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Nearshore Aquatic Habitat Monitoring: A Seabed Imaging and Mapping Approach

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ABSTRACT

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The density of human populations in nearshore areas is more than three times the global average and is one example of why monitoring sensitive nearshore environments is essential. In this paper we outline a method for map-based monitoring of nearshore flora and epifauna using the seabed imaging and mapping system (SIMS) and geographic analysis. This system uses underwater video and sidescan sonar to systematically inventory and classify nearshore habitats. Species presence and abundance were mapped in 2006 and 2009 for a coastal area of British Columbia, Canada, and represented in a geographic information system (GIS). Spatial statistics were applied to maps of change in species abundance, and hot spots of floral and epifaunal change were identified. While minimal overall change within species groups occurs over 3 years, local areas of significant change were found near the marina entrance and the Washington State ferry terminal, where marine boat traffic may be affecting vegetation. The use of spatial statistics with this method reduces the effects of seasonal variability, minimizes impact of data errors, and identifies statistically significant hot spots of change. We have also demonstrated that SIMS generates suitable data for change detection and monitoring.

ADDITIONAL INDEX WORDS: *Seabed Imaging and Mapping System (SIMS), change detection, spatial autocorrelation, grid count, spatial statistics, local Moran's* I*, benthic habitat.*

INTRODUCTION

Human populations in nearshore environments have an average density three times higher than the global average density (Small and Nicholls, 2003). More than one third of the world's population live in coastal areas and small islands that account for just 4% of the Earth's landmass (Brown *et al.*, 2006). Perhaps as evidenced by the recent activities on the coast of the Gulf of Mexico, complex economic systems drive anthropogenic activities in coastal settings. Coastal environments are under pressure (Day *et al.,* 2008; Gaiser *et al.,* 2006; Gormsen, 1997; Kumar and Reddy, 2009; Mimura, 2008; Patin, 2004; Small and Nicholls, 2003; Talaue-McManus, 2010; Tolun *et al.,* 2007; Warner *et al.,* 2009; Yayintaş *et al.,* 2007). As such, there is a need for effective tools for monitoring the impacts of coastal management and use.

The nearshore is generally defined as the subtidal zone from the low tide mark to the 20-m isobathymetric depth. Particularly vulnerable to coastal development (Thedinga *et al.*, 2008) and terrestrial pollution (Johnson *et al.*, 1998; Levings *et al.*, 2004), nearshore environments house critical habitats for fish and invertebrates while also providing ecosystem services such as erosion protection and nutrient cycling (Chittaro, Finley, and Levin, 2009).

Monitoring change in nearshore resources is a priority for many marine and/or coastal conservation and resource management organizations. A variety of monitoring methods have been developed and employed for nearshore environments. These include: mapping eelgrass annually using towed underwater videography (Dowty, 2005); monitoring kelp beds with multitemporal aerial photography, which indicates habitat and environmental conditions (Berry *et al.,* 2005); and monitoring buoys, which measure physical and chemical aquatic attributes (Brancato, 2009).

The goal of this study is to demonstrate a map-based approach to monitoring change in nearshore flora and epifauna in Haro Strait, British Columbia, Canada. Changes in species abundance and spatial distribution will be examined using Seabed Imaging and Mapping System (SIMS) and spatial analysis. To meet this goal we address the following objectives: (1) demonstrate how SIMS data can be spatially represented within a geographic information system (GIS) to enable multitemporal comparisons of species occurrence within Haro

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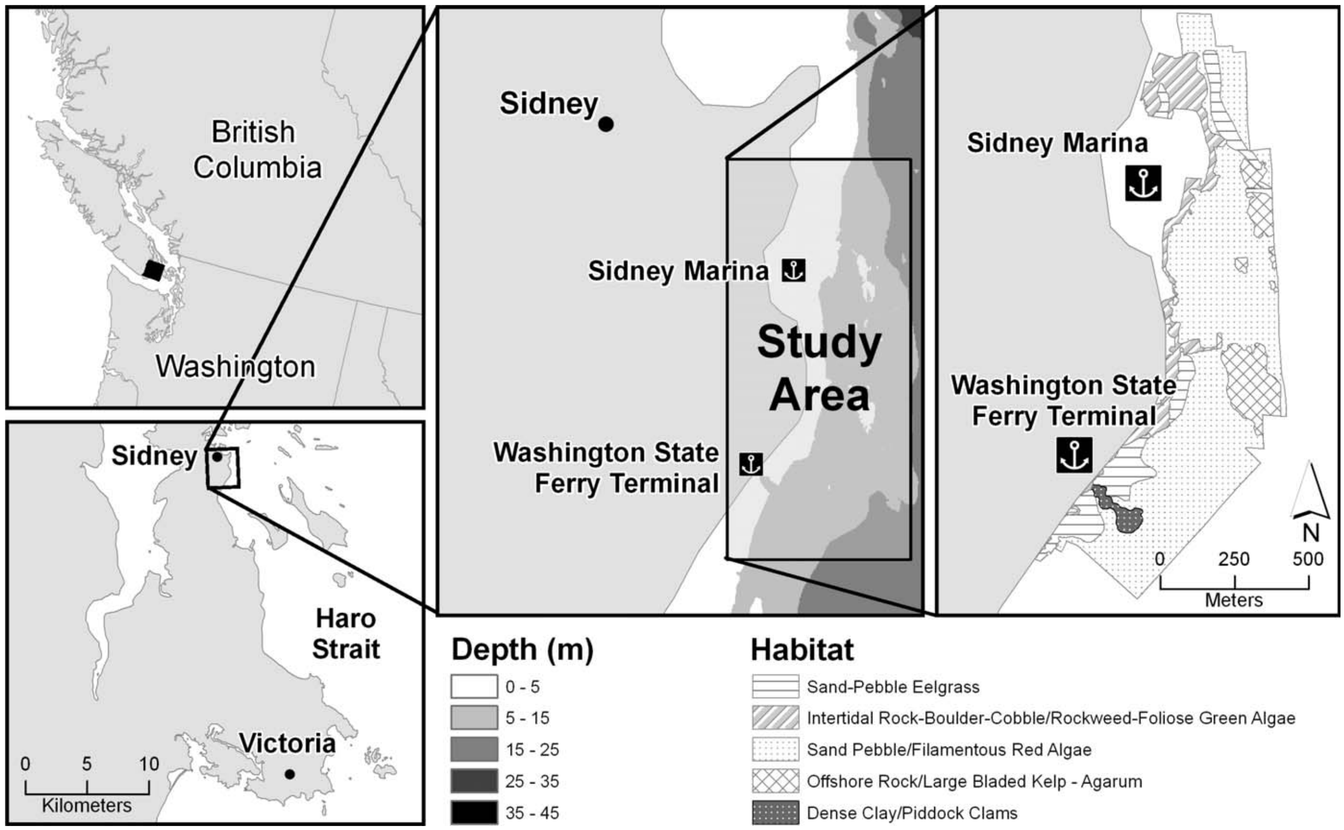

Figure 1. Study area showing nearshore depth.

Strait; (2) describe approaches for representing species abundance categories and demonstrate a method for change detection; and (3) present an approach using local measures of spatial autocorrelation to detect and map hot spots of significant species abundance change. Methods developed for Haro Strait are applicable to other nearshore environments.

STUDY AREA AND DATA

The study area is located off the eastern shore of Southern Vancouver Island, near Sidney, British Columbia, in Haro Strait (Figure 1). The seabed substrates within the study area consist of boulder-cobble or bedrock, a zone of gravelly sand or sandy gravel to about 200 m offshore, and a discontinuous series of north–south oriented bedrock reefs, veneered with boulder-cobble, along the eastern edge of the survey area. The substrate offshore from the Washington State Ferry Terminal (see Figure 1) consists of dense clay as a result of the removal of surficial sediments by propeller wash. Several man-made features are also present within the survey area, including outfalls, riprap, remains of a wharf, reefballs, wrecks, and debris of many other types.

Based on the British Columbia Marine Ecological Classification System (Howes, Zacharias, and Harper, 1997; Zacharias *et al.*, 1998), the study area is located in the Pacific Ecozone, Georgia-Puget Basin Ecoprovince, the Georgia Basin Ecoregion, and the Strait of Georgia Ecosection. The physiographic features of the Strait of Georgia Ecosection are characterized by a broad shallow basin surrounded by coastal lowlands, while the oceanographic features are characterized by protected coastal waters with significant freshwater input, high turbidity, and seasonal stratification, with very warm water temperatures in the summer (Howes, Zacharias, and Harper, 1997).

Haro Strait is one of the primary channels connecting the Strait of Juan de Fuca to the Strait of Georgia, bounded by Vancouver Island to the west and San Juan Island to the east. The tidal mixing that occurs in Haro Strait plays an important role in the seaward export of fresh water from the Fraser River and the landward import of deep return flow (Li, Gargett, and Denman, 1999). Specific areas within Haro Strait are considered primary foraging habitat for the southern resident killer whale population (Bigg *et al.*, 1990), and the strait acts as a major corridor for migrating salmon species (U.S. Department of the Interior 2008).

Seabed Imaging and Mapping System (SIMS)

The Seabed Imaging and Mapping System (SIMS) was developed for the systematic inventory and classification of nearshore habitats (0–20-m depths) (Harper *et al.*, 1998). There are two components to SIMS: a sidescan sonar, which provides

Table 1. *Cover class codes and definitions used for vegetation categories in SIMS classification.*

Code	Class	Abundance
0	None	No visible vegetation
1	Sparse	<5% cover
2	Low	5% to 25% cover
3	Moderate	26% to 75% cover
4	Dense	>75% cover

georeferenced images of seafloor feature morphology, and an underwater video camera that is linked to a differential global positioning system (DGPS), which captures data on georeferenced substrate and biota. Both instruments are mounted on a towfish.

SIMS sidescan sonar data are collected, and georeferenced images of seafloor feature morphology are used to guide the video surveys. The sidescan sonar data are manually categorized using geological classification from the Geological Survey of Canada to identify substrate components and sediment classes (Folk, 1968). Given that the substrate influences infauna, epiflora, and epifauna, the geological classification is a key component of nearshore habitat mapping and guides the biotic classification.

Video images are captured based on a trackline survey grid, with a typical distance of 20 m between tracklines and an imagery swath width of 1 m. The SIMS images are interpreted using manual interpretation and a classification system that allows for the mapping of up to 21 physical themes (*e.g.,* gravel cover, man-made features) and 77 biological themes (*e.g.,* eelgrass cover, total vegetation cover, seastar occurrence). The SIMS image classification provides a standardized methodology that can be applied to a range of marine systems. The digital imagery collected by SIMS provides a permanent record to be used as a baseline and for temporal comparisons of future biotic and abiotic conditions.

Primary, secondary, and tertiary marine flora and fauna observed in the video survey data are classified to species group and coverage or density according to the following abundance and distribution ranges (Tables 1 and 2). Sessile epibenthic animals and vegetation cover are recorded as categories of percentage cover (Table 1). The SIMS classification procedure allows for three species groups (leading species, secondary species, and tertiary species) and their associated cover attributes to be manually classified for imagery sequences based on dominant and subdominant species.

SIMS video data are represented in a geographic information system (GIS) as point features, one for every second of imagery (Figure 2). Assessments of errors associated with the SIMS video mapping indicate that positional accuracy is ± 5 m; individual mappers tend to classify images consistently, but some differences between classifiers do occur (*i.e.,* two mappers classifying the same imagery). Sensitivity analysis of the mapping of eelgrass beds from former projects suggests that cover changes of less than 10% are detectable under most conditions (Bornhold and Harper, 2005). The SIMS system has a layback positional error (± 5 m), which accounts for the influence of currents in determining the relative position of the towfish to the pilot boat.

Data

Data used for this study included two SIMS surveys acquired July 30–31, 2006 and August 26, 2009. Surveys were conducted offshore of Sidney between the northern end of Sidney Marina and Tulista Park to a distance of approximately 300 m. The 2006 study area extent is 320,000 m^2 with approximately 20,000 m^2 of video coverage collected. The 2009 survey followed 2006 survey tracklines, surveyed in the same direction and at the same tidal stage to minimize differences, and achieved this with a mean nearest neighbour distance between survey points of 2.96 m (median distance of 2.29 m). Both the 2006 and 2009 SIMS surveys were imported to GIS as point shapefiles, where each point represented a classified video still image (see Figure 2). Each data set had approximately 40,000 points. When the boat turned during the surveys, the SIMS towfish did not stay directly behind the boat; therefore, all corner points, plus the 10-points that follow the corner, were removed. The 2006 and 2009 trimmed datasets contained approximately 35,000 points each.

Sixty four unique species assemblages were classified in the 2006 and 2009 surveys. Intertidal and shallow subtidal assemblages are most likely to show seasonal variation in abundances, while deeper assemblages are more likely to be perennial. In general, highly mobile species, species with low detectability, or those that are widely distributed were considered inappropriate for monitoring.

Change detection was conducted on six groups of vegetation and epibenthic animals selected for their ecological significance, ease of detection, confidence in classification accuracy, and usefulness for monitoring (Table 2). The selected species groups are (1) *Agarum* (AGR), which includes the benthic kelp *Agarum* as well as some other Laminarians; (2) bladed kelps (BKS), the large bladed kelps *Saccharina latissima* and *S. subsimplex*, *Costaria costata*, and *Cymathere triplicata*; (3) filamentous red algae (FIR), comprising a diverse species assemblage of filamentous red algae including *Gastroclonium*, *Odonthalia*, *Prionitis*, *Agardhiella*, *Neoagardhiella*, and *Gracilaria*; (4) foliose red algae, (FOR) consisting of a mix of species including *Chondracanthus, Mazzaella, Mastocarpus, Palmaria, Constantinia,* and *Opuntiella*; (5) *Zostera* (ZOS) eelgrass beds; and (6) *Bryozoan* complex (BRY), a grouping of sessile epibenthic animals, including bryozoans, ascidians, colonial tunicates, and sponges. Owing to similarities between the AGR and BKS species groups, these two classes were combined and represented as the AGR/BKS assemblage.

METHODS

Converting Data for Spatial–Temporal Analysis

Points were converted to a raster representation to enable mapping of change in abundance and spatial distribution of flora and fauna. Unlike irregular point maps, raster grid cells have the advantage of indexing space so that the contents of a specific grid cell can be compared over multiple years. Raster grid cells were 20 by 20 m, allowing for a fine scale mapping of pattern while including enough points in each cell (typically 30 points) to calculate statistics.

Table 2. *Description of benthic, sessile biota categories classified in Sidney SIMS comparisons.*

Biota Category	Species Assemblage Represented	Nearshore Depth Range in Sidney	Confidence in Interpretation	Significance
BKS: bladed kelps	Not canopy forming, understory kelps; Laminarian bladed kelps, including *Saccharina latissima* (formerly *Laminaria saccharina*), *S. subsimplex* (formerly *L. groenlandica*), *Costaria costata* and *Cymathere triplicata*. *Alaria* may also be present.	Medium	High	• Large plants, easy to detect • When present in high cover categories will obscure smaller sized associated assemblages • Attached to firm immobile substrate • Most species are annuals, although deeper plants of *S. latissima* can be perennial
FIR: filamentous red algae	A diverse species mix of filamentous red algae (including *Gastroclonium, Odonthalia, Prionitis*). Often co-occuring with the foliose red algae group (FOR)	Medium to deep	Low	• Medium to small plants • May be obscured by dense co-occurrence of other assemblages • Most species are annuals
ZOS: eelgrass	*Zostera marina*. Often co-occurring with foliose green algae and/or bladed kelps	Shallow	High	• Always rooted in sand or mud • Easy to identify by morphology and colour • Always in nearshore shallow waters • Perennial
AGR: *Agarum*	*Agarum* (Sieve kelp) is the dominant species but other Laminarians may also occur (*i.e.,* BKS).	Medium to deep	High	• Large plants, easy to detect • Distinctive morphology of blade • Perennial
FOR: foliose red algae	A diverse species mix of foliose red algae (including *Chondracanthus, Mazzaella, Mastocarpus, Rhodymenia, Constantinia, Opuntiella*)	Medium to deep	Medium	• Medium to small sized plants • Attached to firm substrate • Some plants may overwinter; however most are annuals
BRY: filter feeder complex	An assortment of small, sessile filter feeding fauna such as sponges, tunicates, bryozoans, and hydroids	Medium to deep	Low	• Low turf of encrusting fauna will be overtopped by dense vegetation if present • Attached to firm immobile substrate • Perennial

For each grid cell, the proportion of points for a given species/cover class was weighted by the cover category (1 [sparse], 2 [low], 3 [moderate], or 4 [dense]; see Table 1) and divided by the total number of points within the cell. Weighting points by cover category considers changes between each abundance category to be of equal importance. As such, a proportional value for a specific species/cover class was obtained within a given cell for both the 2006 and 2009 surveys. Figure 3 shows an example grid cell for the FIR species group. Every point in the example grid cell contains the FIR species group for both the 2006 and 2009 datasets. In 2006 there are 65 survey points, 62 are moderate (cover category value of 3) FIR (95%) and three are dense (cover category value of 4) FIR (5%). In 2009 there are 62 survey points, 36 are sparse (value of 1) FIR (58%) and 26 are low (value of 2) FIR (42%). The aggregated categorical proportion based on the FIR species group example was calculated as follows:

$$2006:\ (0.95\times 3)+(0.05\times 4)=2.85+0.2=3.05$$

$$2009:\ (0.42\times 2)+(0.58\times 1)=0.84+0.58=1.42$$

Thus we can calculate that the aggregated categorical proportion of FIR in 2006 was 3.05, while by 2009 this value decreased to 1.42.

It is also possible to use the categorical cover midpoint values (*e.g.,* cover category 2 = 5%–25%, midpoint = 15%). If midpoints are used, then the change between categories 2 (midpoint = 15%) and 3 (midpoint = 50%) will be represented as more significant than between any other categories, since the difference in midpoint will be the greatest (35%). In this study, change in sparse categories is important and better represented using rank weights. However, those using this approach to spatial analysis could use either the midpoint or categorical rank value, depending on their specific project.

Detecting Change

Temporal change was detected using raster differencing for each species group (Coppin *et al.*, 2004). Raster differencing was calculated by subtracting the cell values of the 2006 species raster from the 2009 species raster, resulting in a dataset in

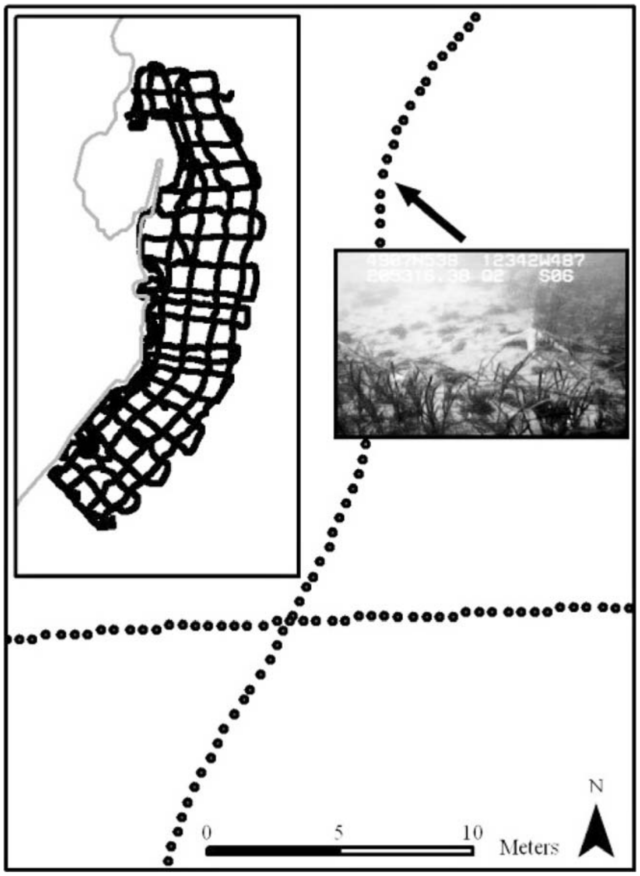

Figure 2. Map showing example of GIS point representation of classified SIMS trackline data points. Seabed video still image is an example of the raw video data from a trackline point. Inset map shows the SIMS survey trackline data for the entire study area of the 2006 survey.

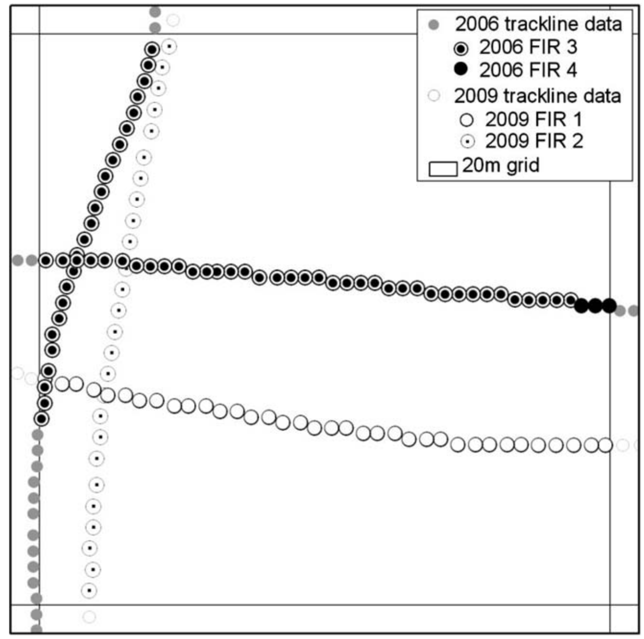

Figure 3. Example grid cell showing distribution of FIR (filamentous red algae) species group and differences in cover values (1 [sparse], 2 [low], 3 [moderate], and 4 [dense]) between 2006 and 2009 trackline data.

which zero values represent no change, negative values represent decreased abundance, and positive values represent increased abundance.

Hot spots of change were identified on the difference maps using a spatial statistic. Based on the principles of spatial autocorrelation, the spatial statistic identifies whether extreme changes in species abundance, relative to mean change (*i.e.,* large positive and large negative values of abundance change), are more clustered than would be expected based on chance (Nelson and Boots, 2008). Rejection of the null hypothesis, that extreme change is randomly distributed across the study area, gives confidence that a particular location's processes are causing clusters of extreme changes in species abundance to occur. The size of the change hot spot also indicates the spatial scale at which change processes are operating. Small hot spots are associated with fine-scale processes, whereas larger hot spots are indicative of broad-scale processes.

The spatial statistic used was local Moran I_i (Anselin, 1995), which has been previously used for ecological hot spot detection (Nelson and Boots, 2008). The local Moran I_i statistic for each raster cell i is defined as follows:

$$I_i = Z_i \sum_{j,j \neq i}^{n} w_{ij} Z_j$$

where the observations Z_i and Z_j are in standardized form and the spatial weight w_{ij} are in row-standardized form. For this study, the spatial neighbourhood, w_{ij}, is defined as a three cell by three cell moving window centred on i. With randomization, I_i is converted to a p value (Nelson and Boots, 2008). The significance level (alpha) was set at 95%, and a two-tailed test used (*i.e., p* value set at 0.05 and 0.95).

RESULTS

Figure 4 shows the cover maps for 2006 and 2009, the difference map, and the hot spot change map for each of the five species groups.

An overall decrease in abundance and a change in spatial distribution of the AGR/BKS assemblage are evident when comparing the 2006 and 2009 maps in Figure 4A. The change is especially evident in the central and southern regions of the study area, where there are gaps in the distribution of AGR/BKS in 2009. The AGR/BKS difference map (Figure 4A) indicates that while there are areas throughout the survey extent that have undergone an increase in AGR/BKS distribution, the majority of the survey area shows a reduction in this species assemblage cover as evident by the dominant pale gray "Loss" pixels. The map of AGR/BKS hot spots of change (Figure 4A) identifies clusters of significant change throughout the study area in both shallow and deeper waters. Several large predominant species change hot spots are situated near the entrance to the Sidney Marina in the northern section of the study area.

The spatial distribution of BRY changed between 2006 and 2009 but remained mainly sparse and low in cover abundance (Figure 4B). Hot spots of BRY abundance change are highly depth-stratified and appear to form an arc near the eastern fringe of the study area.

There was also a decrease in the abundance of FIR species between 2006 and 2009 (Figure 4C). The decrease is especially evident in the northeast section of the study area, while there was an increase in abundance in the centre of the study area. There are several regional hot spots of FIR abundance change, including a large hot spot in the northeast near the entrance to the Sidney Marina and several hot spots along the eastern fringe of the study area in deeper waters. There are also two hot spots in the central section in shallower water and two hot spots that appear to align with the entrance to the Washington State ferry terminal.

While the AGR/BKS, BRY, and FIR maps show an overall decrease in species abundance, the FOR species abundance is relatively consistent, but FOR species experience change in spatial location of the species (Figure 4D). Small hot spots of FOR species abundance change are present throughout the study area, and three large hot spots occupy the central region, which are driven by a marked increase in the distribution of FOR in this region.

The ZOS 2006 and 2009 cover maps are similar in both spatial distribution and abundance (Figure 4E). The hot spots of change are located along the fringe of the eelgrass (KOS) beds including a prominent patch near the entrance to the Sidney Marina.

DISCUSSION

Map-based nearshore monitoring of flora tends to emphasize remote sensing of species visible from the surface such as eelgrass (*e.g.,* Gorman, Morang, and Larson, 1998; Macleod and Congalton, 1998). Monitoring fauna below the surface is less common, in part because of difficulties with repeated data collection and sampling schemes that consistently index space. Combined with spatial analysis, the SIMS system is suitable for monitoring change in flora and epiflora visible below the water's surface.

Monitoring natural environments using spatial pattern methods to detect change has several advantages. First, spatial pattern approaches identify change that is most likely to have arisen from spatial processes as opposed to from chance (Nelson and Boots, 2008). Change hot spots are spatially clustered locations of extreme change in abundance (Nelson and Boots, 2008). While annual variation will lead to differences in abundance, most often seasonal change will influence mean values rather than spatial distribution of extreme change in abundance values. Second, identifying change in abundance based on spatial clusters reduces issues associated with the potential misclassification of a single grid cell (Nelson, Boots, and Wulder, 2005). Clusters of change will not be detected if one grid cell has erroneous difference in abundance values due to issues with classifier accuracy or species detectability. Third, the spatial pattern approach outlined here detects change in species abundance based on statistical significance. Standard change detection is threshold-based, where a threshold, defining change or no change, is applied to the difference between two raster surfaces (See Singh, 1989 for discussion). Thresholds used to define change are often arbitrary. The use of statistical significance as the threshold for change reduces the arbitrary nature of threshold selection. As with all thresholds, statistical change needs to be related to ecological significance.

There was minimal overall change within the selected species groups over the 3-year time interval. Local areas where significant change occurred included near the entrance to the marina (*e.g.,* AGR/BKS and ZOS) and the Washington State ferry terminal (*e.g.,* BRY and FOR), where marine boat traffic may be impacting vegetation. The space–time methods we outline will have additional value if change in abundance is being detected over longer or multiple time periods or in association with a major nearshore event (*i.e.,* human disturbance, sea level rise, or blight).

When species are difficult to interpret (*i.e.,* FIR) or species are present in small numbers (*i.e.,* BRY and ZOS), we expect reduced confidence in the resulting mapped change abundance. Multiple time periods for data collection might also be needed to fully detect change in some marine species. For example, BRY species assemblage, which consists of small, sessile filter feeding fauna found in medium to deep depths that are often overtopped by dense vegetation, would be difficult to detect in any single time period. As such, there may be benefit to developing monitoring systems that simultaneously consider space–time patterns in several combined species assemblages. As a result, data for species that have similar habitat requirements and different levels of detection ease could be collected together.

The SIMS sidescan sonar was used in a limited way to guide video data collection. As study areas increase in size, sidescan scan surface morphology data will have an increased importance for change detection. Given that Moran's I_i detects spatial trends in change values that are extreme relative to *mean* change, while study areas become larger they may need to be partitioned prior to identifying change hot spots (Anselin, 1995). The mean change in species abundance may differ substantially over the expanse of the study area. Surface morphology will often provide appropriate homogenous regions for partitioning and will also aid interpretations of change in species abundance.

CONCLUSIONS

In this paper we demonstrate how the SIMS video data collection system can be combined with spatial analysis to enable monitoring of flora and epifauna in a nearshore environment of the coast of British Columbia. Classified video survey data collected for two time periods (2006 and 2009) are integrated into a GIS. Video surveys are represented in a GIS as point data and are converted to raster. The difference in flora abundance between 2006 and 2009 is calculated for each raster cell, and spatial statistics are used to identify statistically significant clusters of change.

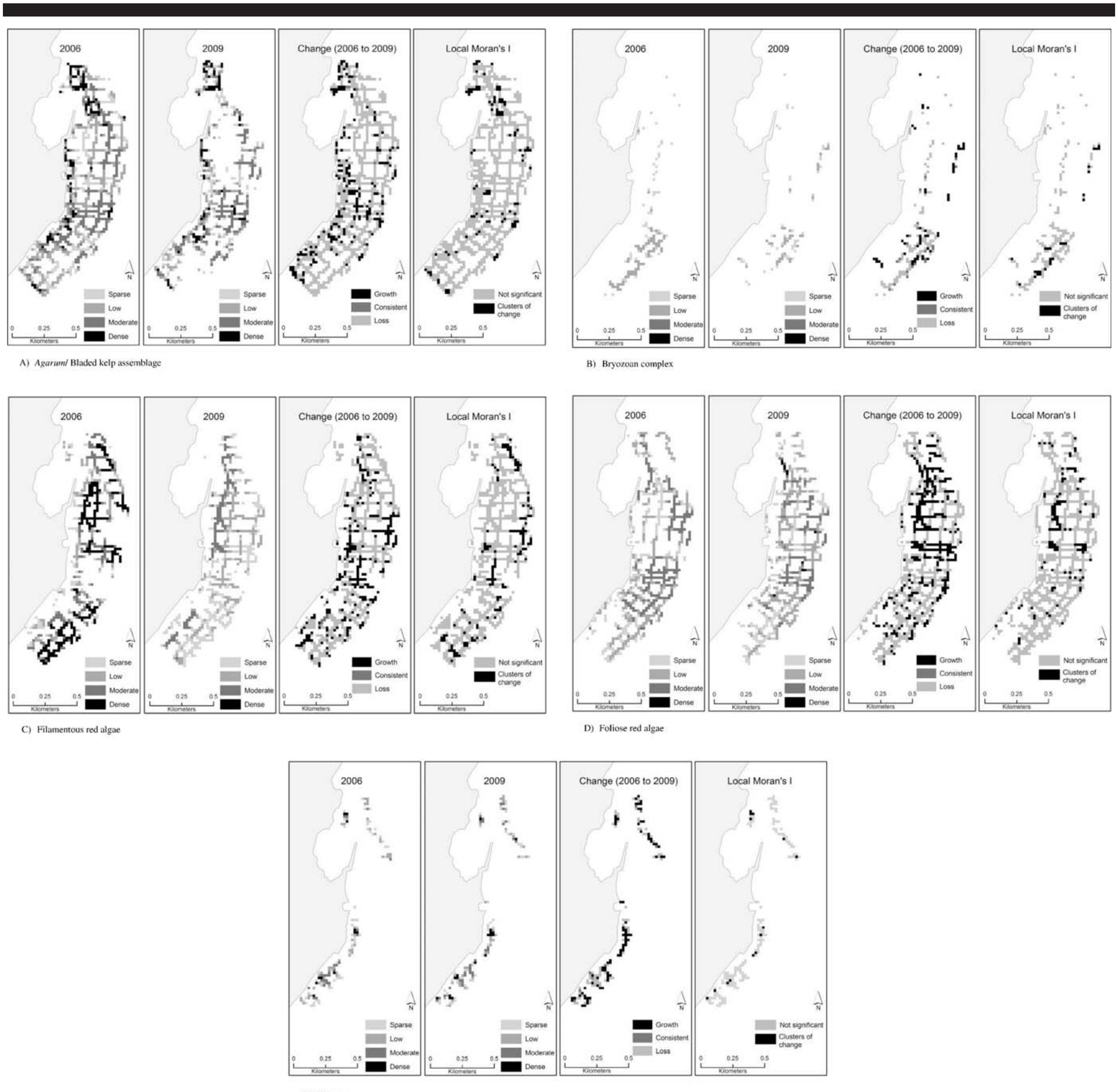

Figure 4. The distribution of species in 2006 and 2009, the difference in distribution between the two time periods, and the identification of clusters of unexpected change between 2006 and 2009. Clusters are defined as locations with statistically significant Local Moran's I values ($\alpha = 0.05$). Species include: (A) *Agarum*/ bladed kelp assemblage; (B) *Bryozoan* complex; (C) filamentous red algae; (D) foliose red algae; and (E) eelgrass.

Combined with GIS and spatial analysis tools, the SIMS system is well suited for monitoring and change detection. Of particular benefit is the creation of a permanent record of continuous data to sample from. Using recorded video imagery, sampling density and classification categories can be enhanced or assessed if required for specific change detection or monitoring applications. Detecting change from SIMS data is relatively simple and can be conducted with standard or even free (*i.e.,* QGIS) GIS software. Improvements to the SIMS system could also include a more intensive survey effort (*e.g.,* survey tracklines at a closer distance), corrected layback, finer grid cell sizes to allow for greater detectability of local anomalies, and finer SIMS categories to allow for improved detectability of minor changes in abundance.

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