

Master's thesis



**Predictive modelling of kelp  
(Laminariales) forest habitat around Haida  
Gwaii anticipating the return of sea otters  
(*Enhydra lutris*)**

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*Modelling potential kelp (Laminariales) forest habitat around Haida Gwaii  
anticipating the return of sea otters (Enhydra lutris)*

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## **Declaration**

I hereby confirm that I am the sole author of this thesis and it is a product of my own academic research.

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# Abstract

Kelp (Laminariales), sea urchins (*Mesocentrotus franciscanus* and *Strongylocentrotus* spp.) and sea otters (*Enhydra lutris*) are key components of an ecological paradigm in which kelp forests depend on sea otters as a keystone predator. Sea otters perpetuate trophic cascades where their predation of herbivorous sea urchins controls urchin grazing pressure on kelp in order to maintain abundant kelp forests. During the maritime fur trade, sea otters were extirpated from most of their geographic range, including Haida Gwaii, by the mid-1800s. The loss of sea otters released their macroinvertebrate prey, including sea urchins, from high predation pressure. Subsequently, urchins overgrazed kelp and created kelp-devoid areas known as urchin barrens. The re-introduction of sea otters to British Columbia (BC) and their eventual recovery to their historic range will again cause dramatic changes in kelp forest distribution and growth. To understand the implications of sea otter return and recovery on the kelp forests of Haida Gwaii in BC, Canada, I created bottom-up, geographic models of potential kelp and urchin barrens habitat to predict the distribution of future kelp growth and indicate the spatial extent of kelp forests restored through trophic cascades. All input data were provided by secondary sources and overlaid to map areas with a combination of abiotic conditions that potentially support kelp and sea urchins. I found that potential ecosystem shifts from urchin barrens to kelp forests were expected to occur over 92,824 ha of temperate rocky reef and stable mixed substrates. This represents 80% of the total potential kelp forest habitat that shows the total area of suitable habitat for kelp forest growth. The remaining 20% represents areas of potential kelp forest habitat unimpacted by urchin barrens. The applicability of results to marine management included detailed mapping of areas with predicted changes in kelp forests growth. Relative difference between potential existing kelp growth and potential increases in kelp growth informs marine spatial planning as a tool for managing vulnerable ecosystems, ecosystem services, and conflicting uses. Kelp management issues for Haida Gwaii include future kelp forest increases that promote and conserve ecosystem services, biodiversity, while building resilience against threats from herbivory, climate change, ocean acidification, introduced species and oil spills. Potential habitat mapping can foster improved marine spatial planning within an ecosystem-based management approach that identifies and manages for trade-offs from shifting ecosystems.

# Table of Contents

List of Figures .....	viii
List of Tables.....	x
Acronyms .....	xi
Acknowledgements .....	xiii
1 Introduction .....	1
1.1 Kelp mapping .....	2
1.2 Coastal and marine management on Haida Gwaii.....	3
1.3 Research question, aims, and hypotheses .....	6
2 Theoretical Overview.....	9
2.1 Kelp forest ecology.....	9
2.2 Sea otter-induced trophic cascades.....	11
2.2.1 Urchins .....	11
2.2.2 Sea otters .....	13
2.3 Ecosystem Services .....	14
2.3.1 Supporting services .....	14
2.3.2 Regulating services .....	15
2.3.3 Provisioning services.....	15
2.3.4 Cultural services.....	17
2.4 Blue carbon.....	18
2.5 Stressors.....	19
2.5.1 Introduced and invasive species .....	19
2.5.2 Herbivory .....	20
2.5.3 Climate change .....	20
2.5.4 Ocean acidification.....	21
2.5.5 Oil Spills.....	22
2.6 Marine governance and management .....	23
2.6.1 Ecosystem-Based Management.....	23
2.6.2 Marine Spatial Planning .....	24
2.6.3 Ecological economics.....	26
2.6.4 Ecological restoration and resilience.....	27
3 Research Methods .....	30

3.1	Study site.....	30
3.2	Habitat modelling and data sources .....	32
3.2.1	Depth as a proxy for light availability .....	33
3.2.2	Substrate .....	35
3.2.3	Wave exposure .....	39
3.2.4	Model phases to refine results .....	42
3.3	Model assessment with independent data .....	45
3.3.1	Known kelp distribution .....	46
3.3.2	Known urchin distribution.....	47
3.4	The Haida Gwaii Marine Plan .....	48
4	Results .....	50
4.1	Potential kelp habitat .....	50
4.2	Independent data evaluation of potential habitat models.....	53
4.3	Potential sea urchin barrens model .....	56
4.4	Potential kelp habitat and Haida Gwaii Marine Plan spatial zoning .....	60
5	Discussion .....	62
5.1	Understanding implications of keystone predator loss through potential habitat suitability modelling .....	62
5.2	Expected shifts and trade-offs in ecosystem services with sea otter recovery .....	64
5.2.1	Kelp habitat suitability modelling as a proxy for ecosystem services and associated species to facilitate ecosystem-based management .....	64
5.2.2	Potential trade-offs in ecosystem services with sea otter return and increase in kelp forest habitat including potential cultural, social and economic consequences.....	67
5.3	Directions for future studies .....	72
5.3.1	Model improvements.....	72
5.3.2	Additional data collection.....	73
5.3.3	Succession .....	74
6	Conclusions .....	76
	References .....	77
	Appendix A .....	87
	Appendix B.....	89

# List of Figures

Figure 1. Map of Haida Gwaii, previously known as the Queen Charlotte Islands and inset of BC in Canada (top right) and ferry terminals on Haida Gwaii (bottom left) (Parks Canada Agency).....	6
Figure 2. A mature Giant kelp ( <i>Macrocystis pyrifera</i> ) plant. A, holdfast; B, primary stipe; C, stub of an old frond; D, sporophyll clusters; E, juvenile frond; F, senile frond; G, stipe bundle; H, apical blade of mature frond, giving rise to additional blades (Neushul & Haxo, 1968). ....	10
Figure 3. An urchin barren on the west coast of Canada characterized by encrusting pink coralline algae and dominated by urchins (Burt, n.d.). Kelp can be observed the barren in higher exposures near shore.....	12
Figure 4. Single sea otter observed in July 2017 on the east coast of Gwaii Haanas. Photo source: C. Houston, Gwaii Haanas .....	13
Figure 5. Haida Gwaii Marine Plan protected zones with IUCN and special management zones. The zones classifications include Wilderness area (Ib); National park (II); Natural monument or feature (III); Habitat/species management area (IV); Protected landscape or seascapes (V); and, Protected areas with sustainable use of natural resources (VI). Areas not zoned are considered part of the general management area (MaPP, 2015). ....	31
Figure 6. Shallow subtidal red sea urchin barrens just below the lowest tide (left), and intertidal kelps <i>Egregia menziesii</i> and <i>Alaria</i> just above the lowest tide (right), along northeast Burnaby Island, Gwaii Haanas. Photo credit: C. Houston. ....	34
Figure 7. Bathymetry data showing depth raster for Haida Gwaii (Gwaii Haanas Parks Canada, 2015).....	35
Figure 8. BType-1 polygons for Haida Gwaii (data from Gregr et al., 2013). ....	38
Figure 9. BC Shorezone wave exposure classifications for the Haida Gwaii coast (Howe et al., 1997). ....	41
Figure 10. ShoreZone exposure points converted into coded Thiessen polygons. ....	41
Figure 11. Conceptual diagram of parameters used in Phase 1 of spatial model development in ArcGIS 10.4.....	43
Figure 12. Multiple phases of the potential kelp model (Phase 1 and 2) and sea urchin model (Phase 1, 2 and 3). ....	45
Figure 13. Known distribution of sea urchins from BCMCA commercial fishery dataset.....	47

Figure 14. Haida Gwaii Marine Plan (2015) spatial management zones that identify kelp as a valued feature.....	49
Figure 15. Potential kelp habitat map from Phase 1 analysis.....	52
Figure 16. Potential kelp habitat map from Phase 2.....	52
Figure 17. Overlap between independent kelp data and Phase 2 potential kelp habitat modelling at Niidan Kaahlii (Naden Harbour) (inset), northern XaaydaGa Gwaay.yaay IinaGwaay (Graham Island), Haida Gwaii. ....	54
Figure 18. Overlap between independent kelp data and Phase 2 potential kelp habitat modelling at Hlkinul ChiiGas.sgi (Fairbairn Shoals) (inset), northeast T'aaxwii XaaydaGa Gwaay.yaay IinaGwaay (Moresby Island), Haida Gwaii.....	55
Figure 19. Potential urchin barrens habitat by exposure class for Haida Gwaii. The inset shows SGang Gwaay.....	57
Figure 20. Area of overlap between Phase 2 potential kelp habitat and Phase 3 potential urchin barrens habitat for Haida Gwaii. The inset shows SGang Gwaay. ....	58
Figure 21. Area of overlap between potential barrens and known kelp distribution. The inset shows SGang Gwaay.....	59
Figure 22. Haida Gwaii Marine Plan (2015) zoning that identifies kelp as a valued feature, from +1 to 20m depth, and areas of overlap with Phase 2 potential kelp habitat. The inset shows Naasduu Gwaay.yaay (Hippa Island) on the west coast of XaaydaGa Gwaay.yaay IinaGwaay (Graham Island).....	61

# List of Tables

Table 1. Kelp species found on Haida Gwaii (Saunders and McDevit, 2014) .....	32
Table 2. General preferred depth zones of Haida Gwaii kelp species (Sloan, 2006).....	34
Table 3. Preferred substrate types for Haida Gwaii kelp species fit according to the BoP substrate classification system (adapted from Sloan, 2006).....	37
Table 4. Hierarchical bottom patch substrate classifications (Gregar et al., 2013). ....	39
Table 5. Wave exposure preferences of different kelps and urchin barrens (Sloan, 2006).....	40
Table 6. Wave exposure classifications and description (Howe et al., 1997).....	42
Table 7. Parameters for kelp habitat modelling Phases 1 and 2, and urchin barrens modelling Phases 1, 2 and 3. ....	44
Table 8. The total number of polygons and the total area for the potential kelp models in Phase 1 and 2 of the modelling and difference in area from Phase 1 to Phase 2.....	50
Table 9. Total area (ha) by substrate layer for Phase 1 and 2 potential kelp habitat modelling and difference in area from Phase 1 to Phase 2 (%). ....	51
Table 10. Total area (ha) by exposure rating for Phase 1 and 2 potential kelp habitat modelling and difference in area from Phase 1 to Phase 2 (%). ....	51
Table 11. CRIMS dataset overlaps with Phase 1 and 2 potential kelp habitat modelling. .....	53
Table 12. Site-specific overlaps between CRIMS data and Phase 2 potential kelp habitat modelling. ....	53
Table 13. IUCN designations for overlapping kelp feature zones and potential kelp polygons by area, and percent overlap relative to the total area of zones with kelp features at depths of +1 to 20m. ....	60

# Acronyms

AMB	Archipelago Management Board
BC	British Columbia
BCMCA	BC Marine Conservation Analysis
BoPs	Bottom Patches
CHN	Council of the Haida Nation
CHS	Canadian Hydrographic Service
COSEWIC	Committee on the Status of Endangered Wildlife in Canada
DFO	Fisheries and Oceans Canada (formerly Department of Fisheries Canada)
EBM	Ecosystem Based Management
EBSA	Ecologically and Biologically Significant Area
GH	Gwaii Haanas
GHG	greenhouse gas
GIS	Geographic Information Systems
HHS	Haida Heritage Site
IPCC	International Panel on Climate Change
IUCN	International Union for Conservation of Nature
MaPP	Marine Planning Partnership
MPA	marine protected area
MSP	marine spatial planning
NMCA	National Marine Conservation Area Reserve
NPR	National Park Reserve
NRCan	Natural Resources Canada
PCA	Parks Canada Agency
PMZ	Protection Management Zone
PSSA	Particularly Sensitive Sea Areas

SARA	Species at Risk Act
VMEF	Valued Marine Environmental Features

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# 1 Introduction

Kelp (Order Laminariales) forests are one of the most productive nearshore ecosystems in the world and play a key role in nearshore food web systems (Smale, Burrows, Moore, O'Connor, & Hawkins, 2013; Sloan & Dick, 2012; Steneck et al., 2002). As an ecosystem engineer, kelp plants modify physical and biotic environments used by other species (Jones, Lawton & Shachak, 1994) and provide an array of cultural, provisional, supportive, and regulative ecosystem services (Hondolero & Edwards, 2017; Bertocci, Araujo, Oliveira & Sousa-Pinto, 2015; Dayton, 1985). Globally, kelp forests are mostly found in polar and temperate subtidal ecosystems. Herbivorous predators, increasing stormy weather, rising temperature caused by global warming, pollution, and invasive species, all have negative effects on kelp (Smale et al., 2013).

In British Columbia (BC), archaeological evidence and studies of nearshore ecology indicate kelp has declined from its historical cover on the Pacific coast (Szpak, Orchard, Salomon & Grocke, 2013; Sloan & Dick, 2012). A study of kelp-derived carbon isotopes in rockfish from the both post- and pre-European contact on Haida Gwaii indicated a decrease in kelp (Szpak et al., 2013). The decline is attributed to be the indirect result of intensive sea otter (*Enhydra lutris*) hunting during the maritime fur trade which occurred approximately from 1790 to 1830. With ecological extirpation of sea otters throughout most of BC by the mid-1800s, nearshore food web dynamics were dramatically altered with sea urchins (*Mesocentrotus* spp.; sea otter prey) able to thrive and increase grazing pressure on kelp (Sloan, 2006). Ecological studies on sea otter-induced trophic cascades on nearshore rocky reefs comparing sites with and without sea otters show that sea otter predation of sea urchins reduces urchin population size and subsequent kelp consumption (Estes & Palmisano, 1974; Watson & Estes, 2011).

Sea otters have begun to return to their historic range along the BC coast following their re-introduction between 1969 and 1972 on the west coast of Vancouver Island (Department of Fisheries and Oceans Canada [DFO], 2015; Sloan & Dick, 2012; Breen, Carson, Foster & Stewart, 1982). Sea otter re-colonization of the Haida Gwaii archipelago in BC is anticipated within the 21<sup>st</sup> century. When sea otters return and recover, their re-colonization is expected

to have profound effects on nearshore community structure and their return to Haida Gwaii, similar to other parts of the BC coast, is mired in controversy (Salomon, Wilson, White, Tanape & Happynook, 2015; Sloan & Dick, 2012). Sea otters represent a threat to some commercially important shellfish species, including crabs, clams, abalone (*Haliotis kamtschatkana*) and sea urchins (Salomon et al., 2015; Sloan & Dick, 2012). However, sea otters also represent the most effective means to restore kelp forests and their associated ecosystem services.

The expected sea otter-induced top-down trophic cascade on rocky reefs will reduce sea urchin abundance and allow for the recovery of kelp forests, with implications for marine planning and management around Haida Gwaii. Management issues surrounding anticipated ecological trophic cascades resulting from sea otter return present a complex and challenging problem for ecosystem-based management (EBM) because of multiple and conflicting stakeholder interests and limited knowledge about the exact impacts of otter re-colonization. Using habitat parameters from existing literature and data on nearshore biotic and abiotic conditions, potential habitat models were created for this study using abiotic factors and parameters from conditions known to support kelp and sea urchin barrens. The models were used to investigate the expected change in spatial distribution of kelp forests, following sea otter re-occupation and range expansion throughout Haida Gwaii, to inform management planning and decision-making.

## **1.1 Kelp mapping**

One of the greatest challenges in marine management is that the ocean surface conceals the spatial and temporal heterogeneity of the sea floor, water columns, species movement and human exploitation (Crowder & Norse, 2008). Current province-wide databases of kelp forests, understory kelps, and other nearshore habitats in BC are fragmented (Grega, Lessard & Harper, 2013; BC Marine Conservation Analysis [BCMCA], 2007; Greene, Bizzarro, O'Connell & Brylinsky, 2007). Continuous and high-resolution mapping of nearshore marine environments (up to 50 m in depth) is particularly limited and known as the “white strip” surrounding land in marine habitat mapping (Grega et al., 2013; Bartier & Sloan, 2007). The nearshore, a part of the interface between marine and terrestrial environments, has typically been a challenging area for mapping and management because of logistical challenges with available technology, conflicting jurisdictions and access. Historical data

with different feature classifications, mapping projections and resolutions was recorded by various agencies. In more recent decades, Geographic Information Systems (GIS) computer mapping programs have made it possible to harmonize and consolidate different datasets.

Specific to Haida Gwaii, some one-dimensional data on kelp distribution is available from aerial images at low tides and multiple observation sources like the Canadian Hydrographic Service (BCMCA, 2011). However, kelp forests remain under-represented in spatial data due to the difficulty and infrequency of survey coverage and incomplete sub-surface data. In general, for kelp forest distribution, available data are often sparse and inconsistent over the long-term, resulting in a lack of baseline data. In particular, there is a lack of data for large scales of spatial variation of kelp forest ecosystems (Krumhansl et al., 2016; Steneck et al., 2002). Existing studies suggest there is high variability among global trends (Krumhansl et al., 2016). An intertidal shoreline habitat mapping initiative via aerial video footage in the 1980s and 1990s, called BC ShoreZone mapping, classified the entire coastline of Haida Gwaii into one-dimensional ‘biobands’ based on biological and physical features. Biobands include canopy-forming kelps that were visible from the intertidal (BCMCA, 2010; Harper & Morris, 2006; Howe, Harper & Owens, 1997). A coastwide comprehensive area-based dataset does not exist, and the creation of this dataset would demand time, expense and difficulty to collect and ground-truth data for the entire Haida Gwaii coastline and the rest of the province (BCMCA, 2007).

Fortunately, bottom-up classification and modelling that uses habitat predictors can be used to fill gaps in existing kelp survey data (Grega et al., 2013; BCMCA, 2007), and efforts to map marine habitat in greater detail for the entire BC coast are currently underway. The Canadian Hydrographic Service (CHS) and the Department of Fisheries and Oceans Canada (DFO) are mapping nearshore substrates using multibeam sonar and backscatter data. With nearshore substrate maps, it is possible to create a framework for modelling habitat maps known as “bottom patches” (BoPs), which can have additional attributes depending on available abiotic and biotic data (Grega et al., 2013).

## **1.2 Coastal and marine management on Haida Gwaii**

The nearshore and coastal environment fall under several jurisdictions in Canada – indigenous, municipal or local, provincial and federal governments. Generally, in BC, local, municipal and indigenous governments may be involved in planning, tenures, regulating and

permitting. Provincial authorities preside over most of the foreshore between the low tide and high tide boundaries. The federal government is the legislative authority for the “Sea Coast and Inland Fisheries” under section 91(12) of the Canadian Constitution (1867). As with matters under provincial jurisdiction, increasing discussions and agreements for co-management of marine areas and resources between federal and indigenous governments in coastal BC have occurred over the last decade and are continuing today (Council of the Haida Nation [CHN], 2017b; MaPP, 2015; Gwaii Haanas Agreement, 1993).

Haida Gwaii and its surrounding air and waters are the traditional territory of the Haida indigenous people (CHN, 2017a). Two marine management plans are currently being developed to encompass the coast of Haida Gwaii - the Haida Gwaii Marine Plan (2015) and the Gwaii Haanas Land-Sea-People Management Plan for the southern end of T'aaxwii XaaydaGa Gwaay.yaay IinaGwaay (Moresby Island). The Haida Gwaii Marine Plan (2015) was developed by the Council of the Haida Nation (CHN; the local Haida government) and the Province of BC (Marine Planning Partnership Initiative [MaPP], 2015). The Gwaii Haanas National Park Reserve, National Marine Conservation Area Reserve and Haida Heritage Site (GH NPR, NMCAR & HHS) is cooperatively managed by the CHN and federal government, represented by Parks Canada Agency (PCA) and DFO (CHN, 2017b; Gwaii Haanas Agreement, 1993; Figure 1). Under the *Gwaii Haanas Agreement* (1993) and *Gwaii Haanas Marine Agreement* (2010), Gwaii Haanas is cooperatively managed by the Archipelago Management Board (AMB) that is composed of three federal government and three CHN representatives. The CHN and federal government hold different viewpoints on the title or ownership of Gwaii Haanas but they have agreed to cooperatively manage this valuable area through the AMB to achieve a high level of protection and sustainable use.

The Haida Gwaii Marine Plan (2015) takes an EBM approach defined as “an integrated approach to management that considers the entire ecosystem, including humans” (Crowder & Norse, 2008). The Plan employs marine spatial planning (MSP), an EBM tool that uses mapping for collaboration and coordination of multiple stakeholders and values in marine planning and management (MaPP, 2015; Douvere, 2008). MSP can be used to define boundaries that incorporate ecological and socio-economic values as well as changing information related to the planning, implementation, and monitoring.

The Haida Gwaii Marine Plan (2015) specifically identifies kelp as an important ecological and cultural feature. Zoning using International Union for Conservation of Nature (IUCN) marine protected area (MPA) classifications are used to develop guidelines and standards for monitoring and protecting key ecological features. The monitoring and protection of kelp are listed as a part of the strategy to identify, maintain, restore and protect critical marine habitats, and ecologically and culturally important features. Although the Haida Gwaii Marine Plan (2015) does not address marine vessel and oil tanker traffic, which continue to increase on the BC coast, detailed knowledge of nearshore environments will be a key component in developing oil spill response and countermeasures programs. Baseline information on distribution will contribute to the evaluation of oil spill damage and loss of kelp forests and associated ecosystem services. For BC, management decisions impacting the distribution of kelp will be an integral part of managing for the protection and promotion of nearshore ecosystem services that contribute to species at risk habitat and increase biodiversity. Spatial management of kelp also involves addressing and evaluating the main threats to kelp forests, including introduced species, herbivory, climate change, ocean acidification and oil spills. Marine spatial planning can identify and address conflicting spatial uses (Crowder & Norse, 2008; Douvère, 2008).

Gwaii Haanas is the first legislated NMCAR in Canada. The NMCAR, designated in 2010, is to be managed as an extension of the terrestrial protected area. Thus, the development of an integrated Gwaii Haanas Land-Sea-People Management Plan is currently underway. The *NMCA Act* (2002) arose from increasing national and international recognition of the need for a national network of ecologically representative MPAs (Dearden & Dempsey, 2004). The NMCAR portion extends approximately 10 km from the terrestrial part of Gwaii Haanas and includes the water column and submerged lands (Figure 1). In general, most of the marine environment, specifically fish and fish habitat, falls within the jurisdiction of DFO (except for kelp which is under the purview of the province). Together, the CHN, Parks Canada Agency and DFO cooperatively manage Gwaii Haanas under the provisions of the *NMCA Act* (2002). The history of Gwaii Haanas dates back to the 1980s with the creation of the Haida Gwaii Watchmen Program (1981) and declaration of the Haida Heritage Site (1985) including protection for the waters surrounding the terrestrial part of Gwaii Haanas. The developing Gwaii Haanas Land-Sea-People Plan integrates terrestrial and marine

planning and management with an overarching vision, goals, objectives and zoning plan for terrestrial and marine areas.



Figure 1. Map of Haida Gwaii, previously known as the Queen Charlotte Islands and inset of BC in Canada (top right) and ferry terminals on Haida Gwaii (bottom left) (Parks Canada Agency).

### 1.3 Research question, aims, and hypotheses

Sea otters have been ecologically extirpated from Haida Gwaii for over a century. Current ecological nearshore conditions reflect their absence (Sloan & Dick, 2012). In anticipation of sea otters returning to Haida Gwaii and recovering, what is the potential distribution of kelp forests around Haida Gwaii? How does this potential distribution compare with the known current distribution of kelp? What is the relevance of potential change in kelp forest

distribution for conservation of nearshore environments around Haida Gwaii? Based on the well-documented sea otter-induced trophic cascade from rocky reefs in BC and Alaska (e.g. Watson & Estes, 2011; Konar & Estes, 2003), I hypothesize that the potential kelp habitat model will show a larger area than known kelp distribution, but will also overlap with known kelp forest areas. I also expect potential urchin barren habitat to overlap with the majority of potential kelp habitat and for known kelp to exist outside of the potential urchin barrens area.

The theoretical overview defines and explains the terms, theories and contexts related to kelp forest recovery and management. The potential habitat models were created to predict the spatial extent of potential kelp forest recovery from sea otter-induced trophic cascades, anticipating the return of sea otters. First, basic kelp ecology provides an understanding of the structure, growth and habitat for kelp forests. An overview of trophic cascades provides information on species relationships, interactions and the anticipated coastwide ecosystem shifts from urchin barrens to kelp forests spurred by the restoration of a top predator. The potential increase in kelp forests is anticipated to promote ecosystem services provided by kelp. Kelp ecosystem services are listed and described in this section. The main threats to kelp forests are outlined as stressors for existing kelp and possible inhibitors of future kelp recovery and associated ecosystem services. Finally, the importance of potential habitat suitability and mapping for kelp forests to marine management are outlined under marine governance and management. Spatial distribution mapping of potential kelp forests is a tool relevant to ecosystem service valuation and the achievement of marine ecosystem-based management objectives. The theoretical overview contains a literature review that describes the state of knowledge in the research field and particular issues and importance for managing kelp habitat.

Using existing data and methodologies for modelling and mapping kelp (Gregar et al., 2013; Gorman, Bajjouk, Populus, Vasquez & Ehrhold, 2013; Bekkby & Moy, 2011; Gregor, Nichol, Watson, Ford, & Ellis, 2006), I combined the results of a physical substrate model (Gregar et al. 2013) with existing data on abiotic variables, including depth as a proxy for light and wave exposure, to model potential change in kelp distribution for Haida Gwaii and to investigate related management issues. Project limitations included the quality and availability of data for model input and the inherent limitations of potential habitat modelling (Halley & Jordan, 2007; Greene et al., 2005). These models represent a simplified version of reality, only accounting for select variables. Kelp is also inherently difficult to model

because abiotic variables affecting kelp growth are not independent, likely varying across depth and other environmental gradients, with additional impacts that likely vary depending on life stage of the kelp (Dayton, 1985). Basic modelling is nevertheless useful as a marine management tool that represents potential trends in habitat (Greene et al., 2007). Model results are discussed in the context of trophic cascades and potential changes in ecosystem services. Findings have relevance to ecological monitoring, protection, and management through MSP and EBM. Anticipating future distribution of kelp and recognizing the vulnerabilities and associated benefits of increased kelp growth and distribution will be an important part of understanding and managing nearshore ecosystem function through the relationship between kelp, sea urchins, and returning sea otters.

## 2 Theoretical Overview

### 2.1 Kelp forest ecology

Kelp is a large brown seaweed species, or macroalga, of the order *Laminariales* and in the class *Phaeophyceae*, meaning brown. Brown algae represent a younger lineage of seaweeds, distinct from red, *Rhodophyta*, and green, *Chlorophyta*, seaweeds (Druehl & Clarkston, 2016). *Laminariales* typically grow in the shallow rocky subtidal zones of temperate coastlines (Dayton, 1985). There are four families of *Laminariales* in the northern hemisphere: Chordaceae, Laminariaceae, Lessoniaceae, and Alariaceae. Each kelp plant is comprised of a holdfast, stipe(s) and blade(s), which are used for photosynthesis (Figure 2). In general, algae are defined as “photosynthetic organisms lacking distinct cellular differentiation and elaborate reproductive systems” (Druehl & Clarkston, 2016). Kelp plants have especially complex life cycles including alternating haploid gametophytes and diploid sporophytes generations which create sori. Kelp forests include an understory and canopy-forming kelp that grows in groups of varying densities and patches (Dayton, 1985). They are characterized by patchy and fragmented coverage with distinct edges (Efird & Konar, 2014). Growth may be restricted by abiotic factors but also depends on biological conditions like grazing, species competition like shading (Wheeler et al., 1986).

Habitat refers to “the area or type of site where an individual or wildlife species naturally occurs or depends on directly or indirectly to carry out its life processes or formerly occurred and has the potential to be reintroduced” (*Species at Risk Act*, 2002). The terms potential habitat and habitat suitability are used interchangeably in this paper to represent possible, but not necessarily actual, species occurrence. In general, important abiotic conditions that determine the local distribution of kelp forest habitat are light, salinity, temperature, nutrients, sedimentation, water movement, and substrate type; however, many other factors can also influence variation in kelp forest distribution (Dayton, 1985). The compensation depth, or maximum depth, for kelp is determined by the amount of light penetration in the euphotic zone, which is more restricted at higher latitudes where ocean waters are cooler and less transparent due to higher abundance of phytoplankton (Wheeler et al., 1986; Dayton, 1985). Seasonal growth takes place in the autumn during higher levels of dissolved nitrate (Dayton, 1985). Growing in the lower intertidal zone and into the subtidal zone allows kelp to avoid harmful ultraviolet rays and freezing conditions (Druehl & Clarkston, 2016). Kelp

must be at least partially submerged during the day to absorb nutrients and secure suitable attachment (Scagel, 1961).

Different kelp species grow to various heights, creating three-dimensional structurally diverse habitats for numerous other species. Giant kelp (*Macrocystis integrifolia*), ngaal in Haida, is a perennial that pursues ideal light and nutrient conditions and creates extensive canopies near the surface. In some regions like California, *Macrocystis* can be found at depths of 30 m, but on the northern BC coast, it generally grows to 10 m depth (Jamieson & Davies, 2004). Bull kelp (*Nereocystis luetkeana*), hlkyama in Haida, is an annual that also forms large canopy kelp forests from Alaska to Southern California. It is considered an opportunistic species because it colonizes and grows quickly on exposed substrates (Dayton, 1985). Understory kelps, stipitate *Laminaria*, are erect species that grow to less than 5 m in height (Jamieson & Davies, 2004; Steneck et al., 2002; Dayton, 1985). Below stipitate are prostrate canopy kelps that cover the benthos with their fronds, like *Costaria costata* and *Agarum* (Steneck et al., 2002; Dayton, 1985). Below these usually grow a patchy corticated macrophyte turf and encrusting coralline algae (Jamieson & Davies, 2004; Steneck et al., 2002; Dayton, 1985).

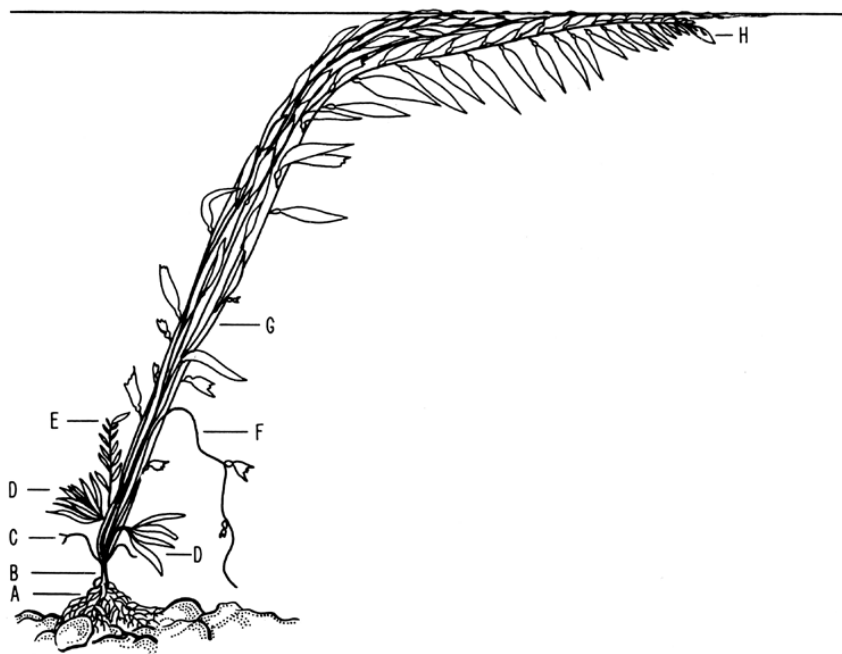


Figure 2. A mature Giant kelp (*Macrocystis pyrifera*) plant. A, holdfast; B, primary stipe; C, stub of an old frond; D, sporophyll clusters; E, juvenile frond; F, senile frond; G, stipe bundle; H, apical blade of mature frond, giving rise to additional blades (Neushul & Haxo, 1968).

The presence and species of kelp vary in different wave exposed conditions and substrate types. Woody-stemmed kelp, also known as stalked kelp or walking kelp, *Pterygophora californica* grows on hard, stable substrates in areas of higher exposure, whereas species like *Saccharina latissima* prefer sheltered areas in protected or semi-protected waters. *Nereocystis* is found in semi-exposed and exposed areas where each plant may stretch up to 30% to withstand the force and stress of waves and currents (Jamieson & Davies, 2004). In the early stages of succession, kelp generally exhibits higher rates of production and lower tolerance of wave exposure and grazing pressure (Druehl & Clarkston, 2016).

## **2.2 Sea otter-induced trophic cascades**

Ecological communities are dynamic, varying across space and time. Major ecological shifts are often complex, involving large areas, lengthy time periods, and many species (Estes et al., 2004). Kelp, sea urchins, and sea otters represent an ecological paradigm in which macroalgal populations depend on the maintenance of a predator-herbivore trophic relationship. When keystone predators, sea otters, were removed by human hunting during the maritime fur trade, sea urchin populations were released from predation pressure and grew in population size and distribution, deforesting nearshore kelp forests (Estes & Duggins, 1995). While additional variables can impact kelp forest growth and recovery, in some places, future kelp forest expansion may be entirely dependent on the recovery of this keystone predator and ensuing ecological trophic cascades. Kelp, urchins and sea otters are the key components of sea otter-induced trophic cascades on temperate rocky reefs.

### **2.2.1 Urchins**

Urchins, related to sea cucumbers and sea stars, are spherical echinoderms and slow-moving epifaunal grazers that feed on kelp. Red sea urchins (*Mesocentrotus franciscanus*) are the largest species and are common throughout the BC coast. These slow-growing, long-lived species usually mature at 5 cm test diameter, but can grow up to 19 cm diameter and live up to 100 years (Ebert & Southon, 2003). Urchin predators in northern BC are limited but include sunflower stars (*Pycnopodia helianthoides*), giant Pacific octopus (*Octopus dofleini*), sea otters and humans (Jamieson & Francis, 1987). Mortality is also attributed to seasonal starvation, disease, exposure and freshwater flooding (Jamieson & Francis, 1987). In the absence of kelp detritus, and when food competition exists with other herbivores, like abalone, urchins act as bio-eroders. Urchins are capable of creating entire ecosystem shifts

from kelp forests to calcareous coralline algal turf known as urchin barrens (DFO, 2012a; Steneck et al., 2002; Jennings et al., 2001; Tegner & Dayton, 2000). Barrens are characterized by a substrate absent of kelp and the diversity of associated species. Urchin impacts on kelp depend on the availability of food and the amount of grazing pressure exerted (Dayton et al., 1992).



*Figure 3. An urchin barren on the west coast of Canada characterized by encrusting pink coralline algae and dominated by urchins (Burt, n.d.). Kelp can be observed the barren in higher exposures near shore.*

Urchin barrens appear pale pink and bleached due to the prevalence of encrusting coralline algae (Figure 2). Urchins are usually most abundant on rocky substrates just below their upper vertical depth limit at the kelp line, with decreasing abundance at greater depths (Lee et al., 2016; Sloan & Bartier, 2000; Jamieson & Francis, 1987). In the absence of sea otters, the greatest sea urchin density and biomass occurs just below the sublittoral fringe, but urchins may still dominate at greater depths (Estes & Duggins, 1995; Stewart et al., 1982). Kelp distribution may be restricted to narrow bands in lower intertidal and upper subtidal zones because of strong grazing pressure by sea urchins (Estes & Duggins, 1995; Watson & Estes, 2011; Lee et al., 2016). When there are sufficient amounts of drifting seaweed fragments to sustain urchin populations, kelp forests and sea urchins may subsist together because urchins will apply less direct grazing pressure on living kelp plants. Defences against grazers vary by kelp species but include efficient colonization, tough woody stems,

the growth of soft tissues near the surface and out of reach, and chemical deterrents (Jamieson & Davies, 2004; Estes & Steinberg, 1988).

### 2.2.2 Sea otters

Sea otters (Figure 4) are apex predators and keystone species that maintain the structure of the nearshore kelp forest ecological community. Archaeological evidence suggests that sea otters on Haida Gwaii were the primary predator controlling urchin populations (Szpak et al., 2013; Sloan & Dick, 2012; Tegner & Dayton, 2000). Male otters can weigh up to 54 kg, and most otters consume up to a quarter of their body weight per day, mostly in macroinvertebrates (Sloan and Dick, 2012). Sea otters belong to the weasel family, Mustelidae. The fur of a sea otter may contain more than 125,000 hairs per square centimetre (Ford, 2014). Thick fur is essential to keeping otters warm as they have no blubber.



Figure 4. Single sea otter observed in July 2017 on the east coast of Gwaii Haanas. Photo source: C. Houston, Gwaii Haanas

Before the maritime fur trade, sea otter distribution ranged from northern Japan to central Baja California (Estes & Duggins, 1995; Estes & Palmisano, 1974). The maritime fur trade began in the late 18<sup>th</sup> century, ecologically extirpating sea otters from most of the BC coast by the mid-19<sup>th</sup> century. By 1929 they were entirely extirpated from the BC coast. Since their re-introduction on the west coast of Vancouver Island between 1969 and 1972, sea otters have returned to 25-33% of their historic range in BC (DFO, 2014). Although there have been sightings of sea otters around Haida Gwaii since 1972, most sightings have been of single animals, and no permanent or breeding populations have been established (Sloan & Dick, 2012). Sea otters only a few predators that include humans and sometimes orcas (*Orcinus orca*) in Alaska (Sloan, 2006; Reisewitz et al., 2005; Estes et al., 1998).

## **2.3 Ecosystem Services**

Amidst generally increasing environmental degradation, the United Nations Millennium Ecosystem Assessment (2001) highlights the importance of maintaining, rebuilding and enhancing ecosystem services, which are essential to human well-being. Ecosystem services are generally recognized as belonging to four categories: supporting, regulating, provisional, and cultural. These services are interdependent, relying on each other and intact, functioning ecosystems for them to maximize their utility. Kelp fulfils a wide range of services under these categories, and with the return of sea otters, areas known for kelp forest habitat have the potential to triple nearshore ecosystem productivity through trophic cascades and kelp recovery (DFO, 2014).

### **2.3.1 Supporting services**

Supporting services are the foundation for other services. They include the production of biomass, photosynthesis, and nutrient cycling (Smale et al., 2013; Jennings et al., 2001). Through nutrient absorption, including the conversion of dissolved inorganic carbon from the water column into biologically available carbon and the production of detritus, kelp recycles nutrients through coastal and marine ecosystems and supports a variety of life with detritus. Kelp provides an important supporting service for biodiversity which is “the variability among living organisms from all sources including...terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part; this includes diversity within species, between species and of ecosystems” (Thomson & Starzomski, 2007).

The northeast Pacific Ocean is known for having the greatest diversity of kelp species (Dayton, 1985). The productivity and functioning services of kelp forests are greater than terrestrial forests and support a wide variety of other species (Steneck et al., 2002). Kelp detritus supports complex food webs for herbivores, detritivores and microbes (Steneck et al., 2002). Food webs are feeding networks among species (Primack, 2010). Drifting kelp particles of different sizes supply sandy beaches, rocky intertidal areas, subtidal areas, and pelagic zones of the ocean with food (Duggins et al., 2016). In California, kelp composes 60–99% of beach-cast autotrophic detritus (Steneck et al., 2002). Kelp forests also provide feeding grounds for fish, birds and sea otters, and supports sessile organisms and animals that feed directly on kelp, like limpet and mussels (Duggins et al., 2016). The diversity of

kelp species and their contributions to oceanic and coastal food webs support species richness through biomass (Arenas et al., 2009).

Kelp also supports biodiversity through ecosystem engineering (Hondolero & Edwards, 2017). Kelp canopies reduce light availability thus providing a more suitable habitat for species that prefer lower light intensity which alters competition between algae species. While many species use these underwater forests for protection and reproduction, they also serve a variety of predators that hunt in the canopies. Some of the species associated with BC kelp forests include echinoderms like sea cucumbers (*Cucumaria miniate* and *Parastichopus californicus*) and gastropods like snails (*Tegula* sp., *Calliostoma* sp., and *Marguerites* sp.). Kelp forests also support a variety of fish species like the China and copper rockfish (*Sebastes nebulosus* and *S. caurinus*), juvenile yellowtail rockfish (*Sebastes flavidus*), black rockfish (*Sebastes melanops*), cabezon (*Scorpaenichthys marmoratus*), kelp greenlings (*Hexagrammos decagrammus*), lingcod (*Ophiodon elongates*), as well as sculpins, juvenile salmon, and spawning Pacific herring (Jamieson & Davies, 2004). Among the species inhabiting kelp forests are several listed under the *Canada Species at Risk Act* (SARA) (2002) such as the northern abalone (*Haliotis kamtschatkana*).

### **2.3.2 Regulating services**

Regulating services moderate environmental processes like climate and air quality by maintaining ecosystem functions like carbon absorption (Porzio, Buia & Hall-Spencer, 2011). Kelp sequesters carbon, reducing the acidity of ocean water. Kelp also regulates physical nearshore oceanic conditions by slowing local currents and reducing wave exposure that causes subtidal and shoreline erosion (Hondolero & Edwards, 2017). With its large canopies, kelp forests absorb and distribute wave energy, dampening waves, and slowing down water and substrate movement. As kelp forests develop and reach climax states, micro-environmental conditions tend to reduce wave stress and lower nutrient levels near the centre of the kelp forest, creating good spawning and juvenile habitat and supporting the recruitment of numerous species (Jamieson & Davies, 2004; Steneck et al., 2002). Biodiversity, in turn, provides supporting ecosystem services.

### **2.3.3 Provisioning services**

Provisioning services by kelp include the present and tangible historical significance to local Haida culture as well as products used globally. Provisioning services are ecosystem

products such as materials, food, and basic life necessities. Kelp presents a breadth of provisional services for human use such food, scientific chemicals, medicine, cosmetics, fertilizers, pesticides, aquaculture food, supplements in animal feed, and a renewable energy source (Smale et al., 2013; Bolton, 2010; Wheeler, 1990; Jamieson & Francis, 1987). Globally, kelp harvesting is a lucrative, billion-dollar commercial industry with commercial harvests occurring in Southern and Central California (Druehl & Clarkston, 2016; Tegner & Dayton, 2000); much smaller-scale important cultural use and harvesting also occur around Haida Gwaii and throughout the BC coast. Historically and currently, Haida harvest giant kelp, ngaal, for herring roe on kelp, k'aaw and dried kelp cakes or xaaydaa gulga (Turner, 2010). The roe on kelp can be dried or frozen and used for subsistence, traded for other items such as eulachon grease, which is a highly valued fish oil obtained from the mainland, or sold (Turner, 2010).

Traditional subsistence harvesting, as well as some recreational and commercial harvesting, of kelp, occurs on Haida Gwaii. Pacific herring (*Clupea harengus pallasii*) and herring spawn-on-kelp, known as k'aaw in Haida, occurs on *Macrocystis integrifolia*, *Egregia menziesii*, and *Laminaria saccharina* which provide substrates and habitat for herring and spawn (CHN, 2011; Sloan, 2006). The commercial spawn-on-kelp fishery was once a lucrative industry on Haida Gwaii but it has been closed since 2005 due to low herring abundances, and traditional fishery harvesting has also been challenging (MaPP, 2015; Jamieson & Francis, 1987).

In addition to being edible, bull kelp, hlkyaaama in Haida, is a functional plant historically used for fishing line, called tl'agaay, and anchoring Haida canoes (SHIP, 2016; Turner, 2010; Turner & Davidson, 2004). Bull kelp was also dried to store grease in the bulbs and upper stipes (Turner, 2010).

Sea otter furs were also highly valued product among the Haida before the maritime fur trade. They were used for clothing items worn by chiefs and high-ranking members of the community as well as bedding, insulation, and a symbol of social status (Salomon et al., 2015; Szpak, 2011). Sea otter fur is still used for Haida regalia today. While archaeological excavation of midden sites showed that the Haida hunted sea otters for millennia, it was exploitation during the fur trade era that led to their extirpation within a few decades (Szpak, 2011; Sloan & Bartier, 2000).

### **2.3.4 Cultural services**

Cultural services are generally considered the intangible benefits of ecosystems such as spiritual, recreational, cultural heritage, and aesthetic human experiences (Hernández-Morcillo et al., 2013). Kelp forests provide cultural services on a local, regional, national and international level. Kelp contributes to recreational activities including snorkelling, scuba diving, free diving, kayaking, wildlife-viewing, and fishing (Beaumont et al., 2008). Internationally, kelp and sea otters are iconic species, and the kelp forest ecosystem that they support is representative of natural and cultural heritage (Sloan & Dick, 2012). Biodiversity and individual species represent national and regional heritage (Alpin, 2002). Heritage value is “historical, cultural, aesthetic, scientific or educational worth” or use (BC Heritage Conservation Act, 1996). Kelp is identified as a key species of conservation value in the Valued Marine Environmental Features (VMEF) assessment for BC (Dale, 1997). Kelp, with its visible canopies, is an aesthetic and functional part of the nearshore seascape, and both sea otters and kelp forests are part of a coastal and spiritual identity. Kelp can also be valued for the preservation of its values for future generations. Likewise, recovering sea otter populations could potentially contribute to jobs in tourism and provide other benefits (Loomis, 2006). Viewing sea otters in the wild, like kelp, is considered a non-consumptive recreational use value, the possibility of seeing a sea otter in the wild in the future is an option value, and there is existence value of knowing that sea otters exist, even without seeing them (Loomis, 2006).

Sea otters, kelp forests, and urchins represent many levels of tangible and intangible importance to Haida culture. Haida Gwaii is and has been the home to the Haida, indigenous people, for over 14,000 years. The name Haida Gwaii translates to “islands of the people.” The Haida have a strong present and historical seafaring culture. They are reliant on a dominant marine diet and travel up and down the coast, historically in cedar canoes, but now with modern vessels (CHN, 2011). Haida culture represents a social-ecological system where culture is inseparable from the surrounding marine environment. The Gwaii Haanas Archipelago Management Board (AMB), which manages Gwaii Haanas, is represented by a Haida crest created by Giitsxaa, a Haida artist; the crest depicts a sea otter, *kuu* in Haida, holding a sea urchin, a design selected by Haida elders (Sloan & Dick, 2012). This image was chosen as a reminder of the archipelago’s vulnerable coastal and marine heritage and the impacts of human exploitation (Sloan & Bartier, 2000).

## 2.4 Blue carbon

The ocean spans 71% of the earth's surface and plays an essential role in climate regulation, including carbon sequestration (Chung et al., 2013). The International Panel on Climate Change (IPCC) (2013) defines a sink as, "any process, activity or mechanism that removes a greenhouse gas (GHG), an aerosol or a precursor of a GHG or aerosol from the atmosphere." The ocean is a carbon sink that has absorbed approximately one-third of anthropogenic CO<sub>2</sub> since the Industrial Revolution (DFO, 2017a). Marine vegetation, like mangroves, salt marshes, and seagrass meadows, represent nearshore habitats that can absorb and store carbon in sediments (Chung et al., 2013; Mcleod et al., 2011). Blue carbon is the term used to define carbon capture in biomass or sediment specific to the marine environment. Kelp has recently been identified as a potential source of blue carbon. The Haida Gwaii Marine Plan (MaPP, 2015) identifies size and connectivity of marine vegetation, possibly kelp, as a source of promoting ecosystem resilience and source of "blue carbon".

Whether kelp forests can be considered a source of blue carbon or not is disputed because kelp plants do not store carbon in sediment. Some macroalgal communities have shown high levels of tolerance for CO<sub>2</sub> and slight changes with increasing acidity (Porzio et al., 2011). Increasing absorption of CO<sub>2</sub> in ocean water is increasing acidity but the acidity level remains more alkaline in kelp forest areas, protecting and providing habitat for invertebrates and shellfish. Sediment-based systems, like marshes, are gaining recognition for long-term carbon storage, but kelp is regarded as a less valuable short-term form of carbon absorption through biomass production. Kelp forests, at a minimum, should be considered valued "carbon donors" because they grow quickly, absorbing carbon and creating large amounts of biomass that contribute to the detrital cycle (Trevathan-Tackette et al., 2015; Wilmers et al., 2012). Furthermore, large amounts of kelp biomass can accumulate in particular locations via ocean currents and may concentrate kelp-based carbon in ocean sinks where it is potentially stored for centuries (Chung et al., 2013). As much as 750,000 to 1,500,000 tonnes of kelp is estimated to be dislodged annually and floating in BC waters (Scagel, 1961). Carbon captured by kelp may dissolve and be recaptured through photosynthesis or returned to the atmosphere (Chung et al., 2013). Detritus is also decomposed by microbes and its energy transferred to the biological system. It becomes respired to CO<sub>2</sub> or stored as particulate and dissolved organic carbon in long-term blue carbon stocks, like salt marshes

(Hill et al., 2015; Trevathan-Tackette et al., 2015). Sea urchins may also represent some mechanism of carbon storage because of carbon capture in their calcium carbonate tests and long-life up to a century or more (Bhaduri & Siller, 2013).

Kelp contributions to carbon capture should also be considered in the context of potential natural and human-manufactured increases. With anticipated sea otter return, the future proliferation of kelp may be considered a greater source of carbon absorption. Furthermore, in recent years, commercial seaweed harvesting removed approximately 0.7 million tonnes of carbon from the sea annually, prompting the proposed expansion of kelp farming beyond the nearshore to increase carbon storage (Chung et al., 2013). For example, the creation of a series of natural and human-made kelp forests can absorb up to 10 tonnes of CO<sub>2</sub> per hectare annually (Chung et al., 2013). Furthermore, developments in bioengineering kelp into ethanol would not only contribute to carbon sinks but also reduce emissions (Smale et al., 2013). With the loss and destruction of numerous terrestrial carbon sinks due to deforestation and urbanization and in addition to increasing ocean acidity, the ocean and nearshore ecosystems' ability to absorb carbon becomes increasingly important as a potential source of carbon absorption and storage.

## **2.5 Stressors**

Anticipating, evaluating, and managing trophic cascades and ecosystem services requires an understanding of the direct and indirect stressors that deplete, degrade or destroy kelp forests (Cogan et al., 2009). Globally, kelp forests are facing numerous stressors and threats including herbivory, climate change, ocean acidification, introduced species, pollution, and oil spills (Duggins, Simenstad & Estes, 1989). The largest short-term threat to kelp forests is herbivory; however, the uncertain but anticipated impacts of climate change and oil spills are potentially catastrophic (Steneck et al., 2002).

### **2.5.1 Introduced and invasive species**

Concerns about introduced and invasive marine species include impacts to native species through competition (DFO, 2017b). Introduced and invasive algal competitors compete with kelp for space on the sea floor (Steneck et al., 2002). The threat of invasive species is higher near ports and populated areas where ballast water and hulls may be transporting foreign species or introduced from aquaculture (Sloan, 2006). Wakame (*Undaria pinnatifida*) and Japanese wire weed (*Sargassum muticum*) are two introduced and invasive Asian seaweeds

that were brought to BC via oysters and vessel hulls (Silva et al., 2002; Sloan & Bartier, 2000). The latter is present around Haida Gwaii (Sloan & Bartier, 2000). Due to the interconnected nature of the marine environment, the possibility of removing invasive seaweed species is low and rarely successful. In California, a multi-million-dollar project was implemented to successfully eliminate *Caulerpa taxifolia*, a green alga (Anderson, 2004), but such success stories like this are rare.

Recent introductions of invasive species, and potential algal competitors, to Haida Gwaii include two species of colonial tunicate, the violet or chain tunicate *Botrylloides violaceus*, and the golden star tunicate *Botryllus schlosseri* (DFO, 2016). Urchin barrens are recognized for lower diversity and coralline algal dominance making them and remaining kelp growth more susceptible to invasive species (Steneck et al., 2002). Tunicates are competitive over coralline algae which can outcompete kelp holdfasts (Konar & Iken, 2005). In general, the introduction of invasive species is recognized as a major and growing threat to biodiversity and ecosystem function (Sloan, 2006).

### **2.5.2 Herbivory**

Kelp forests have been identified as most threatened by herbivory, specifically from sea urchins (Graham et al., 2002; Steneck et al., 2002; Tegner & Dayton, 2000). Kelp forest trophic cascades provide some of the well-known and documented examples of top predator removal changing ecosystem structure and function (McCauley et al., 2012; Myers & Worm, 2005). On a global scale, sea urchin grazing has increased because of the removal of apex predators (Krumhansl et al., 2016; Steneck et al., 2002). While there are a number of other factors contributing to the decline of kelp forests, most deforestation between 40-60°N latitude is attributed to urchin grazing which is persistent and difficult to reverse (Watson & Estes, 2011). The primary herbivores eating kelp around Haida Gwaii are sea urchins. In the absence of sea otters, sea urchin barrens expanded to approximately twenty-three percent of the Haida Gwaii coastline (Sloan, 2006) where sea urchins have thrived on available kelp.

### **2.5.3 Climate change**

Climate changes pose a global and regional threat to kelp forests with a variety of potential and cumulative impacts. Global changes in seawater temperature, storm activity and acidity, spurred by climate change, are anticipated to increase wave height, change salinity and deep-water upwelling, and increase erosion and sedimentation (Harley et al., 2012; Sloan, 2006).

These changes are anticipated to impact kelp distribution and mortality especially through increases in the intensity and frequency of severe storms which naturally destroy kelp forests (Krumhansl et al., 2016; Smale et al., 2013; Harley et al., 2012; Steneck et al., 2002; Dayton, Tegner, Edwards & Riser, 1998; Wheeler et al., 1986; Dayton, 1985). Globally, climate-driven temperature change acts synergistically with other stressors, such as the loss of apex predators, affecting patterns in kelp distribution (Krumhansl et al., 2016). Warming temperatures are also expected to have wide-reaching effects on kelp forest structure, distribution, productivity, and resilience (Smale et al., 2013)

As on land, marine species like kelp are anticipated to shift towards higher latitudes as global warming continues (Koch et al., 2013). In Queen Charlotte, Haida Gwaii, ocean surface temperatures increased by 1.6°C in the 20<sup>th</sup> century (Sloan, 2006). Warmer water kelp species at lower latitudes may increase while species at higher, cooler, latitudes may decrease, affecting nearshore community structure and function (reviewed in Smale et al., 2013; Steneck et al., 2002). Most evidence of species changes in response to climate change are anecdotal. For example, a recent increase in the warmer water kelp *Egregia* was observed around Vancouver Island; this increased *Egregia* growth is occurring in areas previously dominated by colder water species, *Alaria* and *Saccharina sessilis* (reviewed in Druehl & Clarkston, 2016). A large-scale shift of *Saccharina latissima* observed off the coast of Norway in 2002 was attributed to both pollution and climate change (Moy & Christie, 2012). Warm nutrient-depleted waters, such as El Nino events, reduce the average size and growth of kelp because nitrate, which boosts kelp growth, is reduced and becomes absent in waters that are 16°C and higher (Steneck et al., 2002).

#### **2.5.4 Ocean acidification**

While the ocean is typically alkaline, increasing absorption of CO<sub>2</sub> reacts in water to create carbonic acid, H<sub>2</sub>CO<sub>3</sub>, which increases ocean acidity and threatens marine life, especially calcium carbonate shells or exoskeletons. In BC, the Pacific naturally contains high levels of CO<sub>2</sub> concentrations from seasonal upwelling but increasing levels of CO<sub>2</sub> resulting from anthropogenic carbon production has decreased pH levels by 0.1 units over the past two centuries (DFO, 2017a). Much is still unknown about what increasing acidity means for coastal ecosystems, but it is expected to thin and deform the shells and skeletons of numerous marine species with calcified structures like plankton, corals, coralline algae, and other invertebrates (Doney, Fabry, Feely & Kleypas, 2009). Increasing acidity is expected to

facilitate the proliferation of non-calcified, or fleshy, species, especially turf-forming algae that are expected to thrive under increased temperature and CO<sub>2</sub> conditions (Smale et al., 2013). Increases in turf-forming algae may have a detrimental impact on biodiversity, trophic relations, nutrient cycling, and species' habitat (Smale et al., 2013).

### **2.5.5 Oil Spills**

Potential spills from the frequency and magnitude of fuel shipments and vessel traffic present a catastrophic and long-term threat to the marine environment. As marine transportation increases on the west coast of BC, so does the threat of fuel spills, requiring improved risk evaluation and spill response, and knowledge of potential impacts and ecosystem recovery. The marine transport of fuels is especially topical because of the potential development of projects like the Enbridge Northern Gateway Pipeline, which intended to ship crude oil in tankers out of Kitimat, and around Haida Gwaii, to international markets. Increased shipping of goods along the BC north coast and potential increased tanker traffic raises the risk of hydrocarbon spills. The growing threat of spills and the long-term damage resulting from a spill as well as spill clean-up methods are still poorly understood and a significant social and ecological concern for the coast.

For Haida Gwaii, detailed baseline data about nearshore marine ecosystems is necessary to determine coastal vulnerability to potential spills. Haida Gwaii has been declared an area “most at risk from oil spills, based on intensity of shipping activity” (DFO, 2014). Oil spills can have cascading effects on many interconnected species within an ecosystem (Sloan, 2006; Carls et al., 2001). Historical spills like the *Nestucca* barge in 1988 and the *Exxon Valdez* tanker in 1989 are indicative of the type and magnitude of threat presented by vessel traffic and fuel transport. Mapping is essential for identifying pre-impact baseline data and priority areas for protection, clean-up response and appropriate clean-up methods. The government of BC developed the *Marine Oil Spill Prevention and Preparedness Strategy*, which calls for coastal sensitivity and vulnerability analyses and mapping (BC Ministry of Environment, 2013). The original strategy was developed in 1991 as a response to the *Exxon Valdez* and *Nestucca* spills. The absence of pre-impact baseline data for the *Exxon Valdez* made it impossible to distinguish between pre- and post-ecological states and to measure the amount of damage done, either by the spill itself or from the clean-up methods (Towbridge, Baker & Johnson, 2002).

Oil spills have been identified as the greatest threat to the recovery of the sea otters (DFO, 2014). With anticipated sea otter return to Haida Gwaii and recognition of the importance of kelp forests, the future growth and health of kelp forests depends on healthy and expanding sea otter populations and their protection from oil spills. An oil spill would be a devastating loss for potential and existing kelp both directly and indirectly.

## **2.6 Marine governance and management**

### **2.6.1 Ecosystem-Based Management**

The ocean environment is complex and immensely important for its roles in temperature regulation, oxygen production, carbon absorption, and general life support. As we improve our understanding and appreciation of the interconnected ocean environment and its natural limits, there is growing support for applying EBM in ocean management (Curtin & Prellezo, 2010; Sloan, 2006). In general, EBM is recognized as a management approach with best practices for addressing ecosystem health and human interests (Curtin & Prellezo, 2010). In theory, EBM practices a worldview that integrates humans and non-human benefits and provides the best possible model for managing human behaviour and impacts. Levin & Lubchenko (2008) define marine EBM in greater detail as:

...the application of ecological principles to achieve integrated management of key activities affecting the marine environment. EBM explicitly considers the interdependence of all ecosystem components, including species both human and nonhuman, and the environments in which they live. EBM classically defines boundaries for management on the basis of ecological rather than political criteria, although certainly the political contexts of management must be considered. The goal of marine EBM is to protect, maintain, and restore ecosystem functioning in order to achieve long-term sustainability of marine ecosystems and the human communities that depend on them.

EBM can also be considered part of the planning, implementation, and outcome of natural resource management.

The CHN advocates for the application of ecosystem-based approaches to natural resource management on Haida Gwaii. EBM objectives are part of the Haida Gwaii Strategic Land Use Agreement between the Province of BC and the Haida Nation. EBM is represented in the Haida worldview and enshrined in *The Constitution of the Haida Nation* (CHN, 2017a) which states:

The Haida Nation is the rightful heir to Haida Gwaii. Our culture is born of respect; and intimacy with the land and sea and the air around us. Like the forests, the roots of our people are intertwined such that the greatest troubles cannot overcome us. We owe our existence to Haida Gwaii. The living generation accepts the responsibility to ensure that our heritage is passed on to following generations. On these islands our ancestors lived and died and here too, we will make our homes until called away to join them in the great beyond.

Use of EBM by the DFO is defined as long-term management and support for environmental, social, and economic success based on ecosystem health. Ideally, EBM presents a more holistic approach to natural resource management than western sectoral approaches (Sloan & Dick, 2012; Crowder & Norse, 2008). EBM is designed to overcome the typical shortcomings of sectoral management approaches that lack consideration for interactions between activities, cumulative impacts, ecosystem services, and explicit trade-offs between activities (Halpern et al., 2008).

In a study of effective EBM, a key re-occurring barrier to successful EBM was complexity (Tallis et al., 2010). With a more holistic vision of human and environmental welfare, EBM aims to accommodate a better understanding and recognition of the compounding challenges, drivers and impacts on ecosystem function. Unlike siloed sectoral management systems, EBM accounts for the intricate dependencies and relationships that explain multiple and cumulative effects on the environment (Crowder & Norse, 2008). However, there is a disconnection between the theory of EBM and its application in practice, attributed to a lack of specificity in management plans applying an EBM approach and difficulties surrounding stakeholder engagement, participation and conflict (Arkema et al., 2006). To address the complexity and cross-disciplinary nature of natural resource management, a key part of the EBM process is to communicate context, opportunities, limitations, and benefits of management to all stakeholders (Cogan et al., 2009).

### **2.6.2 Marine Spatial Planning**

The purpose of MSP is to recognize the values and consequences of multiple and conflicting uses in the same area (Crowder & Norse, 2008; Douvere, 2008; Halpern et al., 2008; Saaty, 1987). MSP is defined as:

... a mechanism for the integrated management of marine areas in which a central vision for the future of the marine area, in conjunction with knowledge of activity interactions and impacts, guides the location, timing, intensity and future development of all activities in the marine space (McCrimmon and Fanning, 2011).

Demonstrating the presence and potential presence and area of a resource and associated services affords some recognition of the value and registers the possible risks and trade-offs resulting from conflicting activities or risks and the management decisions that could negatively affect areas of kelp forests (Halpern et al., 2008). Identifying multiple and conflicting uses and subsequent trade-offs also contribute to EBM (Halpern et al., 2008). Spatial mapping and management of kelp can also be used in concert with other spatial data representing human activities like shipping. MSP is an essential part of communication, organization, and understanding of human interactions with natural resources for the effective development and implementation of EBM.

Spatial planning and management is standard practice in terrestrial EBM. On land or in the marine environment, spatial planning can be defined as an organization tool used for analyzing and management which may include comprehensive approaches, strategic assessments, and zoning (Albert et al., 2017). MSP is part of the solution to address the challenges of implementing EBM (Halpern et al., 2008). It is a major tool for understanding the complexity of the marine environment, engaging stakeholders, and implementing management goals set by EBM through an inclusive, rational, and value-based process (Takeda & Ropke, 2010; Ehler & Douvère, 2009). The concept of MSP is not new to natural resource management, but in the marine environment, it is associated with the designation of MPAs and underutilized for general management issues (Douvère, 2008).

Once habitat boundaries are defined, particular ecosystems can be studied and monitored, and human activities can be managed more coherently to maintain the integrity of ecosystem function. Without adequate amounts of data at appropriate scales, MSP and management are challenging to develop and apply. By mapping the presence and distribution of marine features, it is possible to define or approximate spatial boundaries and manage those features (Crowder & Norse, 2008; Ruckelshaus, Klinger, Knowlton & DeMaster, 2008). The identification and mapping of ecologically significant sites have been identified as a key step to preserving and promoting a healthy marine environment under the MPA Strategy (2005) and the *Oceans Act* (1996). The strategy also strives to connect MPAs with other conservation objectives. The creation of MPAs is dependent on the knowledge of the distribution and size of sensitive marine ecosystems, habitat, and ecosystem services.

Planning and mapping need to be conducted at appropriate scales to match activities and ecosystem services through the identification of habitat and species distribution (Grega et al., 2013; Cogan et al., 2009; Halpern et al., 2008; Greene et al., 2007; Greene et al., 2005). Greater mapping details help maximize zoning application (Albert et al., 2017; Greene et al., 2007; Greene et al., 2005). Finer scales and resolutions incorporate the heterogeneous benthic environments that often have many variations in depth, substrate type, slope, and rugosity (Halpern et al., 2008; Greene et al., 2007). Furthermore, the nearshore environment is highly dynamic including inter-annual and seasonal changes that contribute to fluctuations in kelp biomass and species composition. To effectively map kelp, bathymetry data should be mapped at a macrohabitat scale of no more than 1: 50,000 to identify potential habitat characterization that may be 1-10 m in size (Greene et al., 2007).

A spatial multiple-criteria analysis is one means of guiding the assessment of activities, uses, and objectives for particular areas or zones using GIS (Villa et al., 2002). Stakeholders may assign weights of relative importance to features and ecosystem services by area, creating an analytical hierarchy process (Villa et al., 2002), which can facilitate numerical trade-offs in decision-making (Saaty, 1987). Once spatial areas and values, like kelp, have been identified and quantified by area in detail, it is possible to qualify, rank, and weigh the importance of particular features and uses. Aggregation of raw data into variables for comparison is a challenging part of the process, in addition to deciding which variables to use and how to classify them (Villa et al., 2002). Spatial data should also be economically and ecologically analyzed as well as context-specific (Stelzenmuller et al., 2013; Troy & Wilson, 2006; Villa et al., 2002). Layers related to kelp forest management could include associated individual species like rockfish, marine vessel traffic, fisheries activities and cultural values.

### **2.6.3 Ecological economics**

Ecosystem services are essential to life on earth (Costanza et al., 1997). Assigning a monetary value to ecosystem services is expected to promote a greater appreciation of ecological benefits that often go undervalued or not valued at all, particularly for their role in human well-being and policy decisions (Troy & Wilson, 2006). While there are many inherent challenges to assigning a monetary value to ecosystem services, the estimated minimum value of global ecosystem services was \$33 trillion US dollars in 1997 (Costanza et al., 1997). The World Bank (2006) estimated global wealth as a sum of produced, natural

and intangible capital. It recommends that nations keep accounts of physical assets and links environmental sustainability to a higher GDP and poverty reduction rate. Kelp represents substantial economic importance relative to the broad array of ecosystem services it provides and their far-reaching effects, which have been economically significant to coastal cultures for millennia (Steneck et al., 2002).

While the direct provisioning services of kelp forests may have an assigned monetary value, there are also non-use qualities where kelp could be recognized for its option or bequest value (Hernández-Morcillo et al., 2013). The recognition and quantification of ecosystem services is an important part of understanding and integrating the contributions kelp makes to coastal and marine management. Provisioning services can be measured by biomass quantified by area or nutrients calculated from biomass (Srivastava & Vellend, 2005). Non-use values include option or bequest values which are “the potential value of the resource for future (direct or indirect) use” (Park & Allaby, 2017) and availability (Krutilla, 1967). Non-use values may also include cultural importance that is difficult to assign monetary value to due to its intangible and subjective nature (Oleson et al., 2015). Not even tangible ecosystem services and functions can necessarily be valued as equivalent to a one-to-one ratio (Costanza et al., 1997). While it is more feasible to identify the tangible presence of some ecosystem services, it may still be difficult to assign a value (Beaumont et al., 2007). Part of calculating value involves recognizing ecosystem services as a public good (Costanza et al., 1997). Economic, cultural, and ecological analyses can evaluate and weight value assigned to ecosystems according to the services they provide (Hernández-Morcillo et al., 2013; Stelzenmuller et al., 2013; Troy & Wilson, 2006; Villa et al., 2002).

#### **2.6.4 Ecological restoration and resilience**

Restoration has growing importance in legislation and our understanding of what constitutes a healthy and resilient ecosystem. Ecological restoration is the “process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed” (Parks Canada Agency, 2008). A restored ecosystem “contains a characteristic assemblage of the species that occur in the reference ecosystem and that provide appropriate community structure” (Parks Canada Agency, 2008). The process of restoration may require the removal or modification of a specific disturbance or stressor, which allows for independent ecological recovery. To envision and restore kelp forest ecosystems around Haida Gwaii, a reference state would likely be from the pre-fur trade era and restoration would involve the removal

of sea urchins, the stressors (Sloan & Bartier, 2000; Duggins, 1980). A ‘restored’ ecosystem may not exactly replicate a past state, but it may achieve the most practical extent of species recovery, or recovery of the groups necessary for a potential or existing functional, developing, and stable restored ecosystem (Parks Canada, 2008). There may be several different forms of equilibrium densities for sea otters depending on site-specific qualities such as herbivore recruitment patterns and sea otter behavioural patterns (Estes et al., 1989).

In 1987, the Haida Nation and the provincial government applied to the BC Wildlife Branch to reintroduce sea otters from Alaska (Salomon et al., 2015; Sloan & Dick, 2012). A debate ensued over the preference for natural recolonization versus active restoration by transplanting sea otters from Alaska (Sloan and Dick, 2012). The application was eventually denied on the recommendation of DFO (Salomon et al., 2015). Currently, there are some management initiatives that would benefit from the recovery of kelp through the natural return of sea otters and the restoration of trophic cascades. The recovery of sea otters to the Haida Gwaii archipelago is consistent with the Haida Gwaii Marine Plan (2015), Management Plan for Sea Otters (2014), and the Multi-Species Action Plan for Gwaii Haanas (2016) that contributes to species management under *SARA* (2002). The potential for kelp recovery and its associated benefits are supported by community values and EBM goals. The Haida Gwaii Marine Plan (2015) vision states:

We see a future for Haida Gwaii that has healthy, intact ecosystems that continue to sustain Haida culture, all communities, and an abundant diversity of life, for generations to come. We will respect the sea around us and restore a balance between marine resource use and the well-being of life of the ocean.

Kelp, specifically, is discussed throughout the Haida Gwaii Marine Plan (MaPP, 2015) as an ecologically valued and significant marine feature to be considered for monitoring and protection. Sea otters were classified as endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in 1978, down-listed to threatened in 1996 and then classified as a species of special concern in 2009 due to continued population growth and range expansion along BC mainland coast and north and west coasts of Vancouver Island (DFO, 2014). The objective of the Management Plan for the Sea Otter (*Enhydra lutris*) in Canada (DFO, 2014) is:

... to conserve abundance and distribution as observed in 2008, and promote the continued population growth and expansion into formerly occupied regions such as Haida Gwaii, Barkley Sound, and north mainland British Columbia coast.

The management plan explicitly recognizes the importance of kelp for sea otter rafting habitat and highlights the keystone role of the sea otter in promoting the growth of kelp and subsequent habitat for other species (DFO, 2014). Finally, the *Multi-Species Action Plan for Gwaii Haanas* (2016) explicitly identifies kelp as a possible opportunity for restoration and highlights its contribution to northern abalone habitat.

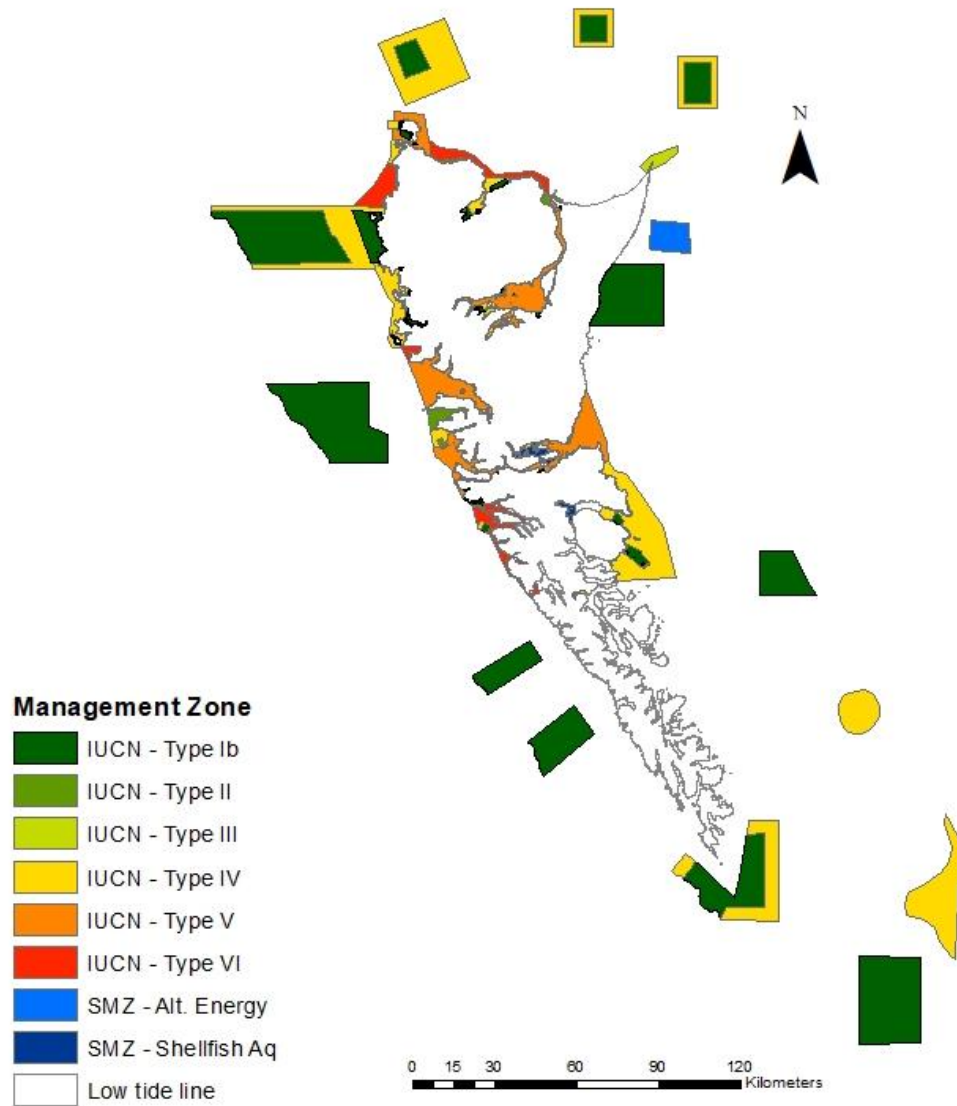
A restored ecosystem may have changes that occur naturally, departing from the state of the reference ecosystem but maintaining ecosystem resilience (Parks Canada Agency, 2008). The terms ecosystem robustness and resilience are used interchangeably to refer to ecosystem health and the ability to provide ecosystem services while resisting threats to ecosystem function and productivity. Ecological resilience is “the capacity of systems to keep functioning even when disturbed” (Levin & Lubchenko, 2008). Although resilience is often interpreted as the ecological ability to recover after a disturbance, it may also refer to the ability to maintain function during a disturbance.

## 3 Research Methods

### 3.1 Study site

My study site was Haida Gwaii, an archipelago of islands located on the northern coast of British Columbia, Canada, in the northeast Pacific Ocean between latitudes 52°N to 54°N. At a distance of 120 km by ferry from the mainland, Haida Gwaii is the most remote archipelago in Canada (Sloan & Dick, 2012) with approximately 4660 km of shoreline and 3674 islands (Bartier & Sloan, 2007). Ocean temperatures in this region range from 5–14°C in the winter and 10–18°C in the summer (Druehl & Clarkson, 2016). The west coast of Haida Gwaii sits on the edge of the continental shelf where upwelling contributes to nutrient exchange and ecosystem productivity in a cool and rich marine environment preferred by kelp (Sloan, 2006). Highly valued cultural and ecological marine features are identified and zoned in the Haida Gwaii Marine Plan (MaPP, 2015) including kelp (Figure 5).

Numerous species of kelp and sea urchins currently occur on Haida Gwaii and there are occasional sightings of lone sea otters (Figure 6). Nineteen species of kelp around Haida Gwaii (Table 1; Saunders & McDevit, 2014) and their depth and spatial extent reflect the ecology of this cold temperate biogeographical region (Druehl & Clarkson, 2016). Three nearshore species of sea urchins are common in coastal waters: red sea urchins are the most ubiquitous and largest species; purple sea urchins (*S. purpuratus*) prefer shorelines with high wave exposure, and green sea urchins (*S. droebachiensis*) are generally less abundant than the other two. Red sea urchins tend to be the most abundant in urchin barrens, with some urchin barrens on the west coast dominated by purple sea urchins (L. Lee, personal communications). Sea otters were extirpated from Haida Gwaii by the early 20<sup>th</sup> century, before 1920 (Sloan & Dick, 2012). Of the three subspecies of sea otters – *Enhydra lutris kenyoni*, *E. lutris nereis*, and *E. lutris lutris* – the first is native to the Haida Gwaii archipelago.



*Figure 5. Haida Gwaii Marine Plan protected zones with IUCN and special management zones. The zones classifications include Wilderness area (Ib); National park (II); Natural monument or feature (III); Habitat/species management area (IV); Protected landscape or seascapes (V); and, Protected areas with sustainable use of natural resources (VI). Areas not zoned are considered part of the general management area (MaPP, 2015).*

Table 1. Kelp species found on Haida Gwaii (Saunders and McDevit, 2014)

Family	Species
Alariaceae	<i>Alaria marginata</i> <i>Lessoniopsis littoralis</i> <i>Pterygophora californica</i> <i>Pleurophycus gardneri</i>
Costariaceae	<i>Agarum clathratum</i> <i>Agarum fimbriatum</i> <i>Costaria costata</i>
Laminariaceae	<i>Cymathaere triplicata</i> <i>Laminaria druehlui</i> <i>Laminaria ephemera</i> <i>Laminaria setchellii</i> <i>Laminaria yezoensis</i> <i>Macrocystis pyrifera</i> <i>Nereocystis luetkeana</i> <i>Saccharina groenlandica</i> <i>Saccharina latissima</i> <i>Laminaria sessilis</i>
Lessoniaceae	<i>Egregia menziesii</i> <i>Eisenia arborea</i>

## 3.2 Habitat modelling and data sources

A spatial model of potential kelp habitat around Haida Gwaii was constructed using available secondary source datasets on physical factors expected to influence kelp distribution. The factors included depth as a proxy for light availability, substrate type, and wave exposure (Grega et al., 2013; Gorman et al., 2013; Greene et al., 2007; Booth, Hay & Truscott, 1996; Wheeler et al., 1986). A bottom-up classification scheme was applied in ArcGIS Version 10.4 using Spatial Analyst, which layered thematic shapefiles and predicted habitat suitability from overlapping polygons of georeferenced abiotic data. The bottom-up classification scheme enabled continuous datasets to connect themes across layers by polygon area (Greene et al., 2005).

### 3.2.1 Depth as a proxy for light availability

Light is important at all stages of the kelp life cycle (Dayton, 1985). Depth was used as a proxy for light availability, which is one of the factors limiting kelp distribution (e.g., Bekkby & Moy, 2011). Known depths of kelp vary by species and can be influenced by sea urchin herbivory (Table 2; Sloan, 2006; Breen et al., 1982; Breen et al., 1976). At the edge of its northern range, *Macrocystis* grows most dense up to approximately 10 m chart datum depth (Sloan & Bartier, 2000). Depth strata for the potential kelp habitat model were based on Gorman et al. (2013), Sloan (2006), Gregr et al. (2013), and Emmett et al. (1995). Sloan (2006) modelled nearshore habitat, including kelp, to 20 m. Gorman et al. (2013) modelled kelp at a 48°N latitude from the lowest tide line to 15 m. Emmett et al. (1995) recorded *Laminaria setchelli* at up to 20 m depth on the central coast. Finally, Gregr et al. (2013) set the end of the photic zone for nearshore mapping in BC at 20 m depth. Based on a literature review, thresholds for upper and lower kelp growth in the potential kelp habitat model were assumed to range from 1 m above (lower intertidal) to 20 m below chart datum (Figure 6).

Urchin barrens occur immediately below kelp forests (Sloan, 2006; Figure 6). Urchins were observed up to the low low tide level in the Goose Islands on the central coast of BC and in Gwaii Haanas (Emmett et al., 1995). Red sea urchin habitat ranges down to 20 m, and greater, and has been modelled in the nearshore shallow subtidal habitat around Gwaii Haanas up to 20 m chart datum depth (Gregr et al., 2013; Sloan, 2006). While sea urchin habitat may extend to greater depths than kelp, the depth parameters for the urchin habitat model were set from zero to 20 m chart datum depth to assess habitat overlaps of urchin barrens in potential kelp habitat.

A secondary source bathymetry dataset was used to model the depth parameters. The bathymetry dataset consisted of multibeam sonar data collected by the Canadian Hydrographic Service (CHS) and processed by Gwaii Haanas Parks Canada (2015) into a raster dataset at 20 m<sup>2</sup> resolution (Figure 7). The bathymetry data was continuous with point data densities of up to one data point per 2 m<sup>2</sup> in some locations.

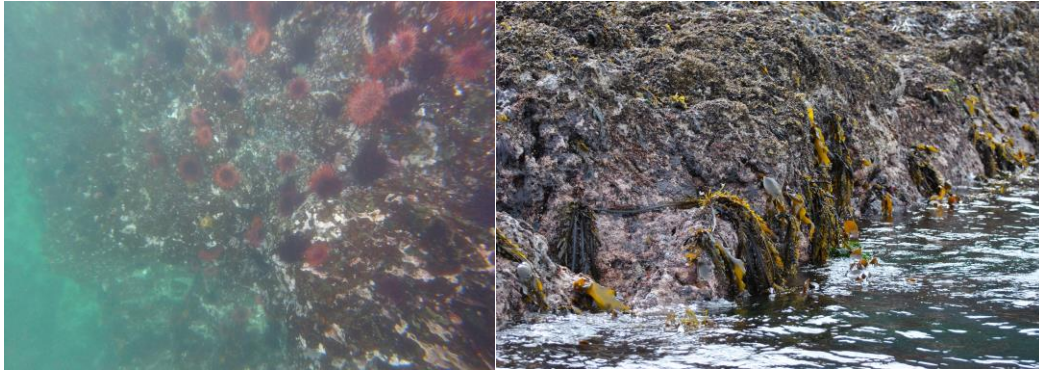


Figure 6. Shallow subtidal red sea urchin barrens just below the lowest tide (left), and intertidal kelps *Egredia menziesii* and *Alaria* just above the lowest tide (right), along northeast Burnaby Island, Gwaii Haanas. Photo credit: C. Houston.

Table 2. General preferred depth zones of Haida Gwaii kelp species (Sloan, 2006).

Species	Depth zone
<i>Agarum</i> spp.	Subtidal
<i>Alaria marginata</i>	Lower intertidal and subtidal
<i>Costaria costata</i>	Lower intertidal and subtidal
<i>Egredia menziesii</i>	Lower intertidal and subtidal
<i>Laminaria</i> spp. <sup>1</sup>	Lower intertidal and subtidal
<i>Macrocystis pyrifera</i>	Subtidal
<i>Nereocystis luetkeana</i>	Subtidal
<i>Saccharina latissimi</i>	Lower intertidal and subtidal

<sup>1</sup>Includes *Saccharina groenlandica* (formerly *Laminaria groenlandica*) and *Saccharina sessilis* (formerly *Laminaria sessilis* and *Hedophyllum sessile*).

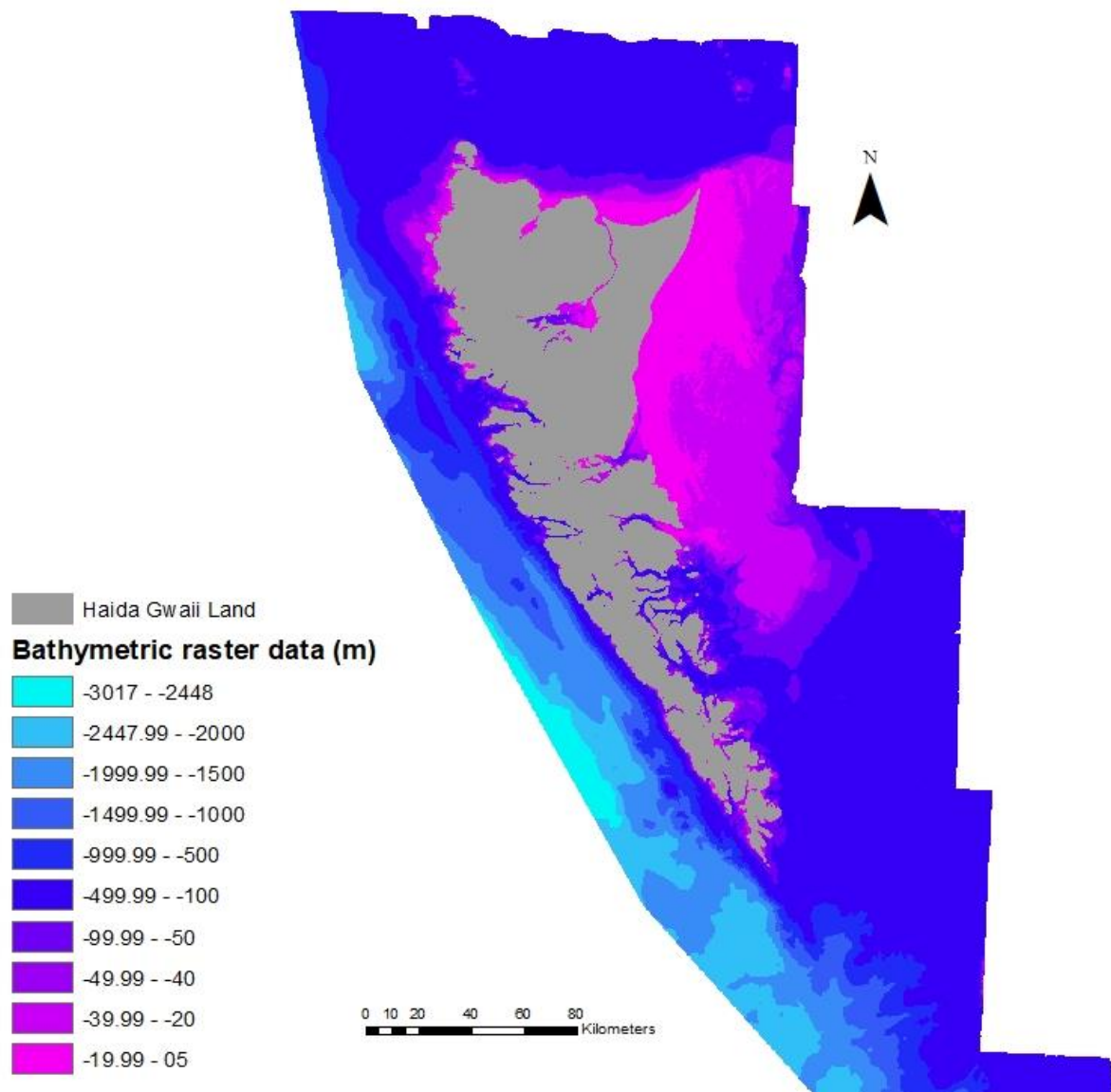


Figure 7. Bathymetry data showing depth raster for Haida Gwaii (Gwaii Haanas Parks Canada, 2015).

### 3.2.2 Substrate

Most kelp forests grow on hard substrates (Dayton, 1985). Kelp generally prefers hard surfaces and cobble but may grow on any substrate where it can establish a holdfast (Table 3). However, it may not be able to persist in areas with less stable substrates and higher exposures because small blades, gametophytes, and juvenile sporophytes are vulnerable to scouring and suffocation from sedimentation (Wheeler et al., 1986; Dayton, 1985). Therefore, hard substrates and mixed substrates under appropriate exposure conditions were selected for suitable kelp habitat.

Substrate data used in the model was a consolidated secondary source dataset of continuous substrate mapping defined as BoPs (Grega et al., 2013; Figure 8). BoPs share similar substrate type and depth characteristics and are intended to link species to bottom type (Grega et al., 2013). Data sources for the BoP dataset were organized in a hierarchical and standardized bottom type classification system that contained sufficient detail to be ecologically significant because of the strong association between species and physical habitat characteristics (Grega et al., 2013).

Bottom patches used multiple sources of data inputs. BoPs included depth, rugosity, physical energy and available substrate type data points from herring and shellfish dive surveys with data contributions from Parks Canada Agency (PCA) and Canadian Hydrographic Service (CHS) surveys, BC ShoreZone mapping, and Natural Resources Canada (NRCan) surveys (Grega et al., 2013). The dataset included bottom patches up to 50 m and divided into four contoured intervals of 0-5 m, 5-10 m, 10-20 m and 20-50 m. Bathymetry data was provided as a 75 m-resolution raster dataset from Natural Resources Canada and a rugosity and physical energy, i.e. from tidal energy and sediment transfer, dataset to provide a continuous background (NRCan; Grega et al., 2013). For areas lacking data, information from observational and grab-sampled survey areas produced Thiessen polygons which are created from an equidistance of surveyed bathymetry points (Grega et al., 2013). Grega et al. (2013) also used line data vertexes from ShoreZone data to create Thiessen polygons.

Available data for the 0-5 m depth included ShoreZone classification of coastal habitats. For 5-10 m depth, substrate data from shellfish and herring spawn dive surveys provided by DFO and Parks Canada was used. Grab samples were also available for this depth range from CHS and PCA-supported multi-beam acoustic ground-truthing surveys to verify depth and substrate type. For 10-20 m depth, lower sample resolution was available from dive surveys and CHS hydrographic survey samples.

The final bottom patch data layer was comprised of primary and secondary bottom type attributes. The primary attribute, BType-1, indicated whether the polygon substrate was Hard (1), Mixed (2) or Soft (3), as determined by an 80:20 rule (Table 4). For example, a classification of Hard substrate threshold was “more than 80% veneer of boulder-cobble over sand” (Grega et al., 2013). Mixed substrate referred to “the patchy nature of nearshore substrates such as sand-mud drapes over bedrock, and discontinuous veneers of boulder-

cobble over sand bottom” (Grega et al., 2013). Mixed substrates were expected to support both infaunal and epibenthic communities. Polygons classified as Soft substrate were excluded from the models of potential kelp and urchin distribution under the assumption that they do not provide a sufficiently stable substrate for anchoring of kelp plants and persistence of urchins.

The secondary attribute, BType-2, provided further detail about the type of substrate within each BoP (Table 4). The BType-1 Hard class included secondary classes of dominant bedrock (a), or boulders and cobble (b) (Grega et al., 2013). The BType-1 Mixed layer included BType-2 classifications of cobble, gravel, pea gravel and whole shell (a), and sand to pebbles and may also include wood debris, sand and whole shell (b) (Grega et al., 2013). Mixed BType-2 ‘b’ was excluded from the potential kelp and urchin models because it included unconsolidated soft substrates presumed to provide poor anchorage for kelp plants. BType-2 classification with a null value had no available secondary classification attribute (Table 4).

*Table 3. Preferred substrate types for Haida Gwaii kelp species fit according to the BoP substrate classification system (adapted from Sloan, 2006).*

<b>Species</b>	<b>Substrate type*</b>
<i>Agarum clathratum</i>	Hard, Mixed, Soft
<i>Alaria marginata</i>	Hard, Mixed (a)
<i>Egregia menziesii</i>	Hard
<i>Laminaria bongardiana</i>	Hard, Mixed (a)
<i>Laminaria setchellii</i>	Hard, Mixed (a)
<i>Lessoniopsis littoralis</i>	Hard (a)
<i>Macrocystis pyrifera</i>	Hard, Mixed (a)
<i>Nereocystis luetkeana</i>	Hard, Mixed (a)
<i>Saccharina latissimi</i>	Hard, Mixed (a)

\* Substrate types refer to Table 3.

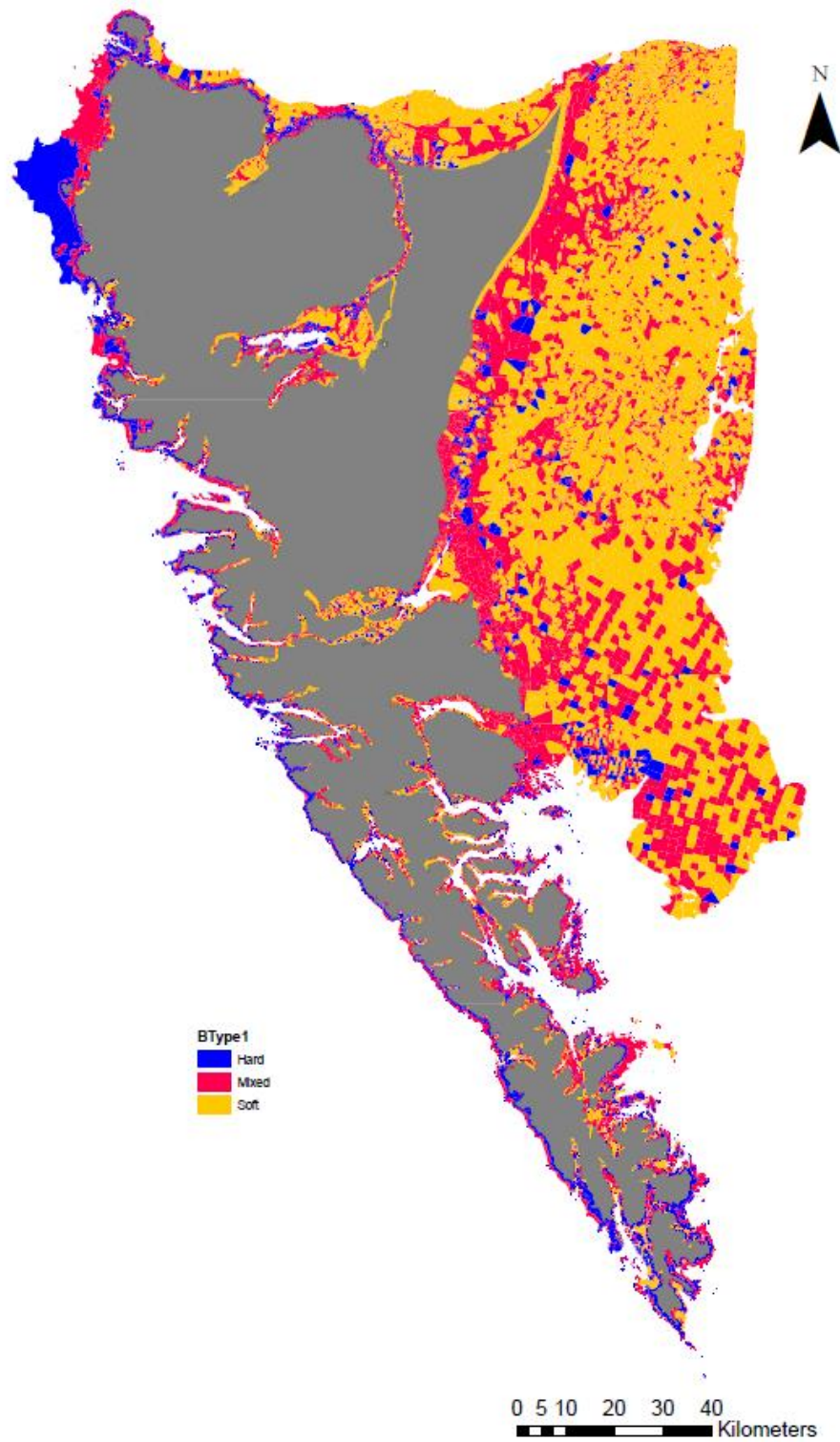


Figure 8. BType-1 polygons for Haida Gwaii (data from Gregr et al., 2013).

Table 4. Hierarchical bottom patch substrate classifications (Grega et al., 2013).

<b>BType-1</b>	<b>BType-2*</b>	<b>BType-2 descriptions</b>
1 (Hard)	Null	
	A	Bedrock dominant
	B	Boulder and/or cobble dominant
2 (Mixed)	Null	
	A	Primarily soft with patchy cobble/gravel
	B	Sand to pebbles
3 (Soft)	Null	
	A	Sand/shell
	B	Mud

\*Null indicates no available secondary attribute for substrate classification.

### 3.2.3 Wave exposure

In addition to depth and substrate type, wave exposure is a major determinant for biota along shorelines. Wave exposure dominates and controls shoreline morphology and sediment distribution (Howe et al., 1997). Exposure is a major contributor to kelp mortality (Dayton, 1985). General wave exposure preferences for kelp species and urchins (Table 5; Sloan, 2006) were used to define parameters for the potential kelp and urchin habitat models: Protected to Very Exposed for the kelp model and Semi-protected to Semi-exposed for the urchin model (Table 6).

Publicly-available BC ShoreZone wave exposure data, in the form of continuous polylines spanning relative wave exposure in six categories ranging from Very Protected to Very Exposed (Table 6), was accessed from the BC Marine Conservation Analysis (BCMCA) (2011) (Figure 9). ShoreZone exposure units were made from groups of similar exposure and tidal features and calculated by “standard engineering practices for estimating wave heights for a particular wind speed and direction” (Howe et al., 1997). Morphology or substrate may vary between units, but the orientation of the coast and fetch windows were similar (Howe et al., 1997). The exposure layer relied on fetch data, “the openwater area offshore from the Shore Unit over which waves can be generated by winds - the larger the fetch window, the greater the wave exposure” (Table 6). To incorporate the exposure data from ShoreZone into the potential models, polyline data had to be converted into polygon data. In ArcGIS, polyline data was converted into point data, and Thiessen polygons were made from the point data (Figure 10; Grega et al., 2013).

Table 5. Wave exposure preferences of different kelps and urchin barrens (Sloan, 2006).

Bioband	Description	Wave exposure
Urchin barrens	Pale pink, bleached-looking encrusting coralline red algae in the shallow subtidal, where red sea urchin ( <i>Mesocentrotus franciscanus</i> ) have grazed away all other algae leaving bare-looking substrate	Semi-protected to Semi-exposed or current-dominated
Giant kelp	Nearshore canopy-forming giant kelp ( <i>Macrocystis integrifolia</i> ) forests; fronds have long stipes with numerous small bulb floats, each with terminal blades	Protected to Semi-exposed
Bull kelp	Nearshore canopy-forming bull kelp ( <i>Nereocystis luetkeana</i> ) forests; often indicates current-affected areas if growing in areas of low wave energies	Semi-protected to Exposed or current dominated
Dark brown kelp	Stalked large browns with leathery and shiny-smooth blades; a mixture of species at moderate wave exposures including <i>Lessoniopsis littoralis</i> , <i>Hedophyllum sessile</i> , <i>Egregia menziesii</i> , <i>Alaria</i> spp., <i>Laminaria setchellii</i> , with single-species monocultures of <i>Lessoniopsis littoralis</i> occurring at Very Exposed sites	Semi-exposed to Very Exposed or current dominated

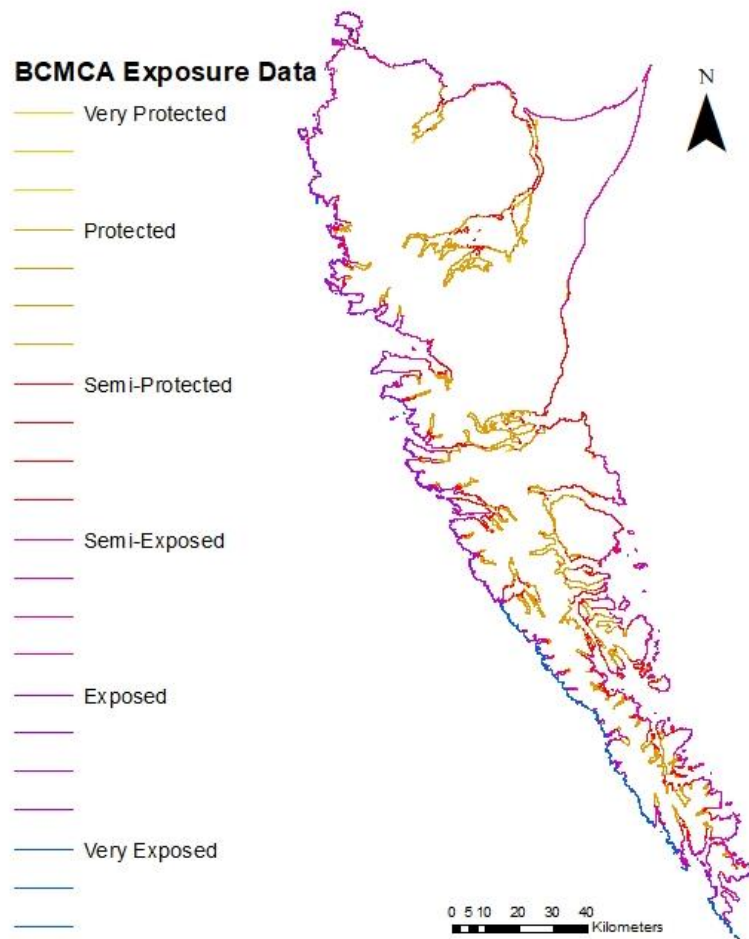


Figure 9. BC Shorezone wave exposure classifications for the Haida Gwaii coast (Howe et al., 1997).

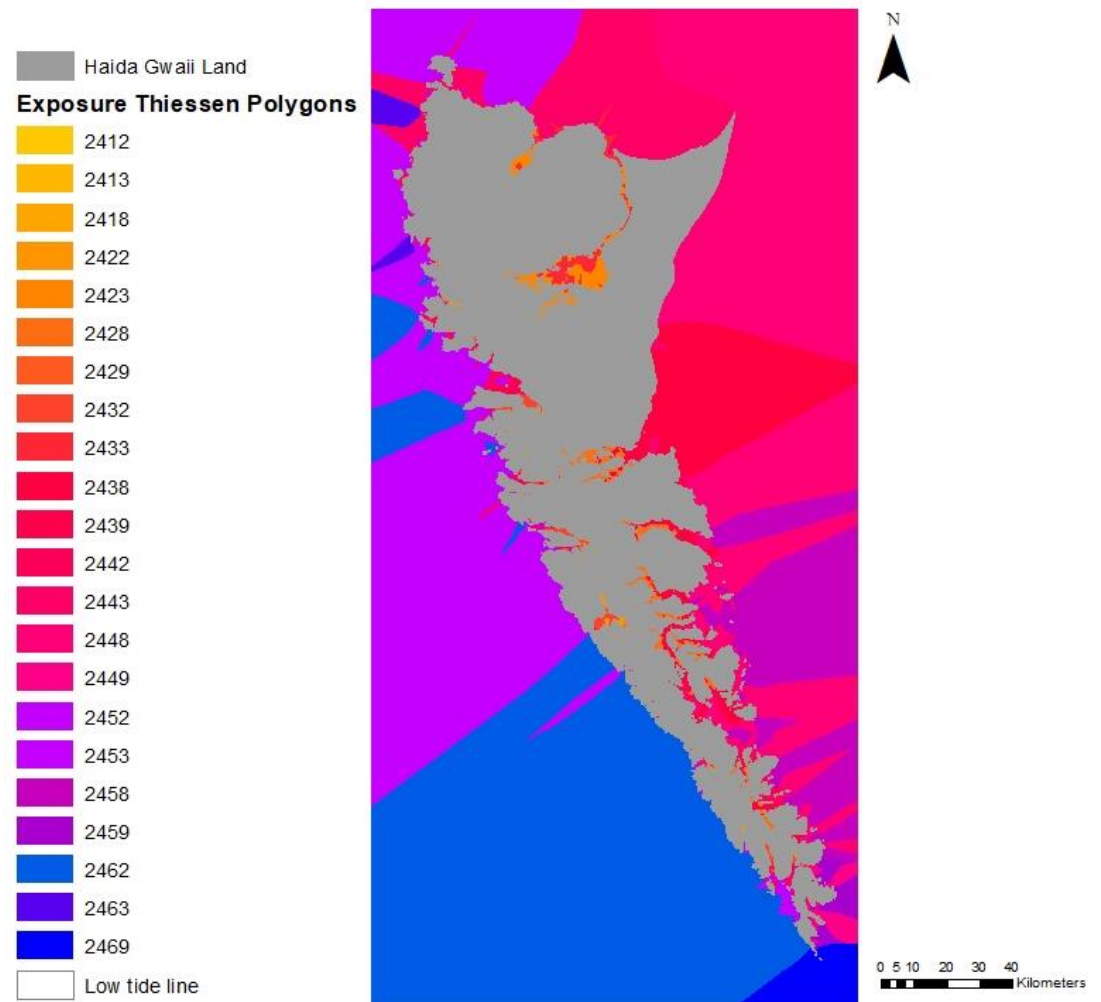


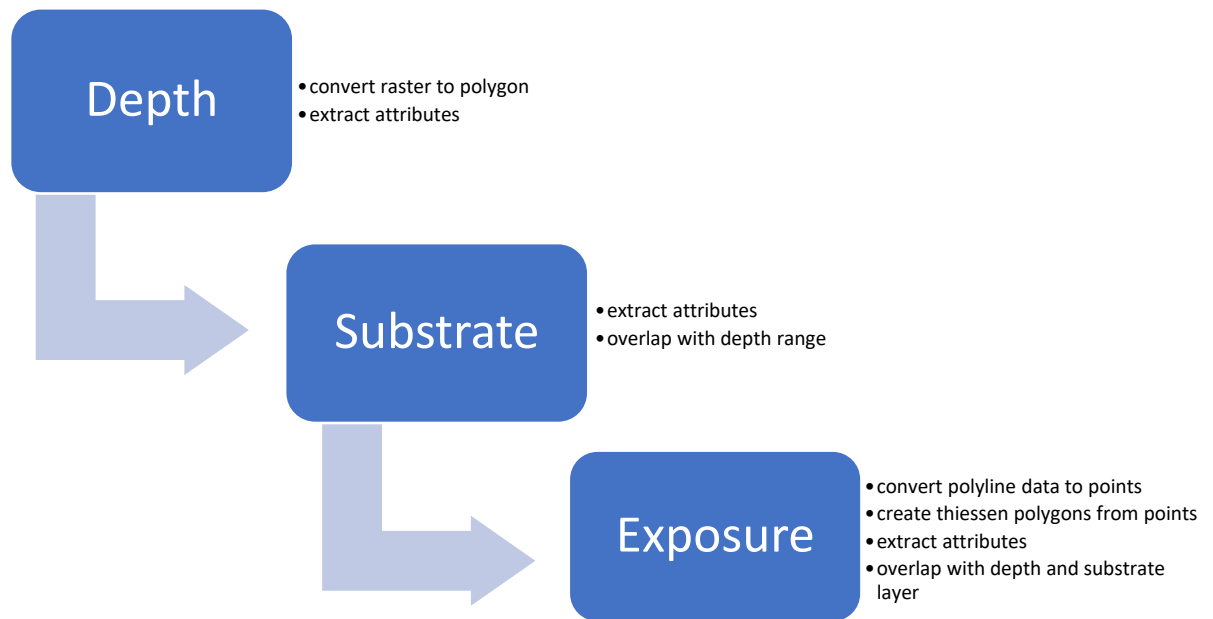
Figure 10. ShoreZone exposure points converted into coded Thiessen polygons.

Table 6. Wave exposure classifications and description (Howe et al., 1997).

Exposure	Code	Description
Very Protected	VP	maximum wave fetch less than one kilometre; usually the location of all-weather anchorages, marinas and harbours.
Protected	P	maximum wave fetch less than 10 km; usually areas of provisional anchorages and low wave exposure except in extreme winds.
Semi-protected	SP	maximum wave fetch distances in the range of 10 to 50 km. Waves are low most of the time except during high winds.
Semi-exposed	SE	maximum wave fetch distances between 50 and 500 km. Swells, generated in areas distant from the shore unit create relatively high wave conditions. During storms, extremely large waves create high wave exposures.
Exposed	E	maximum wave fetch distances 500 to 1,000 km. High ambient wave conditions usually prevail within this exposure category.
Very Exposed	VE	maximum wave fetch distances > 1,000 km. Large swell (>1m) almost always present. Typical of open-Pacific conditions.

### 3.2.4 Model phases to refine results

In Phase 1, the depth layer was used to define the primary nearshore area in which other abiotic factors could be overlaid (Figure 11). Next, polygon attributes were extracted from the substrate layer and overlaid with the refined depth layer to detect overlaps. Finally, an exposure polyline dataset was used to create polygons of exposures where kelp growth is known to occur. Exposure polygons were overlaid with the depth and substrate layers and processed for areas of overlap.



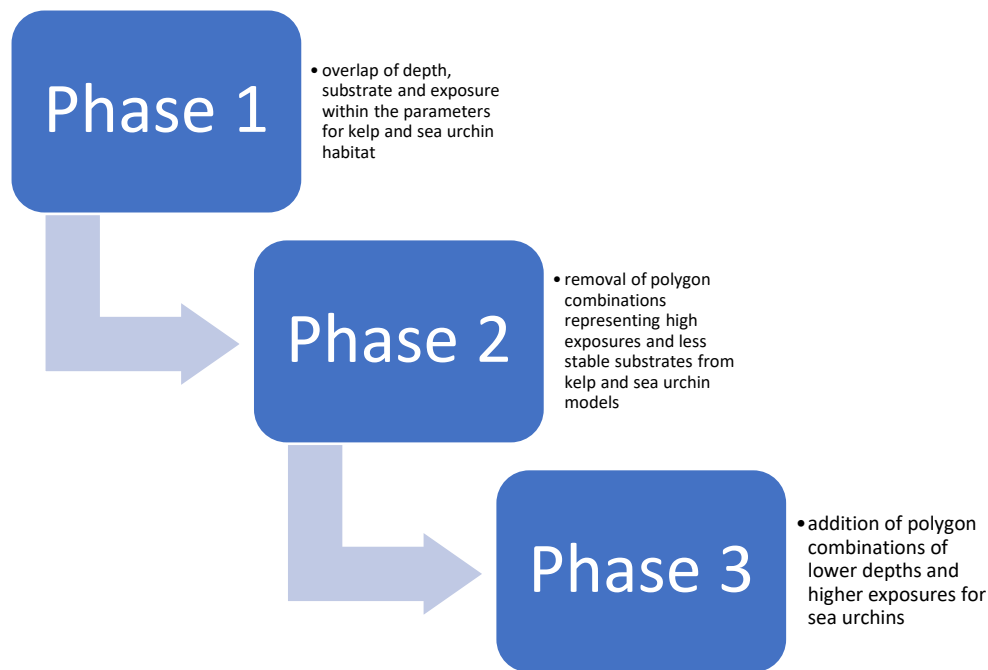
*Figure 11. Conceptual diagram of parameters used in Phase 1 of spatial model development in ArcGIS 10.4.*

Two additional phases were added to the primary modelling approach (Table 7; Figure 12). Model adjustments were made in Phase 2 to account for abiotic combinations known to exclude kelp and sea urchins (Sloan, 2006; L. Lee, personal communication, 2017). Less stable substrates in areas of higher exposure were assumed unsuitable for kelp growth because small blades, gametophytes, and juvenile sporophytes that are vulnerable to scouring and suffocation by sediment (Dayton, 1985). Phase 2 removed polygons that were a combination of Mixed substrates with BType-2 null classifications and exposure ratings between Semi-exposed and Very Exposed (Table 7).

Phase 3 was added to the potential urchin barren model to account for the presence of urchins in higher exposures but at greater depths. Phase 3 of the potential urchin barrens habitat model added polygons from 6-20m depth in Semi-exposed, Exposed and Very Exposed sites with Hard substrates (Table 7).

*Table 7. Parameters for kelp habitat modelling Phases 1 and 2, and urchin barrens modelling Phases 1, 2 and 3.*

	<b>Kelp</b>			<b>Urchin</b>			<b>Geoprocessing</b>
	Depth	Substrate	Exposure	Depth	Substrate	Exposure	
Phase 1	+1-20 m	Hard – a Hard – b Hard – null Mixed – a Mixed – null	Protected to Very Exposed	0-20 m	Hard – a Hard – b Hard – null Mixed – a Mixed – null	Semi-protected to Semi-exposed	Identification of overlapping polygons
Phase 2	+1-20 m	Mixed – null	Semi- exposed to Very Exposed	0-20 m	Mixed – null	Semi-exposed	Removal of overlapping polygons
Phase 3				6-20 m	Hard – a Hard – b Hard – null	Exposed to Very Exposed	Addition of polygons



*Figure 12. Multiple phases of the potential kelp model (Phase 1 and 2) and sea urchin model (Phase 1, 2 and 3).*

Finally, model results were overlapped with existing zones in the Haida Gwaii Marine Plan (2015), including zones that identify kelp as an important feature. Model relevance and importance to marine management around Haida Gwaii was interpreted from the comparison between potential kelp and sea urchin habitat maps and the Haida Gwaii Marine Plan (MaPP, 2015) management zones.

### **3.3 Model assessment with independent data**

Existing data on known kelp and urchin distribution was compared with the potential kelp and urchin barrens habitat model results, although limitations of the known kelp distribution datasets are acknowledged. Using ArcGIS geoprocessing, areas of overlap between potential kelp habitat model results and observed data from the Coastal Resource Information System (CRIMS) were generated and compared. Two smaller geographic areas, Niidan Kaahlii (Naden Harbour) and Hlkinul ChiiGas.sgi (Fairbairn Shoals), were used as reference areas to validate potential kelp model results, which are expected to overlap with known locations of observed kelp. The BCMCA polyline dataset served as a general reference for total

shoreline coverage, providing a more general estimate of kelp distribution coast-wide from one-dimensional data. Low resolution commercial sea urchin data was used to compare the results of the potential urchin barren model with known sea urchin distribution.

### **3.3.1 Known kelp distribution**

Existing kelp distribution datasets were used as an independent source for evaluating the results of the potential kelp habitat model. Additionally, the known kelp dataset was compared with the potential barrens model to assess the overlap between modelled barrens and known kelp distribution. In BC, some canopy-forming kelp has been mapped, but a comprehensive kelp dataset does not exist. Not all areas of the coast have been mapped for canopy-forming kelps, nor have they been mapped using the same survey methods. The spatial extent of understory and prostrate kelps that are not visible from the surface are even less well-documented. As a result, areas without kelp data in the existing datasets do not necessarily represent the absence of kelp. Publicly available datasets included the CRIMS polygon dataset and the BCMCA polyline dataset.

Two sites that are known for kelp growth were chosen to compare potential habitat results with CRIMS data – Niidan Kaahlii (Naden Harbour) and Hl<sup>kinul</sup> ChiiGas.sgii (Fairbairn Shoals) (MaPP, 2015); the BCMCA data was used as a general reference. Niidan Kaahlii (Naden Harbour) is located at the north end of XaaydaGa Gwaay.yaay IinaGwaay (Graham Island). Most of the CRIMS data shows known kelp distribution data collected by the Canadian Hydrographic Service with the addition of more detailed polygon data in particular areas. The CHS data is in individual or overlapping circular polygons of 3.1 hectares. However, the north end of XaaydaGa Gwaay.yaay IinaGwaay (Graham Island), including the Niidan Kaahlii (Naden Harbour) area, had detailed polygon data from a kelp canopy survey in 1976. Hl<sup>kinul</sup> ChiiGas.sgii (Fairbairn Shoals), located on the northeast side of T'aaxwii XaaydaGa Gwaay.yaay IinaGwaay (Moresby Island), is known for supporting the largest connected kelp forest in the southern half of the archipelago (Sloan, 2006). However, available data on known kelp distribution in Hl<sup>kinul</sup> ChiiGas.sgii (Fairbairn Shoals) is only represented by CHS circular polygons. Both sites are known for their ecological and cultural important kelp features in the Haida Gwaii Marine Plan (2015).

The polyline data indicated distribution along the coastline, but no indication of kelp presence by area. The polyline dataset on kelp distribution was available from ShoreZone

surveys were conducted from 1991-1992 for Gwaii Haanas and from 1997-1998, aerial images taken at low tides for 1979 and 2008, and data for *Nereocystis* (BCMCA, 2011; Sloan, 2006; Howe et al., 1997; Appendix B).

### 3.3.2 Known urchin distribution

Existing sea urchin distribution was available from a compiled dataset on the commercial urchin fishery between 2000 and 2005 (Figure 13). The dataset was publicly available from the BCMCA. Sea urchin data was presented in 2 km by 2 km grid cells that included depths greater than the 20m contour. In the comparison between the commercial fishery data and the model results, known urchin data below 20m was excluded for the sake of comparison and because the general limit of the urchin fishery only goes to 20m depth or less. Like the known kelp data, the known sea urchin data does not represent the absence of sea urchins.

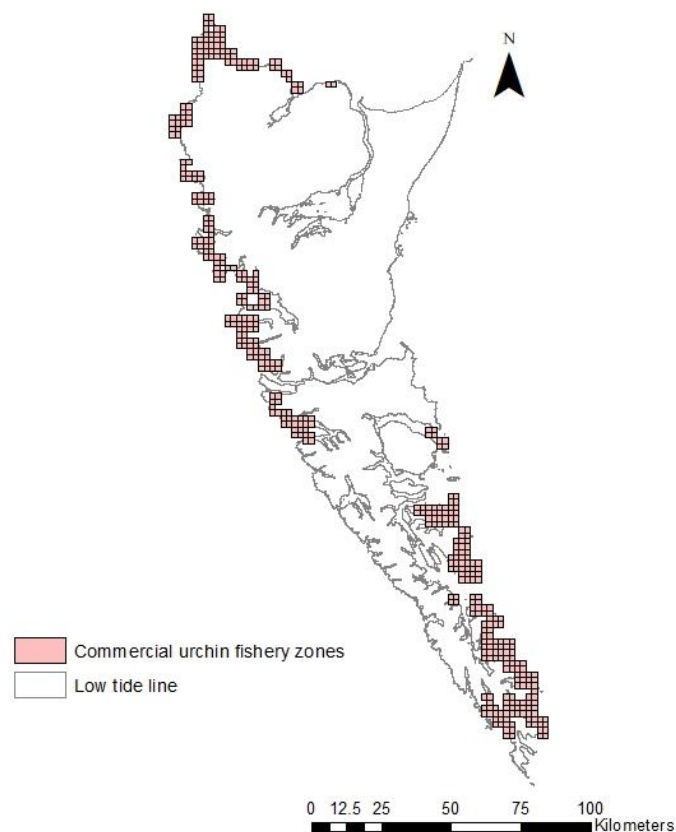
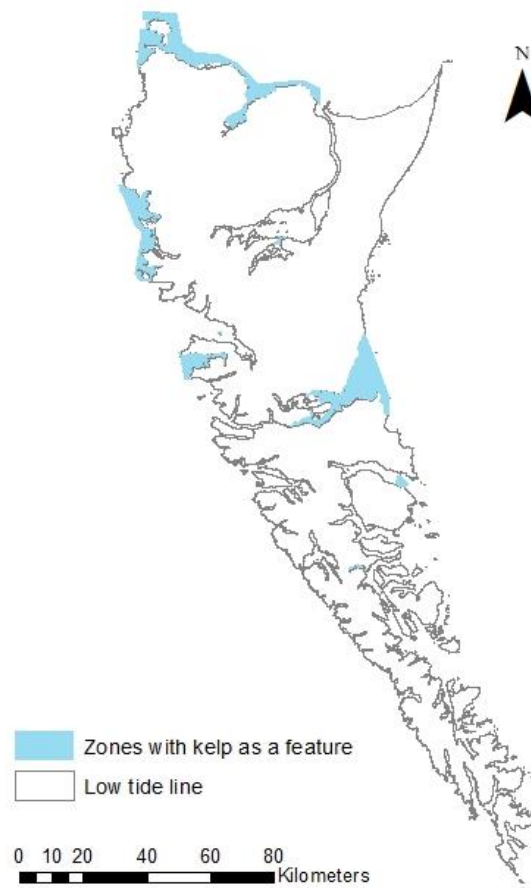


Figure 13. Known distribution of sea urchins from BCMCA commercial fishery dataset.

### **3.4 The Haida Gwaii Marine Plan**

The Haida Gwaii Marine Plan (2015) includes a publicly available shapefile with a spatial dataset depicting marine management zones. Some zoned areas make specific reference to kelp as a valued feature Protection Management Zone (PMZ), e.g. referring to its importance to herring spawn, Haida values and traditional use, and critical habitat for numerous species (Figure 14; Appendix A). Within the PMZ, which included nearly 20% of the plan's area, the zoning applied the IUCN Protected Area Management Categories to MPAs guidelines. The zones classifications include Strict nature reserve (Ia); Wilderness area (Ib); National park (II); Natural monument or feature (III); Habitat/species management area (IV); Protected landscape or seascapes (V); and, Protected areas with sustainable use of natural resources (VI) (Day et al., 2012). Management zones were compared with results from the potential kelp habitat model (Appendix A). Both layers were geoprocessed in ArcGIS for overlaps between potential kelp habitat and known management zone areas with kelp features, regardless of zone type.



*Figure 14. Haida Gwaii Marine Plan (2015) spatial management zones that identify kelp as a valued feature.*

## 4 Results

### 4.1 Potential kelp habitat

Phase 1 of the potential kelp habitat model covered an area of 238,703 ha (Table 8). The substrate layer was 17.7% Hard and 82.3% Mixed (Table 9). Mixed polygons were composed of 12.8% Mixed-a and 87.2% Mixed-null secondary classifications (Table 9). The exposure layer was 57.6% Semi-Exposed, followed by 27.3% Semi-Protected, 7.9% Exposed, 5.2% Protected, and 2.0% Very Exposed (Table 10). Results of Phase 1 showed nearshore habitat with the potential to support kelp forests was dominated by Mixed substrates of unknown secondary classifications and Semi-Exposed conditions.

*Table 8. The total number of polygons and the total area for the potential kelp models in Phase 1 and 2 of the modelling and difference in area from Phase 1 to Phase 2.*

Potential kelp model	Phase 1 (ha)	Phase 2 (ha)	Difference in area (%)
Total area	238,703	116,316	-51.3

After the removal of polygons containing a combination of Mixed-null substrates and exposures ratings of Semi-exposed and greater, Phase 2 resulted in a 51.3% reduction in area, mostly in the Dogfish Banks area of Hecate Strait off NE XaaydaGa Gwaay.yaay IinaGwaay (Graham Island), to 116,316 ha (Table 8; Figure 15 & 16). The Hard substrate layer remained the same as it was in Phase 1, but the Mixed area decreased by 71.4%. Phase 2 substrate proportions were 36.3% Hard and 63.7% Mixed. In the Mixed layer, 33.9% was Mixed-a, and 66.1% was Mixed-null. Areas of Protected and Semi-Protected remained the same in Phase 2, but the areas representing Semi-Exposed and Exposed polygons declined by 19.1% and 6.8%, respectively (Table 10). Proportionally, the Semi-Protected area was 56.0%, Semi-Exposed was 22.6%, Protected was 10.7%, Exposed was 8.0%, and Very Exposed was 2.7% (Table 10). Areas with substrate ranging from Hard-a to Mixed-a accounted for 67,328 ha of potential kelp, the same as Phase 1, but Phase 2 removed a total of 122,387 ha containing Mixed-null polygons (Figures 15 & 16). The results for Phase 2 showed a change in the dominant exposure class to Semi-Protected with a dominant Mixed-null substrate (Table 9 & 10).

*Table 9. Total area (ha) by substrate layer for Phase 1 and 2 potential kelp habitat modelling and difference in area from Phase 1 to Phase 2 (%).*

<b>Substrate</b>	<b>Phase 1 (ha)</b>	<b>Phase 2 (ha)</b>	<b>Difference in area (%)</b>
Hard	42,160	42,160	0
Mixed-a	25,168	25,168	0
Mixed-null	171,376	48,988	-71.4

*Table 10. Total area (ha) by exposure rating for Phase 1 and 2 potential kelp habitat modelling and difference in area from Phase 1 to Phase 2 (%).*

<b>Exposure Class</b>	<b>Phase 1 (ha)</b>	<b>Phase 2 (ha)</b>	<b>Difference in area (%)</b>
Protected	12,384	12,384	0
Semi-Protected	65,172	65,172	0
Semi-Exposed	137,406	26,282	-80.9
Exposed	18,905	9,347	-50.6
Very Exposed	4,836	3,132	-35.2

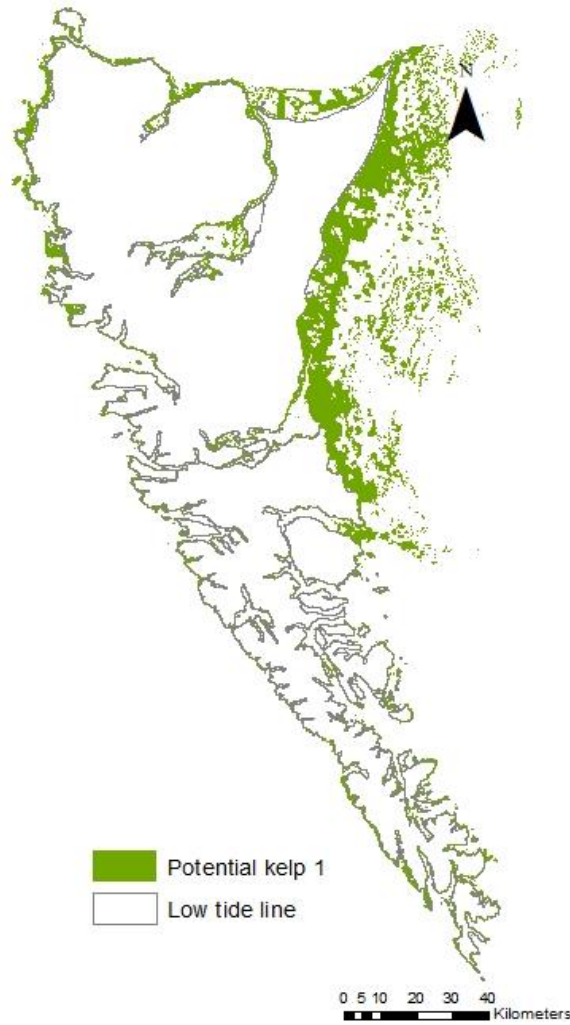


Figure 15. Potential kelp habitat map from Phase 1 analysis.

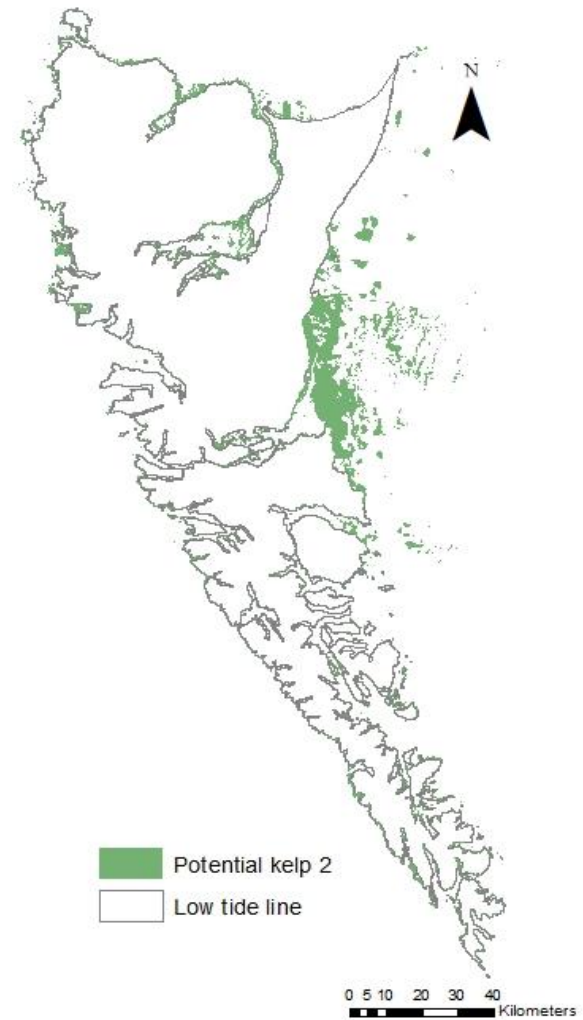


Figure 16. Potential kelp habitat map from Phase 2.

## 4.2 Independent data evaluation of potential habitat models

At a total of 11,828 ha, the CRIMS kelp data represented a fraction of the area identified in the potential kelp model for Haida Gwaii. Relative to the potential kelp model results, the CRIMS data was approximately 5% of the total potential kelp habitat area from Phase 1 and 10% of the total area from Phase 2 (Table 11). Similar areas of overlap were found between both phases of the potential kelp model results and the CRIMS dataset: Phase 1 results overlapped with 66.3% of the CRIMS dataset, and Phase 2 results overlapped with 63.8% of the dataset (Table 12). The CRIMS data overlapped with Hard, Mixed-a and Mixed-null substrate polygons. Phase 2 of potential kelp in Niidan Kaahlii (Naden Harbour) demonstrated a higher proportion of overlap with the CRIMS data at 85.4% (Table 13; Figure 17). Hlkinul ChiiGas.sgii (Fairbairn Shoals) showed 59.5% overlap between CRIMS data and the Phase 2 potential kelp model (Table 13; Figure 18). At Hlkinul ChiiGas.sgii (Fairbairn Shoals), some of the CRIMS data and potential kelp model results did not overlap because of the presence of Soft substrate polygons that were excluded from the potential kelp model in Phase 1 (Figure 17). Overall, the majority of the independent kelp data overlapped with potential kelp habitat model results.

*Table 11. CRIMS dataset overlaps with Phase 1 and 2 potential kelp habitat modelling.*

	<b>Phase 1 potential kelp (ha)</b>	<b>Phase 2 potential kelp (ha)</b>	<b>Difference in area (%)</b>
CRIMS	7,836	6,106	-22.1

*Table 12. Site-specific overlaps between CRIMS data and Phase 2 potential kelp habitat modelling.*

	<b>Niidan <u>Kaahl</u>ii (Naden Harbour)</b>	<b><u>Hl</u>kinul Chii<u>Gas</u>.sgii (Fairbairn Shoals)</b>
Potential kelp area (ha)	2,212	2,057
CRIMS area (ha)	875	311
Overlapping area (ha)	748	185

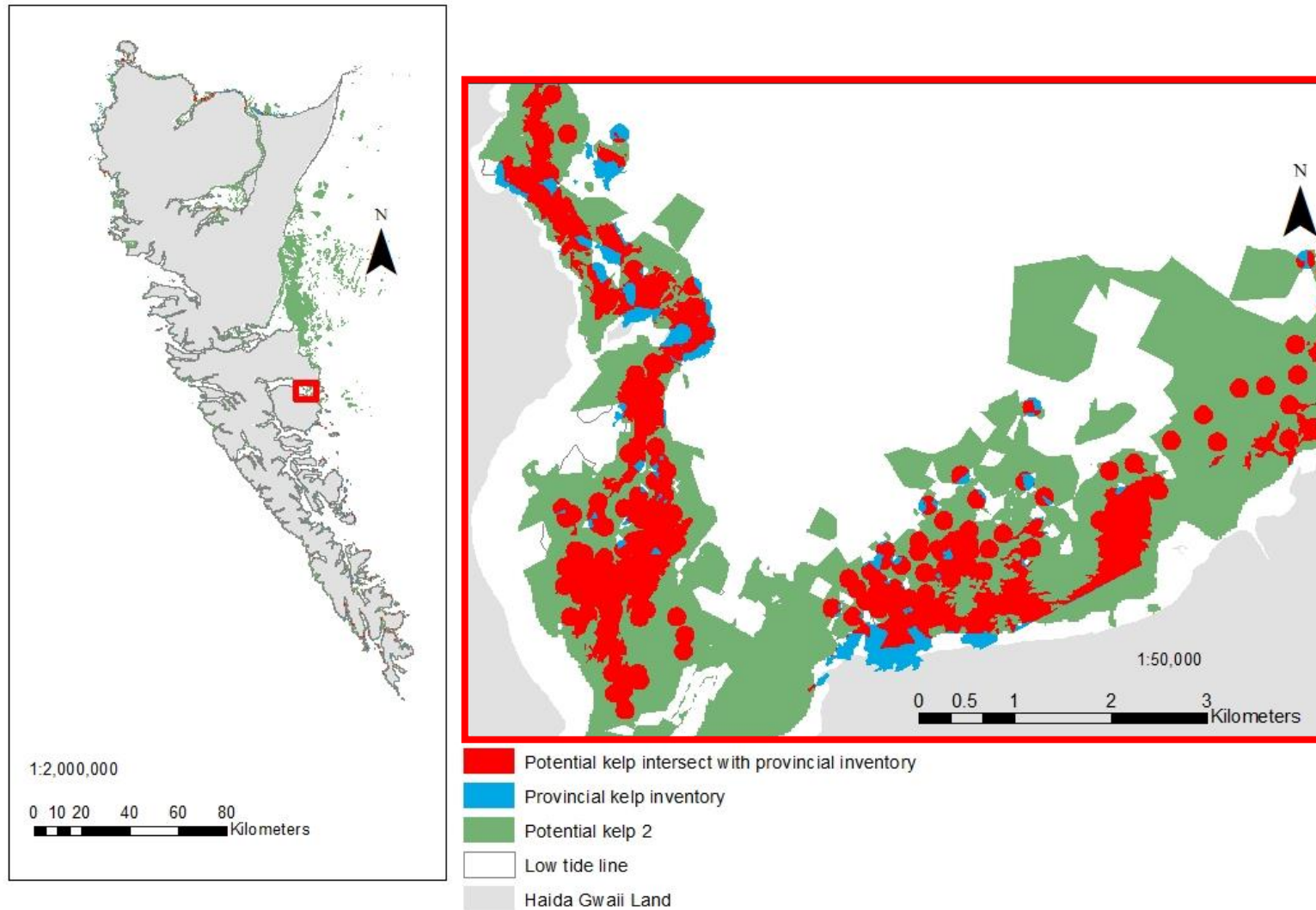


Figure 17. Overlap between independent kelp data and Phase 2 potential kelp habitat modelling at Niidan Kaahlíi (Naden Harbour) (inset), northern XaaydaGa Gwaay.yaay InaGwaay (Graham Island), Haida Gwaii.

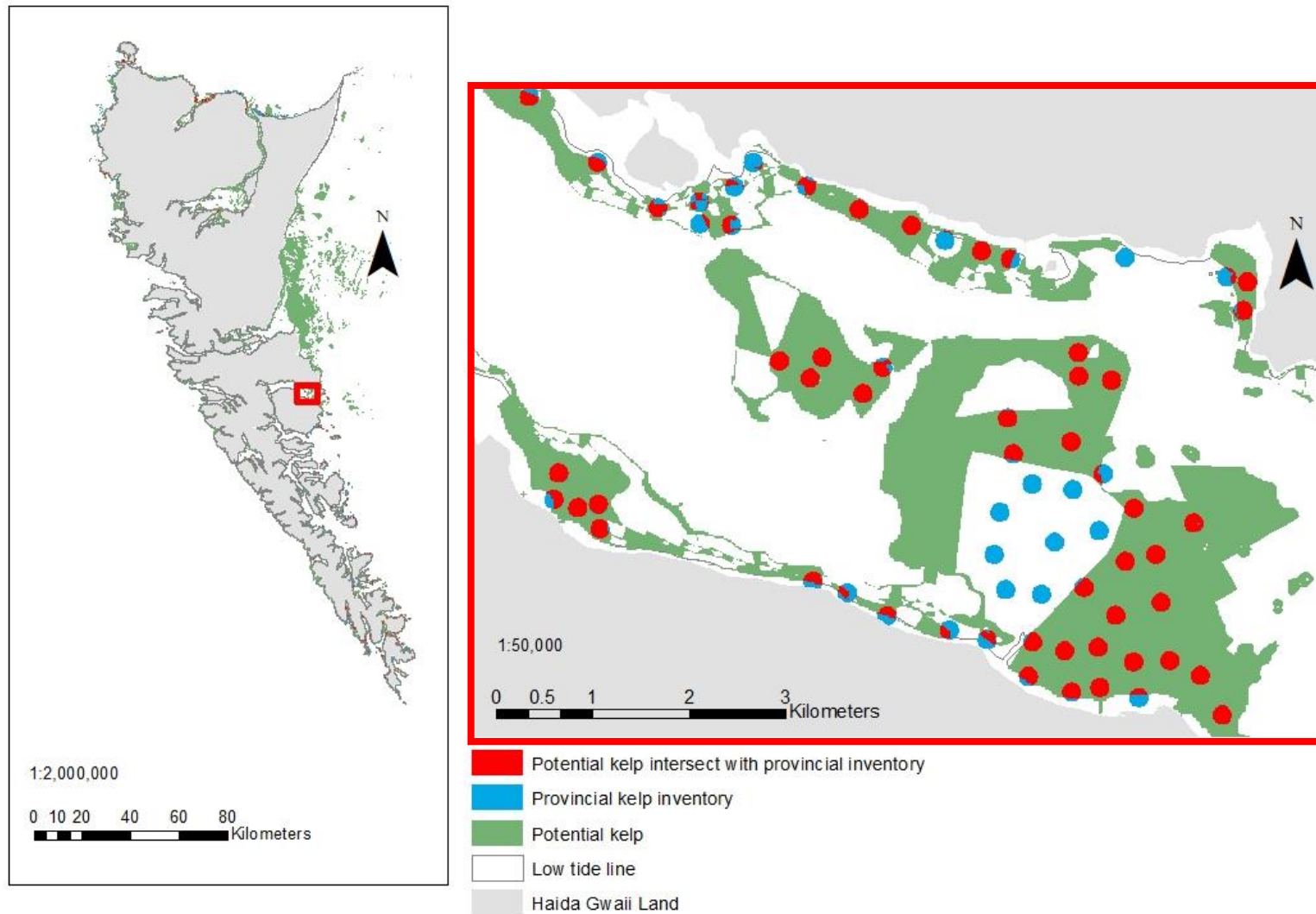


Figure 18. Overlap between independent kelp data and Phase 2 potential kelp habitat modelling at Hl̓kinul ChiiG̓as.sgii (Fairbairn Shoals) (inset), northeast T'aaxwii XaaydaGa Gwaay.yaay InaG̓waay (Moresby Island), Haida Gwaii.

### **4.3 Potential sea urchin barrens model**

In Phase 3, with the addition of polygons in Exposed and Very Exposed areas at depths of 6-20 m, the total area for the potential urchin barrens model were 92823 ha (Table 14; Table 15; Figure 19). Phase 3 potential barrens overlapped with 79.8% of Phase 2 potential kelp habitat (Figure 20). The remaining potential kelp habitat that did not overlap with potential barriers totalled 23492 ha, 20.2% of the potential kelp model. The total area of the Phase 3 potential barrens overlapped with 11,505 ha (50.9%) of the BCMCA commercial urchin fishing areas from 0-20m, a total of 22604 ha. The potential urchin barren results also overlapped with 4565 ha, 38.6%, of the provincial kelp inventory which is less than half of the overlap between potential kelp habitat and known kelp (Figure 21).

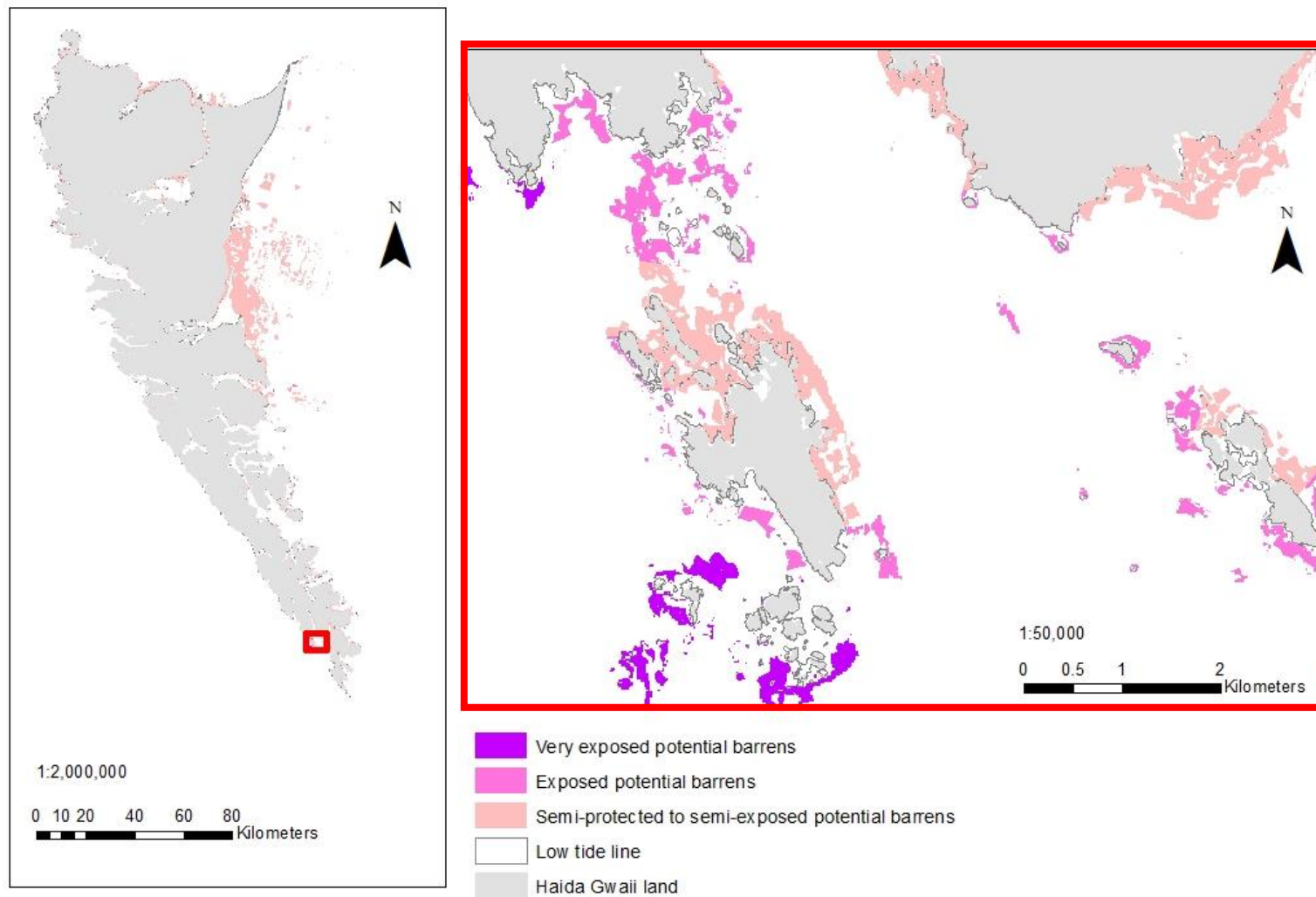


Figure 19. Potential urchin barrens habitat by exposure class for Haida Gwaii. The inset shows SGang Gwaay.

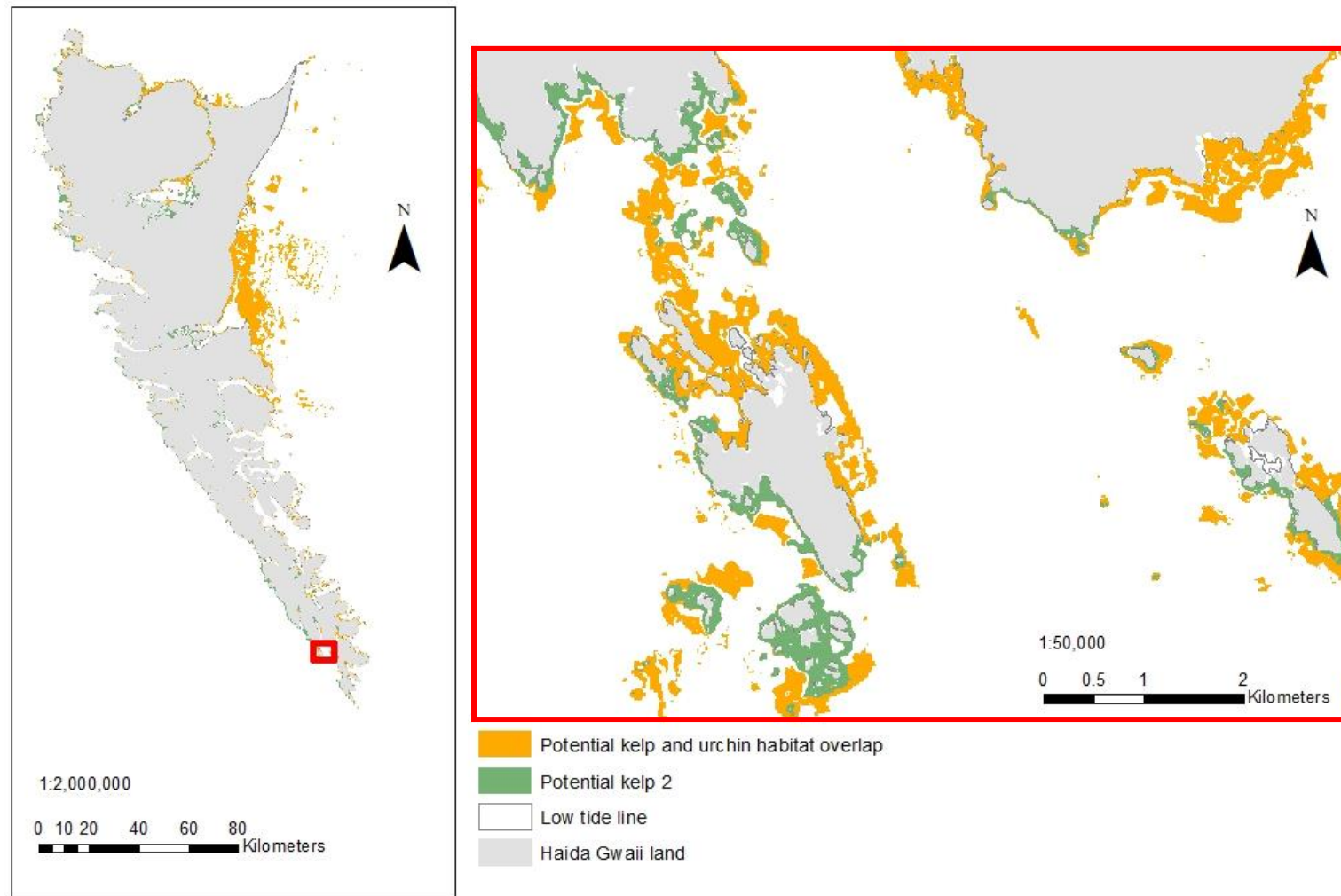


Figure 20. Area of overlap between Phase 2 potential kelp habitat and Phase 3 potential urchin barrens habitat for Haida Gwaii. The inset shows SGang Gwaay.

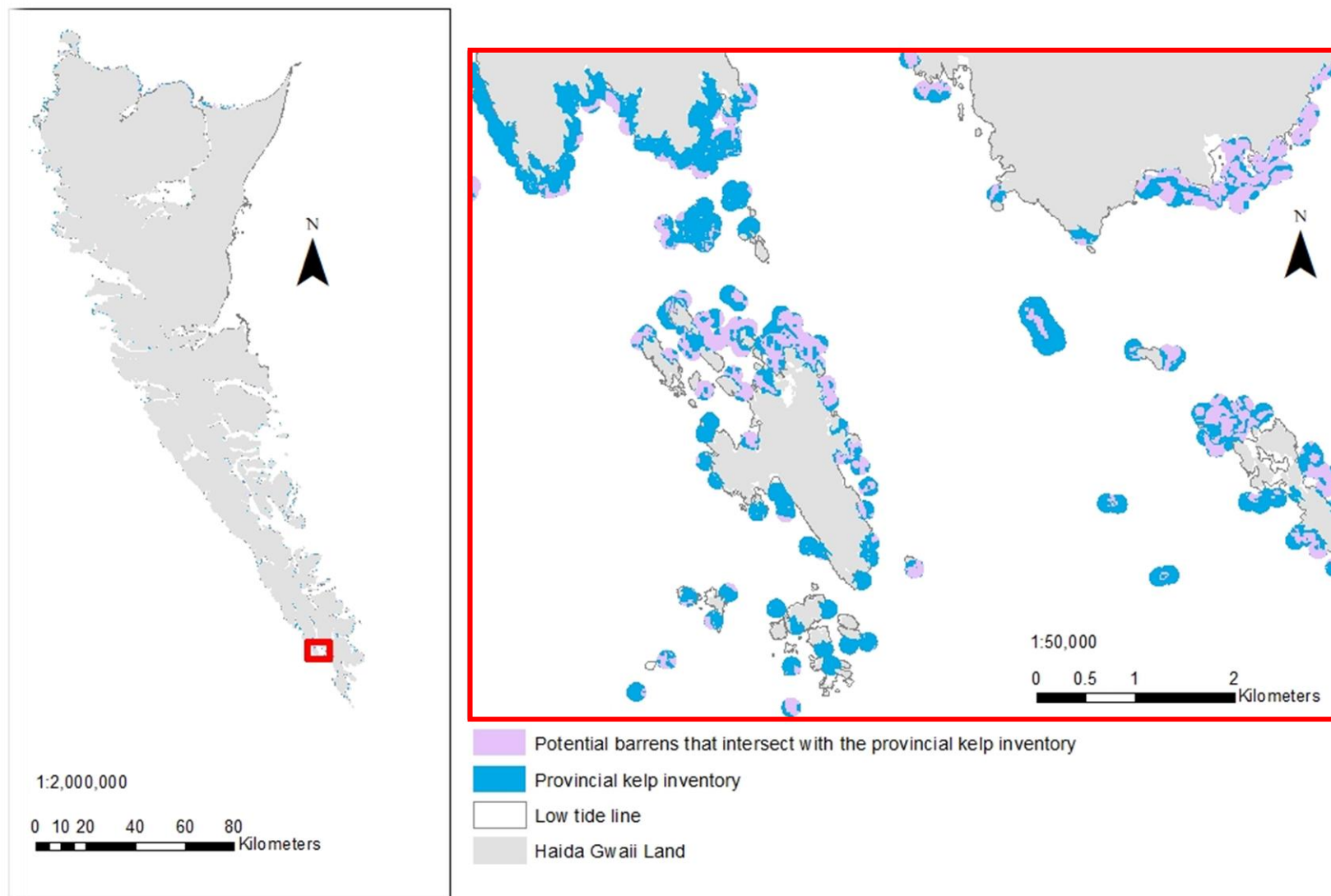


Figure 21. Area of overlap between potential barrens and known kelp distribution. The inset shows SGang Gwaay.

## 4.4 Potential kelp habitat and Haida Gwaii Marine Plan spatial zoning

Of the area zoned for protection and special management in the Haida Gwaii Marine Plan (MaPP, 2015), 19 zones covering 31499 ha have management objectives specifically related to kelp values within a depth range from +1-20m depth (Table 13; Appendix A). The potential kelp model overlapped with 59.8%, covering a total area of 18823 ha (Table 13; Figure 22). Of the overlapping areas, 14.2% fall within the Wilderness area (Ib) and Natural monument or feature (III) classified zones which afford a higher level of protection to ecological values (Table 13). The Habitat/species management area (IV) classification, which provides a medium protection, accounted for 29.1% of the overlapping area. Finally, 56.7% overlapped with Protected landscape or seascapes (V) and Protected areas with sustainable use of natural resources (VI), the lowest level of protection (Table 13). For individual zones, Zone IV captured the highest percent of overlap with the potential kelp model and II captured the least amount of overlap (Table 13). The Niidan Kaahlii (Niidan Kaahlii (Naden Harbour)) area, featured earlier, falls under VI, IV and Ib classifications. Hl<sub>k</sub>inul ChiiGas.s<sub>g</sub>ii (Fairbairn Shoals) falls under Ib classification.

*Table 13. IUCN designations for overlapping kelp feature zones and potential kelp polygons by area, and percent overlap relative to the total area of zones with kelp features at depths of +1 to 20m.*

IUCN designation	Area of zone featuring kelp (ha)	Area (ha) of overlap	Percent overlap with total kelp feature zones (%)
Ib	13500	1832	13.6
II	6850	835	12.2
III	40	7	17.5
IV	7890	5471	69.3
V	59350	9090	25.7
VI	12010	1588	15.3

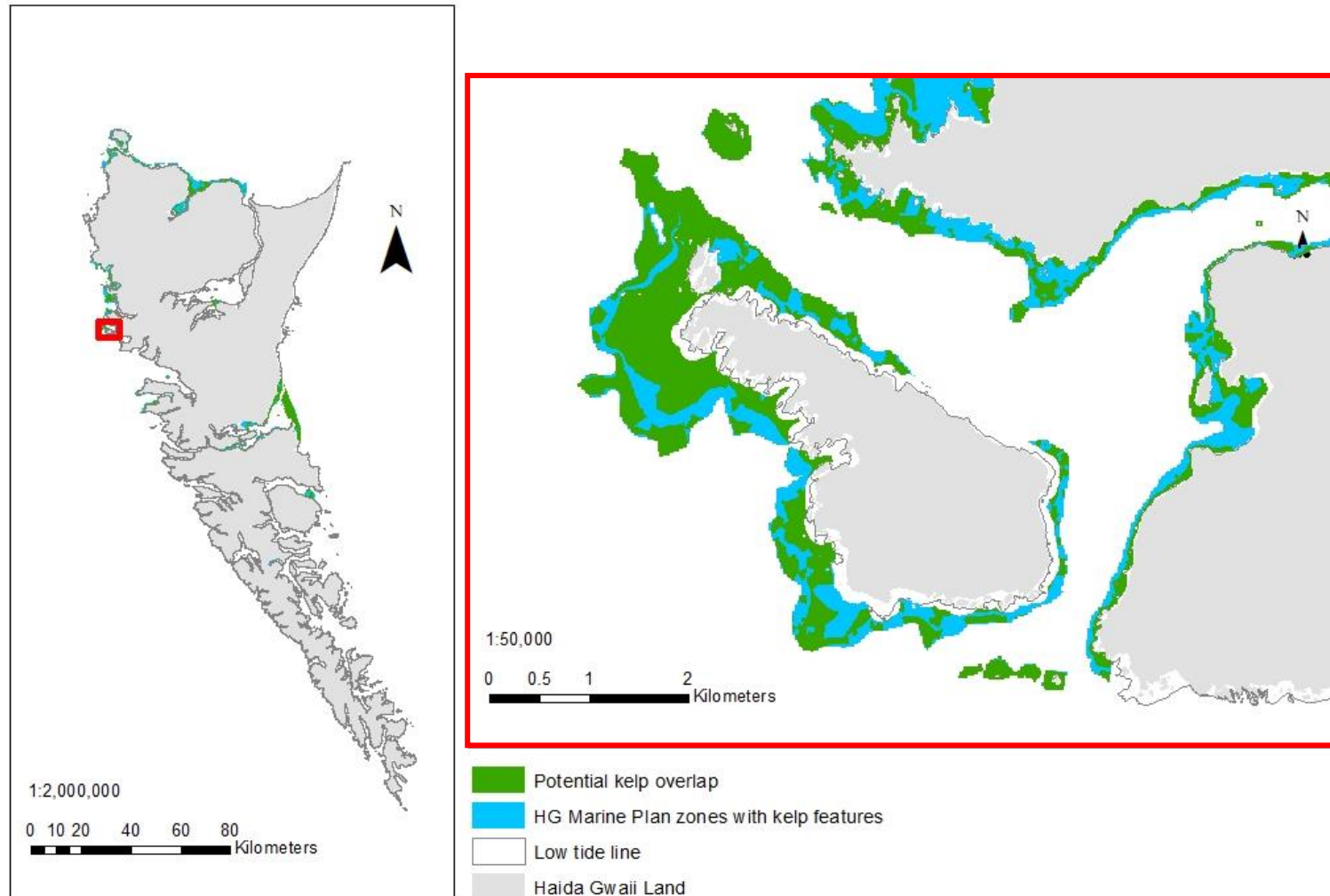


Figure 22. Haida Gwaii Marine Plan (2015) zoning that identifies kelp as a valued feature, from +1 to 20m depth, and areas of overlap with Phase 2 potential kelp habitat. The inset shows Naasduu Gwaay.yaay (Hippa Island) on the west coast of XaaydaGa Gwaay.yaay IinaGwaay (Graham Island).

## 5 Discussion

### 5.1 Understanding implications of keystone predator loss through potential habitat suitability modelling

With limited data on kelp distribution and consideration of historical ecosystem shifts that may have occurred following keystone predator removal, these modelling results provide some insight into potential changes in kelp forest distribution through time. Without a reference dataset or any known historical trajectories prior to the maritime fur trade, it is not known how the spatial distribution of restored kelp forest ecosystems around Haida Gwaii might look. An understanding of kelp ecology, trophic cascades, and the history of keystone predator loss provides some context for interpretation of the habitat suitability models. The habitat models use abiotic data combinations to serve as proxies for potential habitat. The kelp and sea urchin models predict the full range of suitable habitat for kelp and sea urchins down to 20 m depth. Areas of overlapping species habitat predict the extent of possible ecosystem shifts, either historical or anticipated when sea otters return to their natural range around Haida Gwaii. Areas of the potential kelp model that are excluded from overlapping results represent areas potential intact kelp forest habitat.

The potential habitat modelling results predict a maximum total area of suitable habitat for kelp forests of 116,316 ha, including all species of kelp and incorporating the typically patchy and fragmented edges of kelp growth. According to ShoreZone bioband data (Appendix B), kelp should be ubiquitous on stable and rocky nearshore habitats, but the mid and north-east coast of XaaydaGa Gwaay.yaay IinaGwaay (Graham Island) represent some of the most continuously unsuitable habitats for kelp due to unconsolidated substrates. Phase 2 of the model removed most of the Phase 1 polygons on the northeast corner of XaaydaGa Gwaay.yaay IinaGwaay (Graham Island). The absence of some secondary classifications for the Mixed substrate polygons likely provided an over-estimate of polygons in Phase 1 and the removal of polygons with null secondary classifications in Phase 2 likely provides some areas with an underestimate. ShoreZone data shows patchy kelp presence along the southeast shore side of XaaydaGa Gwaay.yaay IinaGwaay (Graham Island); however, the large area

of potential kelp produced in model results on the south east side of XaaydaGa Gwaay.yaay IinaGwaay (Graham Island) were unanticipated, especially at that distance from shore and may have been exaggerated in the model.

The independent dataset of actual kelp varied in resolution and overlap with the model results were higher in some areas compared to others depending on the availability and resolution of known data. Nevertheless, the potential kelp habitat map was consistent with areas of known kelp distribution. The high percentage (63.8%) of known kelp overlap with potential kelp indicates the model can capture the majority of known distributions. Potential overlap with known kelp distribution was greater than the overlap with potential barrens (38.6%) which is consistent with the assumption that known kelp distribution (25.2% of the overlap) exists outside of barrens. Known kelp that overlaps with barrens may be present but degraded or diminished from its reference state. In total, the potential kelp area represented is 10 times as great as the known distribution of kelp which was expected since the known distribution is limited to canopy forming kelps visible from the surface and the potential model was created to also capture unmapped distributions of understory kelps. High percentages of overlap between the model and Niidan Kaahlii (Naden Harbour) and Hlkinul ChiiGas.sgi (Fairbairn Shoals) were anticipated due to historical knowledge of kelp growth in these areas. Lower overlap in Hlkinul ChiiGas.sgi (Fairbairn Shoals) was attributed to lower resolution known data. Even within the limits of available data and varying resolutions, as well as the inherent limitations of potential modelling, the results met expectations as a representation of potential, not actual, species distribution.

The urchin and kelp model comparison broadly highlighted the increase in potential kelp forest habitat that may be realized as sea otter-induced trophic cascades accompany sea otters return and population recovery. Areas of overlap between potential barrens and potential kelp represent areas of potential trophic cascades. Simultaneously, these areas of predicted kelp habitat also represent potential habitat currently under threat from unchecked sea urchin grazing and lowered ecosystem resiliency to potential growing threats from climate change, invasive species and oil spills. Areas outside of the overlap between potential barrens and potential kelp may represent refugia covering 23492 ha which comprises 20% of the potential kelp habitat. According to model results, recovering sea otters may potential induce trophic cascades that increase kelp forests five-fold. The results of habitat suitability models provide spatial awareness and understanding of the implications of keystone predator loss

and recovery, and nearshore ecosystem vulnerability. Nearshore kelp forests may never recover to their historical state, pre-fur trade era, but they may regain a characteristic assemblage of species as well as similar function and production. Potential kelp model results provide an area in which to monitor possible changes in kelp growth and spatial and temporal patterns of kelp restoration resulting from trophic cascades as sea otters return and recover. The 92,824 ha of suitable urchin barrens habitat that overlaps with potential kelp habitat may represent the area of greatest potential for future kelp recovery. Likewise, the 39% of overlap between potential barrens and limited known kelp distribution represents areas of potential kelp loss and degradation due to herbivory. The percent of overlap is consistent with limited data on known kelp distribution and greater limits on the abiotic limits of potential urchin habitat relative to kelp habitat.

## **5.2 Expected shifts and trade-offs in ecosystem services with sea otter recovery**

### **5.2.1 Kelp habitat suitability modelling as a proxy for ecosystem services and associated species to facilitate ecosystem-based management**

Kelp can be considered a proxy or surrogate for mapping ecosystem services (Egoh et al., 2008). As outlined in the theoretical overview, kelp provides a multitude of supporting, regulating, provisioning and cultural services that contribute to the goals of EBM around Haida Gwaii. Habitat suitability modelling contributes to comprehensive recognition and quantification of kelp as an indicator of ecosystem services and a valued marine feature. Coastwide habitat maps provide broader context beyond individual zones for understanding potential ecosystem shifts, gains in ecosystem services and ecological responses to management decisions (Burkhard & Maes, 2017; Day, 2008). Potential kelp covered the majority of nearshore habitat in the zones featuring kelp from +1-20m in the HG Marine Plan (2015) PMZ areas, but potential kelp also extends to an area that is five times greater. Highlighting potential kelp growth in these zones and managing for kelp forests restoration in these areas also provides a means of restoring habitat for individual species of importance like the northern abalone and herring. Furthermore, increases in kelp forests provide the means to build ecosystem resilience and mitigate negative impacts from stressors.

The natural return of sea otters to the Haida Gwaii archipelago will contribute to ecosystem resilience through habitat engineering and the restoration of ecosystem services. Areas of

high overlap between potential kelp and presence of species at risk may warrant higher protection status for services such as increased critical habitat. For example, kelp has been identified as critical habitat, “the 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” (*Species at Risk Act*, 2002) for the Northern abalone. Likewise, increases in kelp from restored trophic cascades in turn provide habitat for sea otters, a listed species, which sleep and forage in kelp forests (DFO, 2014).

Beyond the individual services represented by kelp, kelp distribution should be emphasized for the umbrella services that promote long-term sustainability, ecosystem resilience, and general ecosystem health that contribute to EBM goals. It is incredibly challenging to tailor management decisions to address the individual needs of numerous native species over large areas. With spatially detailed knowledge of potential habitat boundaries, kelp can be used as a surrogate species representing the ecological conditions necessary for other species to live and flourish (Wiens et al., 2008). As an umbrella species, kelp forests can contribute to the management of endangered species like abalone and other species identified in the *Multi-Species Action Plan for Species at Risk in Gwaii Haanas* (Parks Canada Agency, 2016b) and the Canada Species at Risk registry (*Species at Risk Act*, 2002). Kelp forests create biodiversity within and beyond their borders, which is increasingly important as the current rate of global species extinction surpasses that of historical records (Thomson & Starzomski, 2007; Wheeler, 1990). In general, a positive correlation exists between restoration, increased biodiversity and the generation of ecosystem services (Schneiders & Muller, 2017; Benayas et al., 2009). The breadth of services provided by kelp and its potential to increase biodiversity means the identification and comprehensive management of kelp as a surrogate species contributes to holistic EBM.

The benefits from increased kelp growth contribute to a climate change buffer (Hondolero & Edwards, 2017; Smale et al., 2013; Estes & Duggins, 1995; Duggins, 1980), thus kelp recovery has the potential to play a valuable role in climate change adaptation and mitigation. The recovery of sea otters, top predators, initiates the return of historical food webs and increases ecosystem resiliency through greater biodiversity, ecosystem engineering and productivity. Further studies are required in the investigation of blue carbon and the role that kelp plays in carbon absorption and fuel production (Trevathan-Tackette et al., 2015; Smale et al., 2013). However, the potential model results provide a continuous representation of

potential kelp habitat size and distribution for the entire archipelago, informing future possibilities of developing ecosystem resilience as a strategy under the Haida Gwaii Marine Plan (MaPP, 2015). The model results indicate a potential increase five-fold increase in distribution which may translate to a five-fold increase in oxygen output and CO<sub>2</sub> absorption which translates to 10 tonnes of CO<sub>2</sub> per hectare annually in kelp farming (Krause-Jensen & Duarte, 2016; Chung et al., 2013). The potential option value of blue carbon along with increased biodiversity, supporting and regulating services provided by kelp translate into considerable contributions to ecosystem-based adaptation, mitigation and resiliency to threats from climate change and ocean acidification (Colls et al., 2009). Fluctuations in species and quantities of kelp may indicate impacts from climate change, trophic cascades, introduced species, as well as fuel spills and other human-related disturbances. With sufficient temporal and spatial data, it may be possible to record observational patterns and monitor differences between natural and human impacts to kelp. Meanwhile, the benefits of kelp should be promoted by using the precautionary principle of environmental management to build coastal and marine resilience against climate change and other threats.

The primary threat to restoring nearshore kelp forests is shipping of fuels because hydrocarbon spills are the primary threat to sea otters in BC (DFP, 2014) and could prevent or destroy the recovery of sea otter-induced trophic cascades. An oil spill would be a devastating loss for potential kelp both directly and indirectly, and as such, should be a top management priority for addressing future threats to recovering ecosystem function and resilience. Penalties for clean-up costs can provide some incentive for companies to take added precautions to avoid spills. Spill management policies should promote precautionary measures or ensure appropriate funding to address damages, especially damages to non-market values like the natural capital and ecosystem services provided by kelp forests (Tietenberg & Lewis, 2015). Planning, regulation, and accountability for spills has been described as inadequate (Tietenberg & Lewis, 2015). In 2015, the MV North Star and the Simushir cargo ships lost propulsion and nearly collided with Haida Gwaii (Pacific States/British Columbia Oil Spill Task Force, 2016). In 2016, on the central coast, the Nathan E. Stewart tug-boat spilled 110,000 litres of diesel near Bella Bella on the central coast, one of 32 spills that occurred in BC between 2016 and 2017 (Government of BC, 2017). As traffic and shipping increases, future planning and management for spills require more attention to growing marine spill risks and the accompanying loss of ecosystem

services. In the long-term, it is important to assess marine ecosystem vulnerability to threats, both individually and cumulatively, from oil spills, herbivory, ocean acidification, climate change, invasive species, and other pollution (Blackford, 2010).

Despite an existing marine spatial plan that uses zoning with IUCN zone types, kelp is merely identified as a feature in the greater area of 19 zones (Appendix A). In comparison with the potential kelp habitat results, particular zones show higher overlaps with potential kelp and may warrant greater focus in future for kelp restoration management and protection. Niidan Kaahlii (Naden Harbour) and Hl<sup>kinul</sup> ChiiGas.sgii (Fairbairn Shoals) are examples of potential kelp that are encompassed in the zones identified as having kelp features. Niidan Kaahlii (Naden Harbour) and Hl<sup>kinul</sup> ChiiGas.sgii (Fairbairn Shoals) demonstrate varying availability and resolution of known kelp distribution data. At Niidan Kaahlii (Naden Harbour), where the greater resolution of known kelp data exists, the comparison between known kelp distribution and the potential kelp habitat modelling shows a two-fold increase of potential kelp habitat area compared to known kelp areas. Lower resolution data of known kelp at Hl<sup>kinul</sup> ChiiGas.sgii (Fairbairn Shoals) make calculations of apparent increases in potential kelp less reliable. Kelp mapping and modelling need to be presented with sufficient resolution that effectively captures the scale of this particular habitat feature for assessment and monitoring as a valued feature (Greene et al., 2007). Finer details that provide a comprehensive spatial distribution for coastwide kelp habitat contributes to spatially-explicit planning and EBM decisions through the spatial analysis of ecosystem service values, conflicting uses and trade-offs (Egoh et al., 2008; Troy & Wilson, 2006).

### **5.2.2 Potential trade-offs in ecosystem services with sea otter return and increase in kelp forest habitat including potential cultural, social and economic consequences**

While ecosystem shifts from urchin barrens to kelp forests are predicted to increase biodiversity, provide numerous ecosystem services, and restore the integrity of the highly productive nearshore ecosystem, there are some less favourable potential future tradeoffs. Our understanding of the trophic relationship between sea otters, urchins and kelp forests, means that the natural return of sea otters to the Haida Gwaii archipelago will lead to high levels of predation on sea urchins and other valued macroinvertebrates in many locations. When anticipated sea otter populations begin to recover around Haida Gwaii, changes could occur quickly and dramatically in local areas. However, there are uncertainties about the

intensity and timeline of predicted ecosystem shifts and changes throughout Haida Gwaii. Knowledge of suitable habitat for sea urchins and kelp could contribute to valuable baseline data and a record of the changes demonstrating the temporal and spatial patterns of ensuing trophic cascades and ecosystem shifts. These patterns of future ecosystem trends around Haida Gwaii could be analyzed using comparisons with other areas along the BC coast where sea otters have been restored or recovered naturally. For example, once sea otters recolonized in Alaska, kelp forests recovered quickly, establishing dominant understory species while sea urchins exhibited more cryptic behaviour (Estes & Duggins, 1995, Jamieson & Davies, 2004).

Once a breeding population has been established on Haida Gwaii, sea otter and kelp forest recovery on Vancouver Island and BC central coast could be used as a proxy for trends on Haida Gwaii (Lee et al., 2016; Markel & Shurin, 2015; Watson & Estes, 2011). Some otter populations have shown exponential increases in numbers, resulting in the removal of urchin barrens and recovery of kelp forests to a depth of 11 m and across a 50 m transect within 1.5 years (Harrold et al., 1985). The most dramatic impacts recorded at sites of natural population expansion showed sea urchin biomass decline ranged from 50-100% at reoccupied sites within a 3- to 15-year period (Estes & Duggins, 1995). While kelp recovery has shown to be significant at sea otter recovery sites, it has also varied regionally based on urchin growth and sea otter prey selection (Watson & Estes, 2011; Tinker et al., 2007; Estes & Duggins, 1995). Behavioural or ecological barriers may impede the predicted rates or distribution of kelp recovery (Estes et al., 1989). In areas where sea urchin reproduction and recruitment occur frequently and successfully, the density of urchins may initially increase as sea otters consume urchins larger than 30 mm diameter and smaller urchins remain (Estes et al., 1989). As sea otter population densities increase, smaller urchins may be consumed, and kelp may recover over several decades (Estes et al., 1989). Additional biotic factors contributing to temporal and spatial patterns of kelp recovery may include the home ranges of returning sea otters, the frequency of sea urchin recruitment, and the equilibrium density of a recolonizing otter population (Estes et al., 1989).

In consideration of future ecosystem shifts and ecosystem threats, fisheries should be managed with an understanding of the historical, cultural, and ecological context of kelp, sea otter and urchin dynamics, distribution and relation to fisheries. Stakeholders have concerns about sea otter recovery and the subsequent consumption of highly valued

macroinvertebrates. The voracious appetites of sea otters have implications for First Nations' food sovereignty, subsistence, social, and ceremonial rights (Salomon et al., 2015; Sloan & Dick, 2012). There are now several generations of people who have grown up with a marine ecosystem that is absent of sea otters and bountiful with invertebrates. Traditional practices, like sea otter hunting, no longer occur and there is a reliance on accessible shellfish. Furthermore, the commercial sea urchin fishery also lists sea otters as the primary threat to sustainability of the urchin fishery (DFO, 2012a; Sloan & Dick, 2012).

Archaeological evidence suggests that before the maritime fur trade, coastal peoples used kelp forests as a source of food for thousands of years with varying disturbance regimes including localized predator exploitation, invertebrate population release, and limited deforestation (Steneck et al., 2002). Archaeological data collected from shellfish middens around Haida Gwaii show that local people harvested large amounts of invertebrates thousands of years ago, despite the presence of sea otters (Salomon et al., 2015). Middens included large urchins, indicating an absence of sea otters and the dominance of invertebrates in some areas of the coast (Salomon et al., 2015). One hypothesis is that during the pre-fur trade era there was a mosaic distribution of sea otters, with patches of absence around village sites where sea otters either avoided or were controlled spatially by indigenous peoples (Salomon et al., 2015). The historical magnitude of sea otter hunting before the maritime fur trade is unknown, but archaeological evidence suggests that sea otter hunting by indigenous people was ubiquitous in pre-contact times and occurred regularly at a sustainable rate (Salomon et al., 2015; Orchard, 2006; McKechnie & Widgen, 2011). Currently in Alaska, indigenous sea otter hunting occurs for cultural purposes, and similar developments are being discussed in Nuuchahnulth territory on Vancouver Island (Sloan and Dick, 2012). Restricted hunting is a controversial issue but may present an opportunity for reinvigorating traditional practices and knowledge in combination with marine research (Salomon et al., 2015). MSP and multi-spatial criteria analysis could contribute to select management of sea otter populations to reflect historical contexts of top predator management around Haida Gwaii.

Urchins are considered an indigenous coastal food, but they were not fished commercially on the BC coast until the latter half of the 20<sup>th</sup> century. The fishery began in the 1970s for roe, or uni, as a result of macroinvertebrate population release after the fur-trade era (DFO, 2012a; Sloan & Dick, 2012). The roe is eaten raw, often on sushi. However, none of the

commercial urchins are processed on Haida Gwaii, and few of the fishermen are island residents (Sloan, 2006). Urchins are shipped to Vancouver where they are processed and sent to Asian markets (DFO, 2013). Despite fears of future commercial losses, one scenario involves kelp restoration contributing to the profitability of the urchin fishery through the improvement of gonad biomass (Claisse et al., 2013). Due to the increase in urchin barrens, lack of kelp food for urchins has resulted in low to no gonad development and reduced quality of roe in the urchin barrens (DFO, 2013). Despite the economic profits of the urchin fishery, residents on Haida Gwaii benefit more economically from razor clam and Dungeness crab fisheries which are also prey species for otters (Sloan 2006).

At present, sea otter consumption of macroinvertebrates may still be felt as an acute loss of individual marine species with commercial, recreational, and traditional importance, but the wider implications and potential benefits to other fisheries and opportunities will be less obvious. Increased detritus and habitat provision from kelp forest recovery will support a variety of species including those of commercial interest, like salmon and rockfish (Sloan & Dick, 2012). The extent of these benefits may depend on the structural complexity of kelp forests, including stipe density (Bertocci et al., 2015). In general, there are direct and indirect positive correlations between kelp and fishery-relevant variables, most particularly the protection and food sources provided to juvenile species (Bertocci et al., 2015). Benefits to fisheries could potentially contribute to some of the more valued commercial fisheries which include the sablefish, halibut and Dungeness crab (*Cancer magister*) fisheries as well as fisheries that have been closed due to overexploitation such as for herring and abalone (MaPP, 2015; Sloan and Dick, 2012). Kelp is identified as a feature of critical habitat for abalone (DFO, 2012b). For example, on Haida Gwaii and the BC coast, kelp biomass has been strongly associated with larger abalone and greater abalone biomass (Lee et al., 2016). As an algal-drift feeder, abalone may out-compete urchins when there is an abundance of detritus, as well as subsist cryptically with the presence of sea otters (Tegner & Dayton, 2000; Hines & Pearse, 1982; Lowry & Pearse, 1973). Herring that spawn on kelp and use kelp habitat during early rearing are anticipated to benefit from increased kelp growth (Wheeler, 1990). Benefits to herring are important for local indigenous as well as potential commercial fisheries for herring roe-on-kelp. Finally, greater kelp growth increases opportunities for cultural and commercial harvesting of kelp. Additional factors to include

in multi-criteria spatial analyses for kelp harvesting may include data on nutrients and temperature that contribute to the quality of kelp growth as well as accessibility to harvesters.

Assessing the potential gains and losses from a restored historical trophic structure in the nearshore could provide complex challenges for EBM (Tallis et al., 2010). With the use of potential mapping and analyses, related or conflicting issues and uses can be evaluated together using spatially explicit data. Tangible kelp services can be assigned monetary valuations for spatial analyses. It is also possible to analyze non-market economic valuations, many of which are context-specific. Predicted increases in kelp growth from model results indicate a potential five-fold increase in valued kelp forests. Furthermore, spatial analysis using potential habitat modelling provides an opportunity to consider multiple future outcomes resulting from different ecological changes and impacts of management decisions. For example, spatial analyses might be able to contribute to assessment and management of practices surrounding traditional sea otter hunting. The Haida Gwaii Marine Plan species identifies some particular values associated with kelp forests such as herring spawn, traditional use and critical marine habitat. All types of valuations can be mapped with biophysical data to produce value transfers to species distribution (Troy & Wilson, 2006).

MSP provides a means of incorporating multiple objectives and stakeholder values with ecological data into management discussions and provides a tool to work towards conflict resolution through integrated approaches to management (Douvere, 2008). For example, a conflicting use may include shipping of hydrocarbons. Should a large oil spill destroy a significant portion of the BC sea otter population and damage nearshore ecosystems, potential kelp habitat modelling could assist in the calculation of kelp ecosystem services lost, providing a more accurate analysis of spill consequences, and informing management decisions about how potential spill risks could be addressed. For example, the International Maritime Organization designates Particularly Sensitive Sea Areas (PSSA) as protected by shipping route regulations where ships are supposed to avoid certain areas (International Maritime Organization [IMO], 2014). MSP policies, like PSSA, could apply to the results of the BC Marine Oil Spill Prevention and Preparedness Strategy sensitivity and vulnerability analysis and mapping (BC Ministry of Environment, 2013). Detailed nearshore mapping and predictive modelling could contribute to future spill preparedness and response plans through MSP and the cost evaluation of oil spills.

## 5.3 Directions for future studies

### 5.3.1 Model improvements

The methodology for developing habitat suitability models was successfully used to map potential kelp habitat distribution, but the results were limited by available data sources and resolution of the data. Furthermore, the models require validation with ground-truthed data that was limited by the availability, type, resolution, and attributes of secondary data sources (Greene et al., 2005). For example, the lack secondary classifications for substrate data limited geoprocessing of substrate types. Outside of the Hard-a to Mixed-a polygons, representing 67,328 ha, there is less certainty about the suitability of the substrate layer for kelp habitat. Additionally, while the ShoreZone data indicates the presence of kelp on the southeast corner of XaaydaGa Gwaay.yaay IinaGwaay (Graham Island), kelp forest growth was not expected over a spatial distribution at that distance from shore. Potential presence polygons could indicate the growth of prostrate kelps or, in contrast, may be the product of limited exposure data resolution at greater distances from shore.

In general, it is extremely difficult to display or calculate the amount of error in habitat mapping (Halley & Jordan, 2007). Potential habitat models may not be representative of actual habitat because the scale or resolution of the data used is low in particular datasets or not uniform throughout (Green et al., 2005). All data input layers for the potential habitat models had varying levels of point data resolution and extrapolation. To verify results, ground-truthed data should be overlaid with model results and have a confusion or error matrix applied (Halley & Jordan, 2007). Future studies may also include a random sampling of known kelp and urchin barren distribution to provide high-resolution data for comparison and verification of potential model results. The currently limited knowledge of errors and uncertainties associated with the potential habitat models need to be acknowledged when applying model results. High resolution independent biotic data in addition to ground-truthing would contribute to the repeatability, transparency and robustness of the data and model results (Halley & Jordan, 2007). Examples such as Hlkinul ChiiGas.sgi (Fairbairn Shoals) highlight the need for high-resolution data for more detailed comparison between model results and independent data.

### 5.3.2 Additional data collection

Modelled information could be verified and updated with dive surveys providing more point, line, and polygon data, especially for areas of uncertainty in the model results, like the southeast portion of XaaydaGa Gwaay.yaay IinaGwaay (Graham Island). To better understand and monitor additional variables, measurements for canopy-forming kelps could be taken from boat-based and in-situ instruments or satellite-based sensors (Wright & Heyman, 2008). Recent application of advanced mapping technologies, like multibeam sonar and backscatter data collection, means there is an opportunity to make improved maps and models with greater detail (Wright & Heyman, 2008; Halley & Jordan, 2007). Additional data to populate substrate, depth, and exposure datasets, as well as the inclusion of other variables like temperature and slope, are also expected to refine model results. Furthermore, comprehensive samples of kelp would help accommodate seasonal and inter-annual data needed to compare modelled distribution and abundance over time. Future studies that advance the resolution of biotic and abiotic data would contribute to accuracy and application of the potential kelp habitat model to management processes. However, even with additional data, marine habitat mapping is inherently uncertain due to habitat heterogeneity (Halley & Jordan, 2007; Kostylev & Hannah, 2007).

If the abiotic conditions necessary for kelp are present and mapped with sufficient resolution, there are still other factors that may influence the difference between actual and potential kelp habitat distribution. Other variables not included in the model, but that are known to impact kelp recruitment, survivorship, and density, are longshore currents, slope, aspect and temperature (Konary & Iken, 2005; Dayton et al., 1992). For example, currents affect the transport of nutrients that kelp absorbs for growth. Other more irregular variables may include some areas that may have poor reproduction, no historical dispersion, or a stressful event such as pollution that prevents kelp presence (Druehl & Clarkson, 2016; Wright & Heyman, 2008). For example, there are often exceptions to habitat classification, such as *Macrocystis* that grows in protected areas with soft bottoms (Dayton, 1985). Mixed substrates are not always alike and may have varying amounts of integrated soft bottoms and sedimentation that are known to scour and damage kelp which is why the detailed secondary classification of substrate BoP data is important (Dayton, 1985). Furthermore, some environments may be hospitable for certain life stages but not others (Dayton, 1985). Dissolved nitrogen and phosphate, as well as other trace amounts of nutrients, are important

for kelp growth, but variations in nutrients are impacted by temperature, light, and water motion (Dayton, 1985). It would be extremely difficult to isolate the impact of temperature on kelp in the field where kelp may not be impacted by temperature so much as it is impacted by nutrient depletion in warm water (Dayton, 1985). Temporal variations that influence kelp growth include seasonal stresses as well as irregular, extensive, and infrequent events like El Niños that produce warm and low nutrient waters, and acute storms (Sloan & Bartier, 2000). It is also these irregularities and seasonal changes in distribution that make predictive modelling a strong counterpart to relying on field-based observations which may not represent true absences or may over-represent rare or irregular species presence (Bustamante & Seoane, 2004). The potential habitat maps provide ecological boundaries concerning the abiotic conditions that might limit kelp growth; however, species behaviour, reproduction, interactions and dynamics introduce another level of complexity for kelp forest recovery. In addition to mapping potential kelp habitat, further research on the recovery of species composition and density of kelp would contribute to the study of kelp forest restoration and quantification of ecosystem services.

### **5.3.3 Succession**

Bottom-up habitat classification alone is not sufficient to determine kelp forest succession but it can provide a spatial framework for changing and increasing datasets, as well as define areas in which to analyze fluctuations in population. Further development of potential habitat distribution mapping may be able to contribute to mapping density and composition of kelp species. Advances in computer technology, as well as SCUBA and underwater research tools, have increased the capacity for underwater monitoring and the means to observe predicted ecological changes. With advances in nearshore habitat mapping and ground-truthing, projections for annual and perennial species of kelp could also be incorporated into the potential habitat model to provide a time series of kelp succession before and after sea otters return to Haida Gwaii. Particular kelp species recruitment and assemblages depend on variations in light, depth, and exposure variables (Smale et al., 2013; Dayton et al., 1992; Watson and Estes, 2011). However, additional factors like nutrients and temperature may be especially important to patterns of succession (Tegner et al., 1997). Opportunistic species like *Nereocystis* are anticipated to initially colonize followed by species like *Pterygophora* or *Saccharina groenlandica* (Watson & Estes, 2011). Further efforts in the ecological monitoring of kelp habitat could contribute sufficient detail to model short-lived, annual,

and long-lived perennial kelps, which could then be mapped according to zonation and succession timing (Leinaas & Christie, 1996).

## 6 Conclusions

Potential kelp forest habitat can be modelled through geoprocessing of nearshore depth as a proxy for light, substrate, and wave exposure GIS data layers. Actual kelp habitat is dependent on a complex range of biotic and abiotic variables and interactions, but potential modelling of kelp and sea urchin barrens contributes to a general understanding of kelp growth, biotic interactions and anticipated future changes. Bottom-up classification of potential kelp habitat mapping provides a means of estimating possible historical distributions and future recovery scenarios so managers can consider different nearshore ecosystem states and how decisions that impact kelp restoration can contribute to or detract from management objectives. There are limitations inherent in modelling, but with the appropriate recognition of these limitations, modelling can still be an effective tool for marine spatial planning that can inform an ecosystem-based management approach to marine planning and management. Detailed mapping of kelp also contributes to building a proxy for incorporating ecosystem services into EBM approaches.

Decisions about future kelp forests management and associated benefits will depend on an inventory of marine plants, including the distribution, species, and biomass of kelp (Sloan & Bartier, 2000). Ground surveys for a comprehensive inventory are not feasible due to cost, difficulty and the dynamic nature of nearshore kelp communities. Geographic information systems provide an efficient and cost-effective tool for mapping potential habitat by compiling and manipulating multiple datasets to analyze and present information for bottom-up habitat classification (Grega et al., 2013). Mapping kelp habitat presence and distribution is an essential part of monitoring the marine environment and incorporating and assessing the many complex combinations of viewpoints, values, and objectives involved in an EBM approach.

Mapping kelp habitat is also an important part of EBM and MSP because kelp forests contribute to growing healthy and resilient nearshore ecosystems, assist with the protection of species of conservation concern, and provide numerous and varied ecosystem services. While the topic of sea otter return is controversial, discussions about the future management of sea otters should include trade-offs with the myriad of potential direct and indirect benefits associated with the expected recovery of kelp forests (Sloan & Dick, 2012). Through the creation of spatial data that is context-specific, multiple and conflicting objectives and

stakeholder views can be mapped and assessed together (Douvere, 2008). The creation of spatially explicit EBM objectives could contribute to the implementation and effectiveness of sustainable management plans, restoration efforts, and holistic management approaches (Kaufman & Tschirky, 2010; Levin & Lubchenko, 2008; Villa et al., 2002). Some example objectives that would benefit from management based on spatially explicit data include increasing biodiversity, recovering species at risk, enhancing fisheries, and measuring and calculating ecosystem services. While there are many unknowns related to kelp forest recovery, our current understanding of trophic relationships affirms the need to integrate different types of spatial data to address cross-sectoral conflict and cumulative challenges in coastal and marine management around Haida Gwaii.



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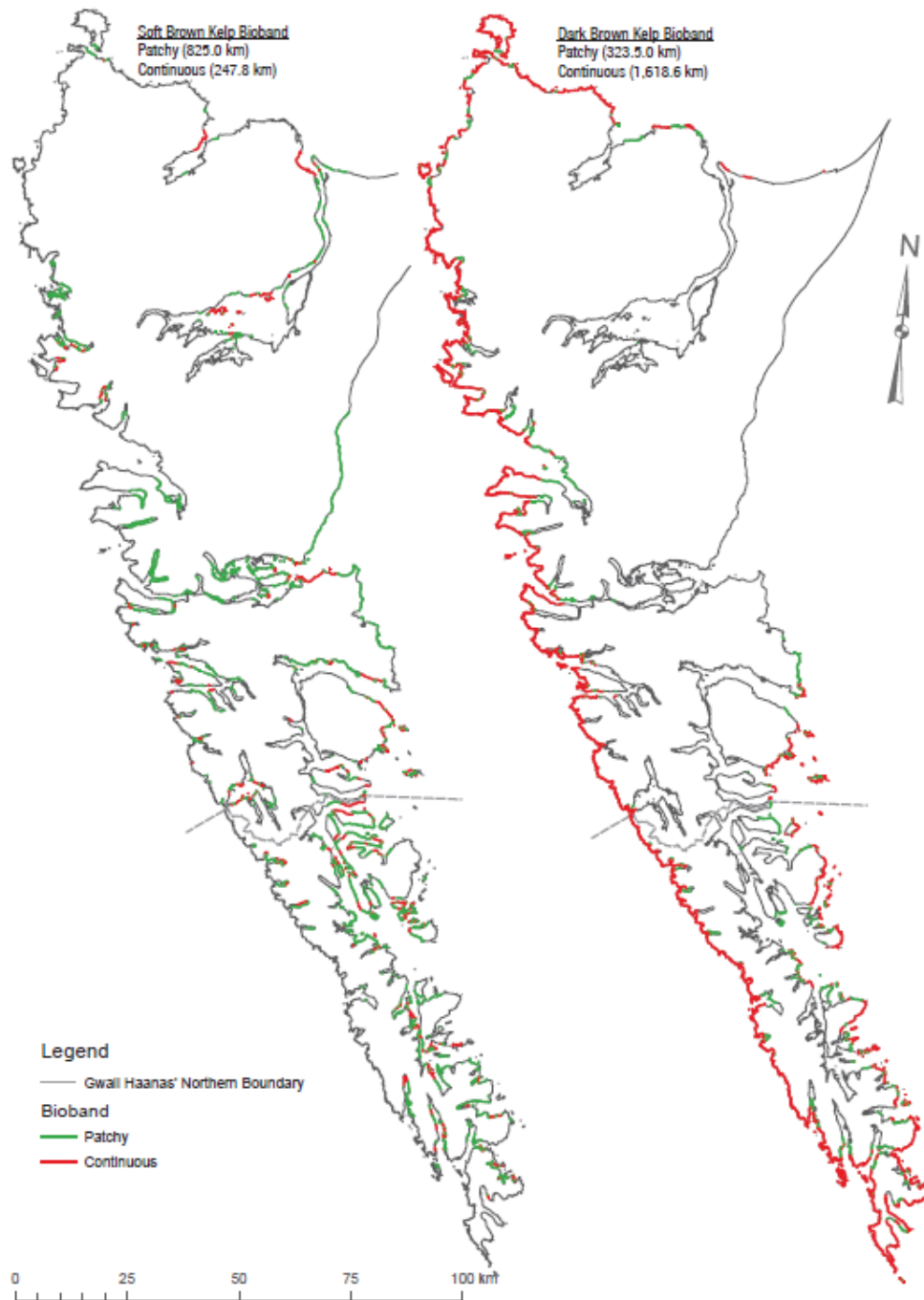
## Appendix A

*Protection Management Zones (PMZ) referring to kelp around Haida Gwaii (Haida Gwaii Marine Plan, 2015).*

Location	IUCN	Area (km <sup>2</sup> )	Description
Juu K'iijee Justkatla Narrows	IV	5.0	Protection of kelp beds and eelgrass meadows, critical habitat for a variety of marine species (including herring spawn) and an area with important Haida values, including traditional use.
Gáw Masset Inlet	V	255.4	Protection of important estuaries, herring spawn and Bull Kelp habitat in the unique ecosystem of Masset Inlet, and an area with important Haida values, including traditional use.
HI Gaagilda Llnagaay SGaagiidaay Skidegate Village	II	5.0	Protection of important estuaries, herring spawn and Bull Kelp habitat in the unique ecosystem of Masset Inlet, and an area with important Haida values, including traditional use.
Tluu T'aang.nga SGaagiidaay Northeast Maude Island	III	0.4	Protection of natural history site (unique fossils) and protection of eelgrass and Giant Kelp habitat and significant historic herring spawn.
Xaana Kaahlii SGaagiidaay Skidegate Inlet	V	240.2	Protection of the unique inlet separating Graham and Moresby Islands which contains the estuaries of multiple salmon streams, historical herring spawning grounds, important bird areas, eelgrass and kelp habitat, and an area with important Haida values, including traditional use.
Kehdaa Gwaayee NW Graham - Small Islands	Ib	0.6	Protection from disturbance of nesting seabird colonies and of surrounding waters rich in kelp, and an area with important Haida values, including traditional use.
Gwaays Kún Gagadiis West Langara Nearshore	Ib	3.0	Protection of important nearshore kelp beds, rockfish habitat and associated species assemblages, foraging habitat for marine bird species at risk, and an area with important Haida values, including traditional use.
T'aalan Stl'ang Gagadee Lepas Bay Inside	II	4.1	Protection of kelp habitat and an area with important Haida values, including traditional use.
K'iis Gwaay Aduu – Langara	V	97.9	Protection of nearshore kelp beds, rockfish habitat and associated species assemblages, nesting sites and foraging habitat for multiple marine bird species at risk, identified important area for Gray, Humpback

			and Killer Whales, and an area with important Haida values, including traditional use.
K'wayandáas Sda NW Graham Cape Knox	IV	24.2	Protection of nearshore kelp and eelgrass habitat, foraging habitat for marine bird species at risk and an area with important Haida values, including traditional use.
Jaalan <u>G</u> agadiis Jalun to Naden	VI	78.5	Protection of nearshore kelp beds, rockfish habitat and associated species assemblages, identified important area for Humpback and Killer Whales, and an area with important Haida values, including traditional use.
Xuuj <u>G</u> andlee <u>G</u> agadiis Virago East	Ib	10.9	Protection of coastal habitat representative of northern Graham Island, including multiple salmon streams, an important estuary, kelp and eelgrass beds, and an area with important Haida values, including traditional use.
T'alaasdaaw <u>G</u> agadee Old Massett	II	3.6	Protection of area adjacent to the village of Old Massett that contains significant Giant Kelp habitat and an area with important Haida values, including traditional use.
Needan <u>G</u> awee Niidan <u>K</u> aahlíi (Naden Harbour)	IV	48.0	Protection of important estuaries, eelgrass and kelp habitat and locations of significant historical herring spawn and an area with important Haida values, including traditional use.
Nang Xaldangaas	VI	41.6	Protection of coastal habitat along northern Graham Island including multiple salmon streams, an important estuary, kelp beds and an area with important Haida values, including traditional use.
Sasga Sda <u>G</u> agadiis Frederick Island to Tian	Ib	120.5	Protection of nearshore values, including inshore rockfish habitat and associated species assemblages, a significant estuary, Bull and Giant Kelp habitat, foraging habitat for marine bird species at risk and a Steller Sea Lion haulout
Kaa.nuu <u>G</u> aw <u>G</u> aay <u>S</u> <u>G</u> aagiidaay Kano Inlet	II	55.8	Protection of inshore rockfish habitat and associated species assemblages, kelp and eelgrass beds, and an area with important Haida values, including traditional use.
Chaahln Gwaay <u>S</u> <u>G</u> aagiidaay Gospel Island	IV	1.7	Protection of inshore rockfish and kelp habitat around Gospel Island in the middle of Rennell Sound and an area with important Haida values, including traditional use.

## Appendix B



*ShoreZone bioband data representing patchy and continuous polylines of kelp.*

