynes Sound has changed between the two periods. Prior to the development of the foreshore for aquaculture, regions of high bird used included polygons 2–23 (Comox Harbour) and 33–46. In 2003–2005 for Dunlin and the two scoter species, areas of high used shifted to polygons 2–23.

Of special note and concern are changes in bird distribution and in abundances for the Pacific Loon and

Western Grebe. Differences in survey methods between the two time periods precludes direct comparison of numbers. However, differences in abundance and distribution for these two species are so striking that some explanation is warranted. Recently, Martell (2008) reported on trends in bird populations in the Comox Valley, British Columbia from 1976 until 2006, a period of time coinciding with that of our study. Based on counts made during December of 17–24 (Christmas Bird Count), trends (% change in year) in numbers from 1976 to 2006 for the Surf and White-winged Scoter, Bufflehead, Pacific Loon, Western Grebe and Dunlin were 1.1, 0.7, 1.7**,−7.7*,−10.8*, and 7.2* respectively (* $p<0.05$ and ** $p<0.01$) . Hence, there was no trend detected for both scoter species, a positive trend for numbers of Bufflehead and Dunlin, whereas significant declines were noted for the Western Grebe and Pacific Loon. These trends support the observed distribution patterns in Fig. 8a–f and for those species in significant decline there are marked differences in numbers and use of the sound.

Martell (2008) suggests that declines in the Pacific Loon may be attributed more due to differences in winter distribution than to general changes in population. Reported declines in numbers of Western Grebe however are consistent with trends reported by the National Audubon Society (2007). Badzinski et al. 2008 has reported a recent increase in numbers however after a 90–95% decline in numbers for the past 30 years. Other surveys within the same geographic region, Puget Sound, south of Baynes Sound also note a 95% decline in numbers of Western Grebe (Nysewander et al. 2005). Such declines justify immediate conservation action for the protection of this species.

Within Baynes Sound, the primary change in intertidal use during this 30 year period has been the development of the foreshore within polygons 33–46 for aquaculture, with the true extent of its footprint determined by high resolution aerial photography coupled with GIS. This tool also shows that these polygons are located within a sensitive estuarine habitat which possibly contributes to the reason as to why, historically, this was a region of high bird use. As the majority of overwintering birds are now with found within the Courtenay River Estuary (Comox Harbour) or are distributed along the coastline with no one significant region of high bird use, it would appear that key habitat historically used by these species is no longer available.

Comparison of our outcomes with those of Žydelis et al. (2006) highlights the strength of a spatial approach in indentifying regions of conservation importance. Using multiple regression, Žydelis et al. (2006) attempted to assess the role of shellfish aquaculture in addition to various environmental attributes on densities of wintering Surf and White-winged Scoters within the same area as the current study. Nautical charts of 1:40,000 resolution were used to assess the intertidal zone, broad scale bioregional frameworks, as cautioned against by Banks and Skilleter (2007) were applied to describe intertidal substrate type and the percent of the intertidal covered by predator netting was visually estimated by observation. Beach coverage by oysters was expressed as a presence/absence variable in their model rather than actual area covered. Outcomes of this approach were that densities of wintering Surf and White-winged Scoters were related to intertidal area, clam density and sediment type with shellfish aquaculture variables being poor predictors of bird densities. These outcomes lead the authors to conclude that shellfish aquaculture and scoter densities could be mutually sustainable. Analysis of the distribution of both scoter species from polygon 2–45 possibly explains why this conclusion was reached, in that although scoters are still observed in polygons where farming occurs, they have also have been displaced from historic regions of high bird use and presumably high food availability to areas where food availability has not been compromised by the shellfish industry i.e., polygons 2–23. Variables that would describe these areas would be clam density and sediment type, which is co-correlated to clam density.

In contrast to the approach of Žydelis et al. (2006), aerial photography with GIS allows for a quantitative measure (km^2) of the amount of key habitat being used by the industry. Rather than a presence/absence and subjective estimates, the amount of intertidal area covered by oysters can be accurately measured as with the amount of intertidal covered by netting. This information coupled with historical and present areas of high bird use suggests a different outcome and hence conservation recommendation. Aerial photography with GIS identified that polygons 36–46 is under intense use by aquaculture. Prior to 1980 these regions were relatively unaltered and areas of high bird use. During 2003–2005 this was no longer the case with birds being displaced to Comox Harbour. If bird conservation is an important priority a management decision then, based on the shift in bird distribution and also identification of this region as estuarine habitat, would be to rehabilitate regions within polygons 36–46. Further, special attention to be given to the Comox Harbour as this region is now the primary important bird area within Baynes Sound and should be protected and carefully monitored for further degradation.

Conclusions

High resolution thematic mapping has as its first goal to characterize the region of interest. The next steps are to use this spatial visualization to determine what impact if any, the activity will have habitat use within the spatially defined region. In our case study we mapped the extent of the anthropogenic footprint of the shellfish industry on an ecologically important region on the British Columbian coast. We then used this information to define the habitat put at risk due to this activity and then presented management recommendations such that these regions and their ecological uses would not be further compromised. Examples of other key areas at similar spatial scales that could benefit from such an analysis include regions designated as Marine Protected Areas and Marine Reserves and sensitive estuarine habitat. However, to make this approach effective, cumulative impacts must be recognized and links to the possible consequence the impacts may have on the habitat made.

Further, the degree of impact may not be simply a linear function of the spatial size of the anthropogenic activity. For example, an industrial activity such as anti-predator netting, may cover only 25% of the viable intertidal, however, this 25% may provide a key ecosystem service, such as food availability for sea ducks, not provided for in other parts of the foreshore. High resolution imagery is then needed to identify such regions of key habitat. Banks and Skilleter (2007) also conclude that use of finer-scale physical data is more likely to achieve representation at habitat and microhabitat levels, increasing the likelihood that conservation goals will be met. Finally, Baynes Sound is just one region of Pacific west coast that is undergoing intensive use by the shellfish industry. Information generated from this study could be added to other similar studies of regions undergoing the same anthropogenic activity such that true estimates of the loss of a particular type of key habitat can be made. Now, only general estimates are made and not linked to ecological outcomes. Aerial photography coupled with GIS then seems to be a effective tool, however rather than first assess the anthropogenic impact and then the consequences of the impact, ideally the coastal manager would first establish the importance of a region from an ecological perspective and the services the region provides, and then develop the coastal region such that these ecological roles remain unaltered.

Acknowledgements We thank R. Ydenberg for allowing us access to the 2003–2005 bird count data. Funding for this study was through a National Science and Engineering Research Council (NSERC) Strategic Operating Grant (STPGP246079-01) to LB.

References

Badzinski S, Cannings RJ, Armenta TE, Komaromi J, Davidson PJA (2008) Monitoring coastal bird populations in BC: the first five years of the Coastal Waterbird Survey (1999–2004). B C Birds 17:1–35

Ban N, Alder J (2008) How wild is the ocean? Assessing the intensity of anthropogenic marine activities in British Columbia, Canada. Aquat Conserv 18:55–85

Banks SA, Skilleter GA (2007) The importance of incorporating fine-scale habitat data into the design of an intertidal marine reserve system. Biol Conserv 138:13–29

Bendell-Young LI (2006) Contrasting the community structure and select geochemical characteristics of three intertidal regions in relations to shellfish farming. Environ Conserv 33:21–27

Booth BP (2001) Baynes Sound/Lambert Channel-Hornby island waters important bird ares conservation plan. Canadian Nature Federation, Federation of BC Naturalists, Wild Bird Trust of BC Important Bird Areas Program. 44 p. www.ibacanada.com

British Columbia Ministry of Environment. (2005) Report: Sensitive Ecosystems Inventory (SEI): east Vancouver Island and the Gulf Islands (includes 2002 disturbance mapping). http://www.env.gov.bc.ca/sei/index.html Accessed June 29th 2009

British Columbia Ministry of Sustainable Resource Management. (2002) Baynes Sound Coastal Plan for Shellfish Aquaculture. http://srmwww.gov.bc.ca/rmd/coastal/planning/south_island/baynes/docs/Baynes_Plan_Dec19_2002.pdf

Carswell B, Cheesman S, Anderson J (2006) The use of spatial analysis for environmental assessment of shellfish aquaculture in Baynes Sound, Vancouver Island, British Columbia, Canada. Aquaculture 253:408–414

Dawe NK, Buechert R, Trethewey DEC (1998) Bird use of Baynes Sound-Comox Harbour, Vancouver Island, British Columbia. 1980-1981. Technical Report Series No. 286. Canadian Wildlife Service, Pacific Yukon Region, British Columbia

Deo K (2002) First nations and shellfish aquaculture: consultation, accommodation and participation. Environmental Law Centre Society. University of Victoria, Victoria BC 22 p

Dierschke V, Kube J, Probst S, Brenning U (1999) Feeding ecology of dunlins *Calidris aplina* staging in the southern Baltic Sea, 1. Habitat use and food selection. J Sea Res 42:49–64

Gibson LA, Wilson BA, Cahill DM, Hill J (2004) Spatial prediction of rufous bristlebird habitat in a coastal heathland: a GIS-based approach. J Appl Ecol 41:213–223

Higinbotham CB, Alber M, Chalmers AG (2004) Analysis of tidal march vegetation patterns in two Georgia estuaries using aerial photography and GIS. Estuaries 4:670–683

Jamieson GS, Chew L, Gillespie G, Robinson A, Bendell-Young L, Heath W, Bravender B, Tompkins A, Nishimura D, Doucette P (2001) Phase 0 review of the environmental impacts of intertidal shellfish aquaculture in Baynes Sound. Canadian Science Advisory Secretariat Research Document 2001/125, ISSN 1480-4883, Canada [www document]. URL http://www.dfo-mpo.gc.ca/csas/

Jickells TD, Rae JE (1997) Biogeochemistry of intertidal sediments. Cambridge Environmental Chemistry Series, Cambridge University Press, Cambridge, pp 1–139

Martell AE (2008) Trends in bird populations in the Comox Valley, British Columbia, Canada, from 1976–2006. B C Birds 18:2–14

National Audubon Society (2007) Common birds in decline. http://stateofthebirds.audubon.org/cbid/. Accessed June 27th 2009

Nysewander D, Evenson J, Murphie B, Cyra T (2005) Report of Marine Bird and Mammal component, Puget Sound Ambient Monitoring Program for July 1992 to December 1999. Final revision of 2001 MS. WDFW Wildlife Management Program

Sale PF, Butler MJ IV, Hooten AJ, Kritzer KP, Lindeman KC, Sadovy de Mitcheson YJ, Steneck RS, van Lavieren H (2008) Stemming decline of the coastal ocean: rethinking environmental management. UNU-INWEH, Hamilton

Shepherd PCF, Lank D (2004) Marine and agricultural habitat preferences of dunlin wintering in British Columbia. J Wildl Manage 68:61–73

Sheppard CRC, Matheson K, Bythell JC, Murphy P, Myers CB, Blake B (2006) Habitat mapping in the Caribbean for management and conservation: use and assessment of aerial photography. Aquat Conserv 4:277–298

Sitati NW, Walpole MJ, Smith RJ, Leader-Williams N (2003) Predicating spatial aspects of human-elephant conflict. J Appl Ecol 40:667–677

Whiteley JA, Bendell-Young LI (2007) Ecological implications of intertidal mariculture: observed differences in bivalve community structure between farm and reference sites. J Appl Ecol 44:495–505

Winberg PC, Lynch TP, Murray A, Jones AR, Davis AR (2007) The importance of spatial scale for the conservation of tidal flat macrobenthos: an example from New South Wales, Australia. Biol Conserv 134:310–320

Žydelis R, Esler D, Boyd WS, LaCroix DL, Kirk M (2006) Habitat use by wintering surf and white-winged scoters: effects of environmental attributes and shellfish aquaculture. J Wildl Manage 70:154–162

Zharikov Y, Skilleter GA, Loneragan NR, Taranto T, Cameron BE (2005) Mapping and characterizing subtropical estuarine landscapes using aerial photography and GIS for potential application in wildlife conservation and management. Biol Conserv 125:87–100