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Identification and Quantification of Rockweed using High-Resolution Satellite Imagery

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Executive Summary

Ascophyllum nodosum (rockweed) is a fucoid seaweed attached to rocky substrata in the intertidal zone of the east coast of North America, part of an extensive pan-North Atlantic distribution. Acadian Seaplants Limited (ASL) is involved in the processing of rockweed for worldwide food, biochemical, agricultural, and agri-chemical markets. Located in the Gulf of Maine and along the Atlantic shoreline, ASL manages and monitors the harvesting of rockweed resources along approximately 2,500 km of shoreline, distributed across 11 government-granted leases. The identification and quantification of the resource is challenging as a result of its occurrence across varied and extensive intertidal zones. Traditional aerial photography (used principally for forest resource assessment) is not flown with a low tide criterion, thereby limiting the value of the photos for monitoring intertidal species and habitat. With recent advancements in high-resolution satellite imagery (< 5 m) and the ability to angle the sensor, the repeat time to acquire an image over a site has been reduced. In this study, we have acquired four satellite images at low tide for areas in Southwest Nova Scotia. Three of the images are from the Worldview-2 satellite (0.5 m panchromatic and 2 m multispectral), including one image with all eight spectral bands and the other two with visible and near infra-red (NIR) bands only. One site was acquired using the older Quickbird Satellite (0.6 m panchromatic and 2.4 m multispectral) and provides visible and NIR bands.

Qualitative and quantitative results show that these data can be used to map the distribution and surface area of rockweed and other intertidal features over various seasons. Requirements include low tide, calm ocean waters (to reduce wave action and increase clarity), cloudless, and the inclusion of multispectral channels blue, green, and near-infrared. The first near-infrared channel of the Worldview-2 imagery proved as useful as the second near-infrared channel for classifying rockweed, leading to the suggestion that further imagery considerations require the standard R-G-B-NIR channels only. Area calculations of rockweed acquired by ASL for multiple sectors were provided and compared with area calculations derived from classification. Over 27 sectors, classification derived area yielded 22.37 ha more surface area of available rockweed than measured by ASL. Mean normalized difference vegetation index (NDVI) of available rockweed was higher during its fruiting season (May), than in August, which is likely attributed to the increased biomass while fruiting during the spring, although further ground truthing would be needed to confirm this.

1.0 Introduction

Acadian Seaplants Limited (ASL) is a worldwide leader in *Ascophyllum nodosum* harvesting for food, biochemical, agricultural, and agri-chemical markets. *Ascophyllum nodosum*, or rockweed, is harvested from over 2,500 km of shoreline in Atlantic Canada, much of which is complex shoreline with many offshore islands that make traditional locating and ground sampling methods very difficult.

Rockweed is the dominant species found in the intertidal zone attached to stable substrata like large boulders and rock outcrops (Chopin & Ugarte). Rockweed is nutrient rich and has many uses, from food to botanical additives (Seaplants, 2012).

The study area consists of three sites in Southwest Nova Scotia (Figure 1). These areas were chosen to represent complex coastlines within productive areas of ASL's government granted leases.

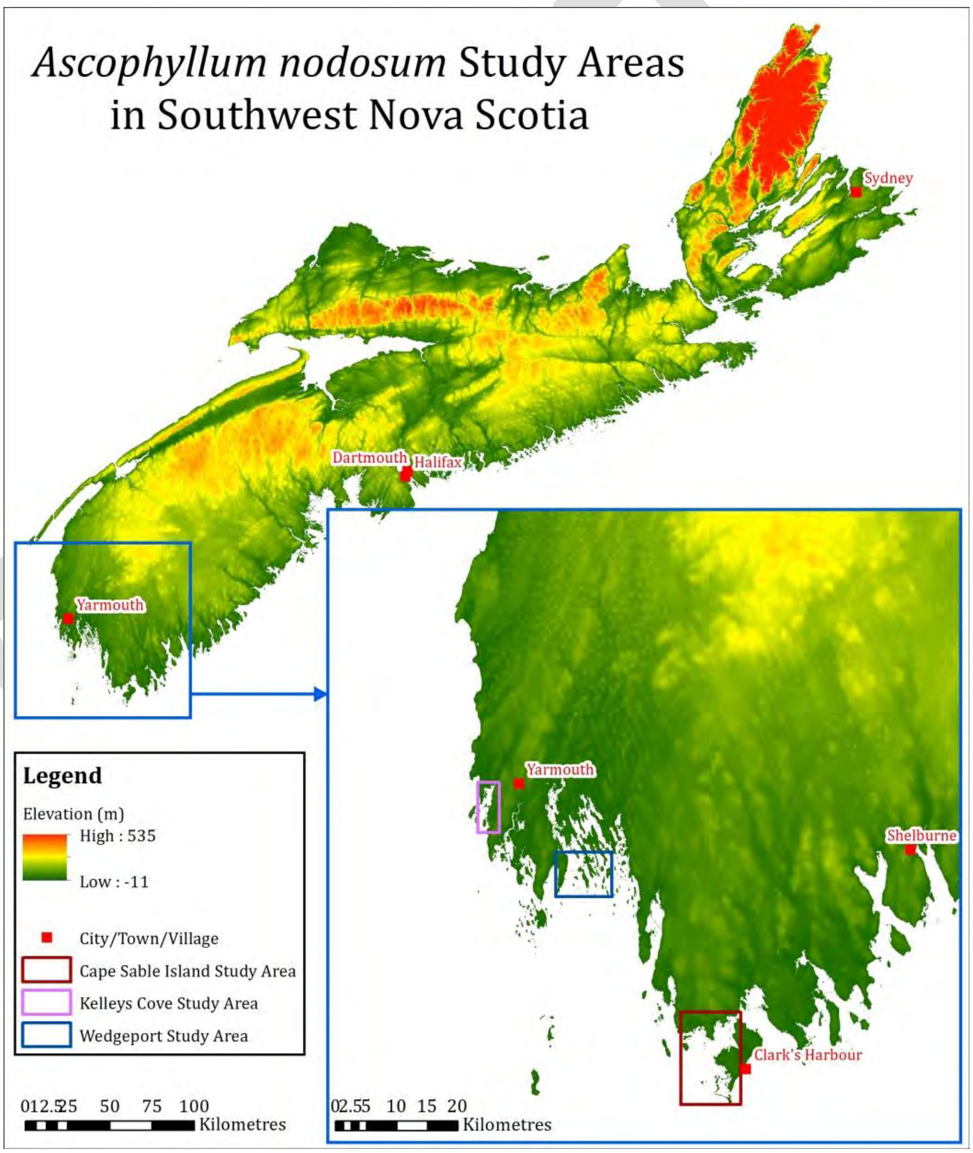

Figure 1. Study areas where satellite images were obtained for locating and quantifying rockweed.

The study areas consist of coastline in Kelleys Cove and Wedgeport, both in Yarmouth County, and Cape Sable Island in Shelburne County. All study areas comprise a mix of sandy, rocky and muddy shorelines, sometimes with large areas of salt marsh grass and other mudflat vegetation. A representative shoreline of the Wedgeport area, shown in a true and false colour composite (Figure 2), consists of long grass and shrubs on the land, a strip of cobblestone sized rocks, a muddy but firm strip of long beach grass, and large patches of rockweed interspersed with sandy and pebbly areas. Rockweed nearest to the shore has been exposed the longest due to the outgoing tide and is thus the driest.

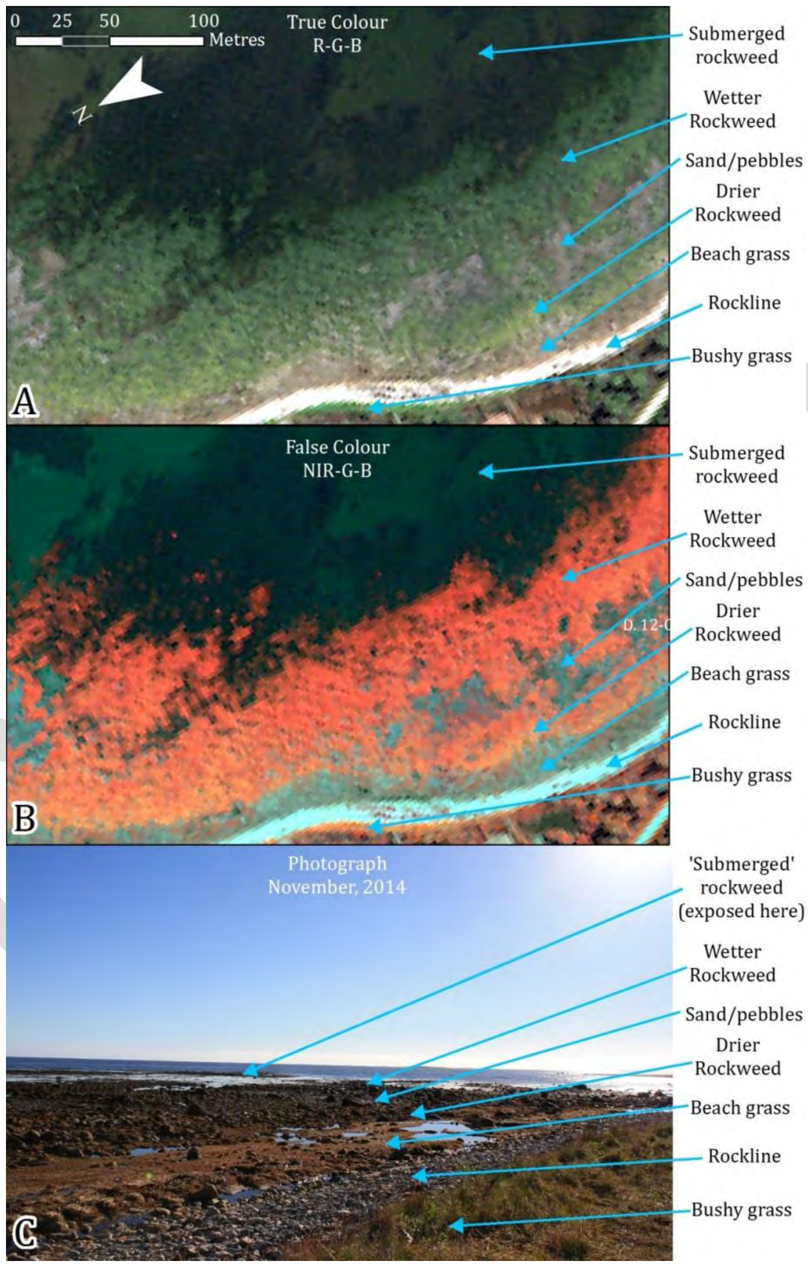

Figure 2. Examples of a typical Wedgeport area shoreline showing various features in addition to rockweed. Note the reflectance differences between the different features, particularly the beach grass and wetter versus drier coastal rockweed on both an R-G-B composite (A) and NIR-G-B composite (B). Photograph taken in November, 2012.

The current method of locating and quantifying rockweed involves visually assessing old aerial photos to delineate rockweed and non-rockweed areas. These aerial photos were gathered traditionally for forest resource assessments, and as such were not necessarily flown with a low tide criterion. In addition, these aerial photos were not flown systematically, resulting in incomplete coverage and adjacent photos spanning as much as a decade through different seasons.

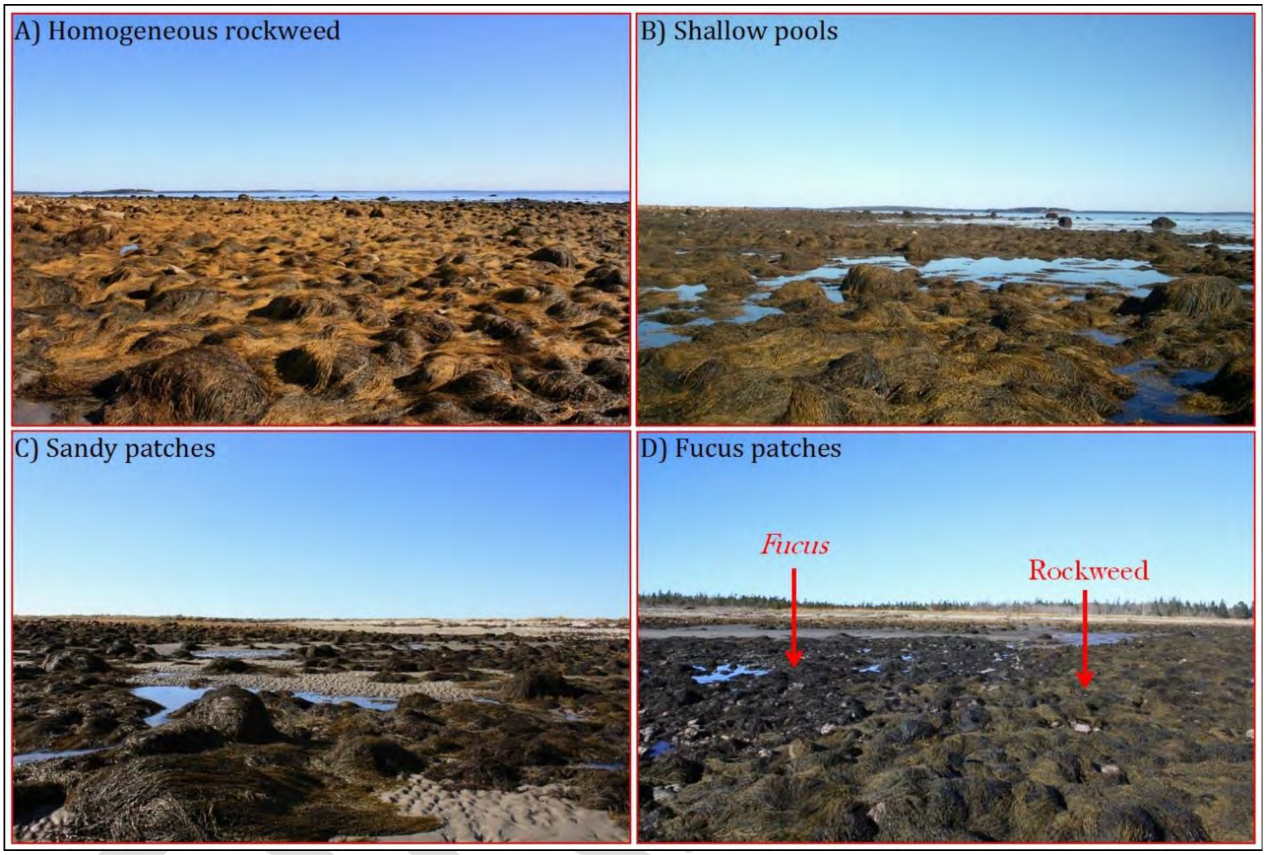

Figure 3. Photos showing an optimal shoreline of homogeneous rockweed (A), compared with more problematic shorelines featuring patches of water (B), patches of sand (C), and patches of an undesirable *Fucoid* seaweed (D). All photos taken in November, 2012.

Finally, there is no colour balancing between the photos which can cause interpretation problems such as exclusion of legitimate rockweed or inclusion of patches of sand, shallow pools of water, or patches of an undesirable group of seaweeds known as *Fucus* (Figure 3). Such interpretation problems can cause over or underestimates of available rockweed biomass. To compound the colour issue, rockweed changes colour throughout the summer. It changes from a very green colour in early spring to a bright yellow colour in late fall (Figure 4) as plant nitrogen levels decline.

Figure 4. Rockweed is very green in the early spring (A) compared with a yellow colour (B) later in summer.

Various studies have addressed the possibility of using remote sensing to identify a coastal resource, though many of them focus on kelp and fucoid seaweeds. Kim et. al. (2010) concluded detection of floating kelp beds is possible through Normalized Difference Vegetation Index (NDVI, a well-known index of vegetation health) analysis of high-resolution imagery, although excessive sun glint and cloud cover causes confusion with classification. Guillaumont et. al. (1993) successfully related cover to biomass for *Fucus* sp. and *Ascophyllum nodosum* using SPOT imagery combined with extensive ground field surveys. Another case study conducted by Pauly (2011) details successful monitoring of intertidal vegetation using classification of blue, green, and near-infrared mosaicked aerial kite photography. The same study concludes classification of intertidal features using a blue, green, near-infrared composite image is superior to classification of a true-colour image (Pauly, 2011). Recent research using new spectral bands of the Worldview-2 satellite indicates new bands, particularly the coastal blue, allow further penetration into the water column to obtain information about the shallow seabed (Silva, 2011) (Kerr, 2011), although none of these studies focused specifically on identifying seaweeds.

The proposed solution is to classify rockweed using recent high-resolution multispectral satellite imagery. Satellite images of Atlantic Canada are constantly being taken, and a vast archive of recent, high resolution multispectral imagery exists and is easily accessible. Satellites easily capture images of large swaths of land, including complex coastlines, and if a suitable recently archived, low-tide image is not available then the satellites can easily be tasked (ordered) to collect the required data. In addition to fulfilling recent, low tide, cloudless criteria, satellite imagery contains various multispectral bands that provide uniquely informative information. The most useful band for viewing vegetation is the near-infrared (NIR) band (0.7~ 0.9 µm) as vegetation is highly and uniquely reflective compared with water or dry bare soil/sand (Figure 5).

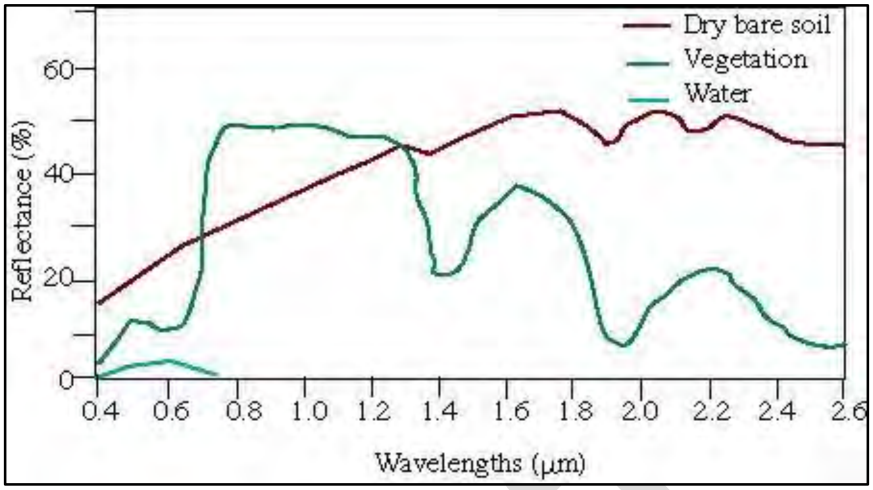

Figure 5. Reflectance of vegetation (green line) compared with that of water (blue line) and dry bare soil (brown line) through various multispectral wavelength. (http://www.ucalgary.ca/GEOG/Virtual/Remote%20Sensing/reflectance.gif)

DigitalGlobe's WorldView-2 Satellite, launched in 2009, contains four new bands in addition to the typical red, green, blue, and NIR. The new channels – coastal blue, yellow, red edge, and a second NIR channel – are potentially beneficial for classifying rockweed. The coastal blue may help increase the amount of information for submerged features in coastal zones while the red edge and the second NIR channel may help increase information of exposed vegetation.

Additional bands that are derived from analysis of multispectral imagery may be potentially beneficial for classification. Principal Component Analysis (PCA) extracts unique information from input bands and compiles it into new raster channels that represent the most important information from the input bands. Normalized Difference Vegetation Index (NDVI) is a well-known index of vegetation health, and is a mathematical calculation between spectral bands such that:

$$NDVI = \frac{(\text{NIR} - \text{Red})}{(\text{NIR} + \text{Red})}$$

In addition to classification potential, the relationship between NDVI (vegetation health or vigour) and biomass for each class of rockweed will be explored.

Classification algorithms for both supervised and unsupervised methods analyze the spectral information in user defined input channels, and group the spectral reflectance data based on user-defined input such as number of output groups (or land cover classes). Unsupervised classification algorithms group naturally occurring clusters of similar reflectance values into clusters that must then be interpreted by the user to determine what ground feature they represent (Lillesand, 2008). Unsupervised algorithms compare the various input bands and compute a mean digital number (DN) for each class, the number of which was previously defined by the user, and classifies each pixel by iteratively defining clusters in spectral space based on which unsupervised algorithm is chosen. Supervised classification algorithms require an additional training step before classification to outline pure areas of each desired feature to be classified. Supervised algorithms then analyze the spectral response of each feature's training area to determine various parameters including mean, standard deviation, variance, and co-variance between input bands. Supervised classification lets the user manipulate threshold settings for these parameters, allowing the user to fine-tune the classification of a particular feature. The process of classification is highly iterative, and requires visual interpretation of the results after each process is complete to determine if the results are successful. A perfect classification would include all rockweed in the image while excluding all non-rockweed features. However, in reality features have overlapping spectral responses, so a small degree of omission (desired feature not classified) and commission (incorrect feature classified) is expected.

2.0 Methods

2.1 Image Acquisition

There were many criteria to include when searching for ideal satellite images from the archives. Worldview-2 (WV-2) satellite images are thought to have the most potential due to a 2.5 m multispectral and 0.5 m panchromatic resolution, as well as four new multispectral bands. Quickbird (QB) imagery was also considered a possibility, with a 2.4 m multispectral and 0.6 m panchromatic resolution with a NIR band. Both sensors have large databanks of archived imagery that can be queried and viewed online, making choosing the most appropriate imagery possible. Since the NIR band does not penetrate water and is sensitive to vegetation, it is important that the rockweed be exposed above the water line.

Rockweed occurs only in the intertidal zone, requiring images to have been taken at the lowest possible tide to maximize viewing potential biomass. When WV-2 and QB satellites image the three study areas, they do so between 1500-1530 UTC which occasionally coincides with low tide. In addition, coastal imagery provides the clearest data when taken on calm, cloudless days. Submerged vegetation will be more difficult to classify due to the multispectral absorption qualities of water, and images taken on windy days may have large breakers and rough waters that make viewing any near-shore submerged rockweed even more difficult to locate. As well, cloudy conditions can cause classification problems due to cloud opacity and associated ground shadows. The final criteria requires images be taken recently (in the last few years) and optimally mid-June to mid-September. This time frame coincides with summer harvesting. As well, rockweed produces large fruiting vesicles in May as part of its reproductive cycle (Seaplants, 2012), and this extra temporary biomass could cause an overestimation of available rockweed.

Finding images that adhered to all criteria was challenging despite the abundance of archived imagery. For example, at the time of image selection there were 17 archived images that existed for the Wedgeport area (Table 1), but none adhered to the ideal acquisition timeframe of June – September, requiring an expanded timeframe of May - October. Ultimately, four images were obtained to be analyzed and while the criteria were adhered to as closely as possible, two acquired images were taken outside the optimal time frame (Table 2) but within the expanded timeframe. One image was acquired for Wedgeport, one for Cape Sable Island, and two were obtained for Kelleys Cove (Appendix A). Two image dates were acquired for Kelleys Cove, May 7, 2010 and August 19, 2010 to compare seasonal and other environmental effects. Having two images just three months apart (and one in May) allows for a fruiting versus non-fruiting comparison, as well as a sensor comparison as one of the images between WV-2 and QB.

Table 1. The number of available archived images for the Wedgeport area before (17) and after (0) selection criteria were applied, necessitating an expanded timeframe to obtain one clear, low tide image.

Wedgeport Area	# of Available Images
Archived images of area	17
Cloud-free in area of interest	5
Strict timeframe (June – Sept)	0
Expanded timeframe (May - Oct)	4
Low tide	1

Table 2. Multispectral bands, sensor types, and acquisition dates of 4 obtained images.

Study Area	Image Acquisition Date	Sensor	Resolution	Bands
Wedgeport	24-Oct-12	WorldView-2	2.0 m MS, 0.5 m PAN	Pan/Red/Green/Blue/NIR/Coastal Blue/Yellow/Red Edge/NIR2
Cape Sable Island	11-Sep-12	WorldView-2	2.0 m MS, 0.5 m PAN	Pan/Red/Green/Blue/NIR
Kelleys Cove	7-May-10	WorldView-2	2.0 m MS, 0.5 m PAN	Pan/Red/Green/Blue/NIR
Kelleys Cove	19-Aug-10	Quickbird	2.4 m MS, 0.6 m PAN	Pan/Red/Green/Blue/NIR

Without exception, all four images were obtained at the lowest possible tide. The predicted tide cycles for the closest tidal site to each study area were plotted to determine when the lowest tide occurred between 1500 and 1530 UTC. Figure 6 shows the predicted tide cycles for the closest tidal prediction site to each study area, with the time the acquired image for that area was captured overlain in red.

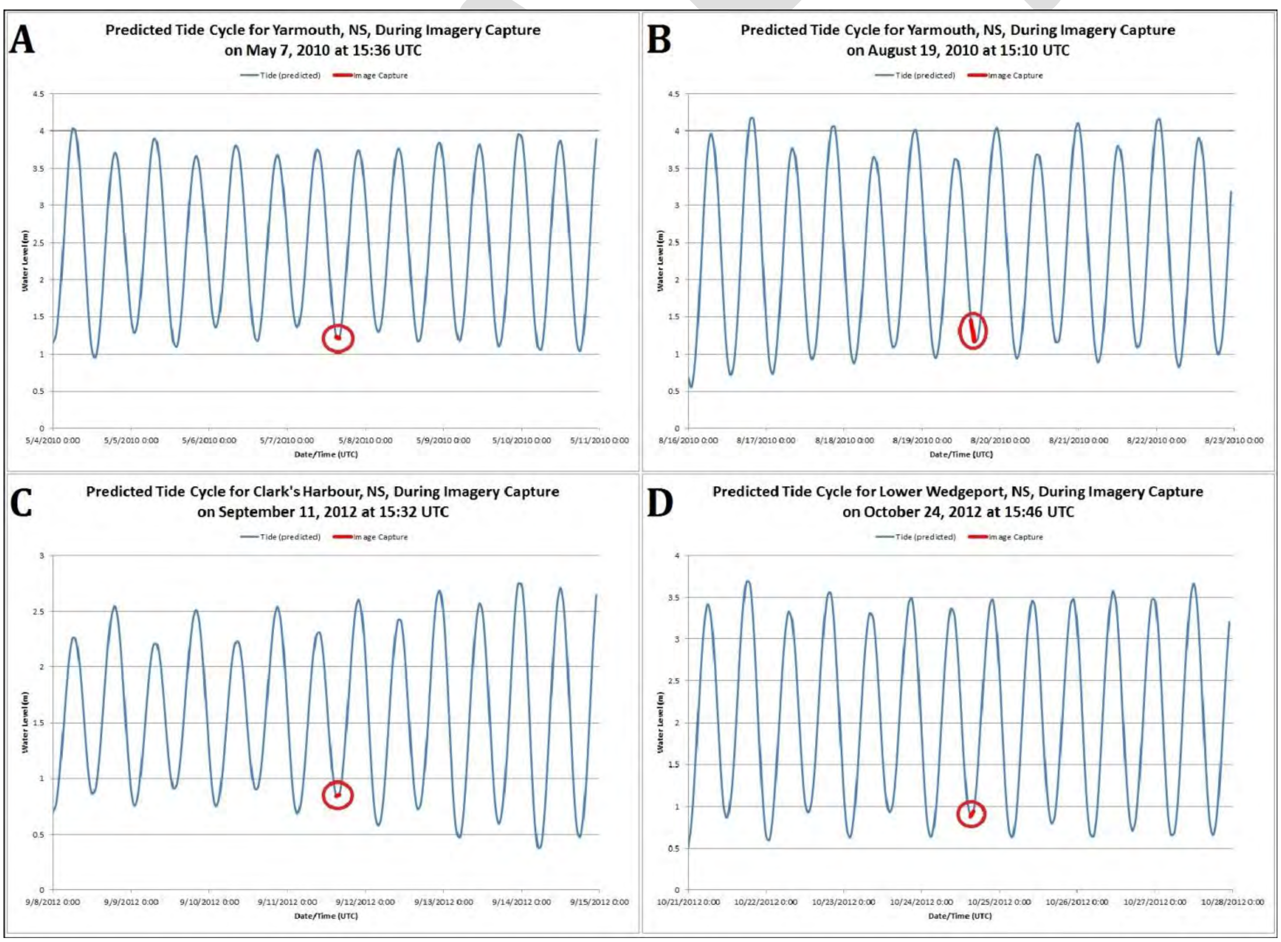

Figure 6. Predicted tide cycles (blue lines) for closest tidal prediction site to each study area, with exact time each respective image was captured (red line).

2.2 Pan-sharpening

While traditional air photos have a ground resolution of 0.5 – 0.6 m, no multispectral (MS) channels have such a fine resolution. Pansharpening using the panchromatic (PAN) band provides similar detail at 50 cm resolution, and thus all four images were pansharpened using a combination of the multispectral and panchromatic channels. All satellite image channels were georeferenced by image provider Digital Globe, thus no image co-registration was required prior to pansharpening. However, the MS images were scaled from their original 16-bit storage format (numbers stored using decimals) to accord with the PAN channel's 8-bit storage format (0 – 255, no decimals). Through a series of raster calculations, new pansharpened bands were produced by combining 80% MS and 20% PAN data. For image processing and raster calculations, PCI Geomatics' Geomatica 2012 image processing software suite, including Focus and EASI programs, were used in conjunction with ESRIs ArcGIS suite of GIS software.

2.3 Profile Creation

The WV-2 image of the Wedgeport area was acquired with eight multispectral bands (Table 3), including four new bands of the WV-2 satellite.

Table 3. Worldview-2 8 spectral bands

Worldview-2 Spectral Bands	
Coastal Blue*	400-450 nm
Blue	450-510 nm
Green	510-580 nm
Yellow*	585-625 nm
Red	630-690 nm
Red Edge*	705-745 nm
Near infrared	770-895 nm
Near infrared 2*	860-1040 nm
Panchromatic	450-800 nm
***new bands**	

To investigate which bands provided the most spectral separation between desired features, and if the new four channels provided useful information, spectral profiles were created through variable coastal features (seaweed, sand, pools of water, etc) in the Wedgeport area and the pseudo-reflectance values, or digital number (DN) values, analyzed through the eight different bands. A field visit to the Wedgeport area by Candace MacDonald and guided by Dr. Raul Ugarte on November 23, 2012 provided the knowledge and photographic observations necessary to select appropriate profiles which address the major coastal features of concern in this study.

One profile (Figure 7) was created adjacent to a wharf in the Wedgeport area and spanned from the wharf, through the rocks and rockweed, and into the water.

Figure 7. A subset of the Wedgeport true colour composite image (A, B) with a photograph taken from the ground (C) showing the profile line in the photograph (D) and on the satellite image (E). The line at the bottom represents the features through which the profile spans.

Another profile was completed in a different area within the Wedgeport WV-2 satellite image. This profile was located on a section of beach with a known patch of undesirable *Fucoid* seaweed, shown in a November, 2012 ground photo (Figure 8) and the same area on the imagery which was taken a month earlier.

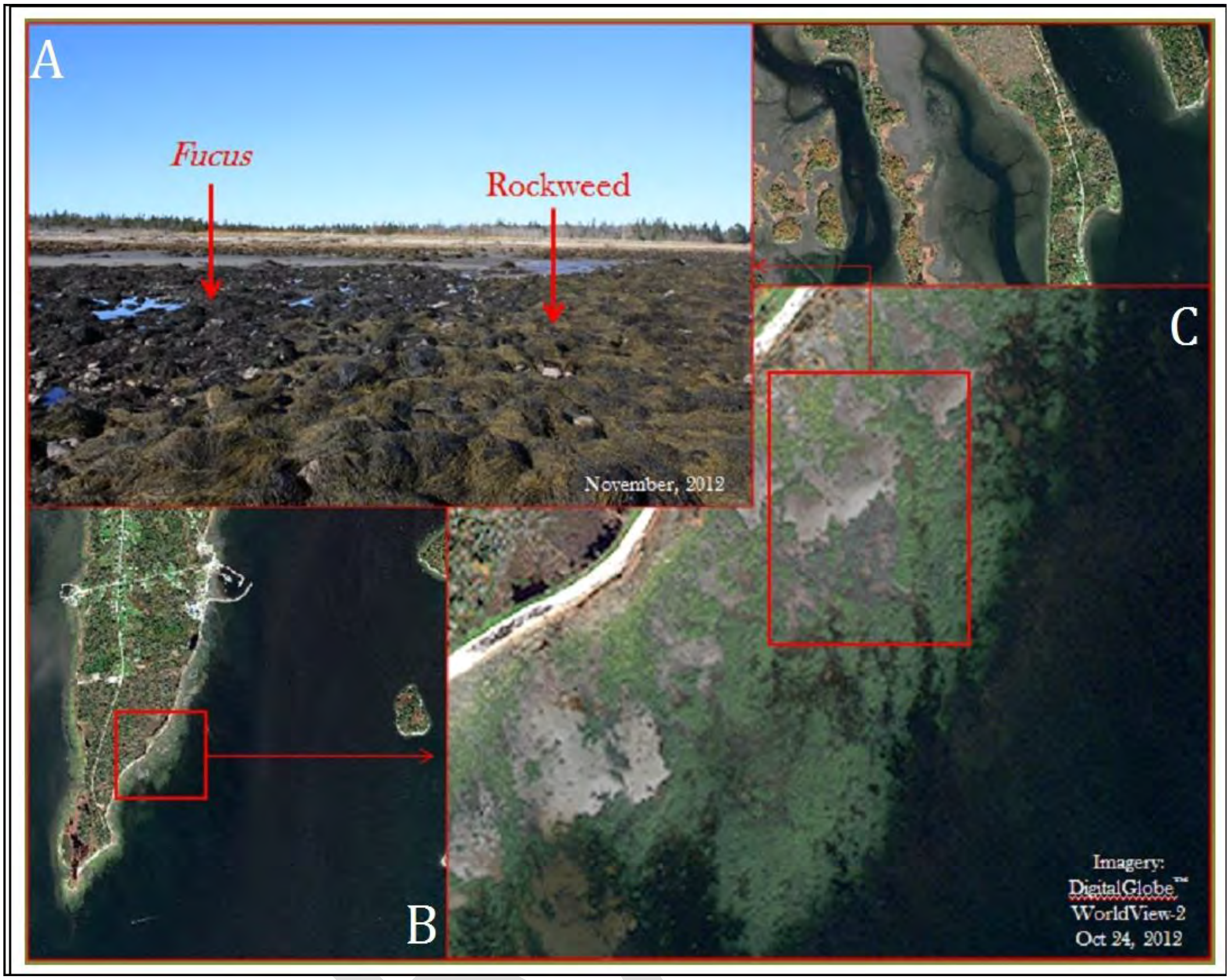

Figure 8. A ground photo (A) of a *Fucus* patch adjacent to a rockweed patch. The *Fucus* and rockweed beds can be seen on the RGB composite of the image, large scale (B) and smaller scale (C).

Figure 8 and Figure 9 show the profile spanning from a sandy patch, through the *Fucoid* type seaweed, and into a dense patch of rockweed. The profile passes over two shallow pools noted in the profile.

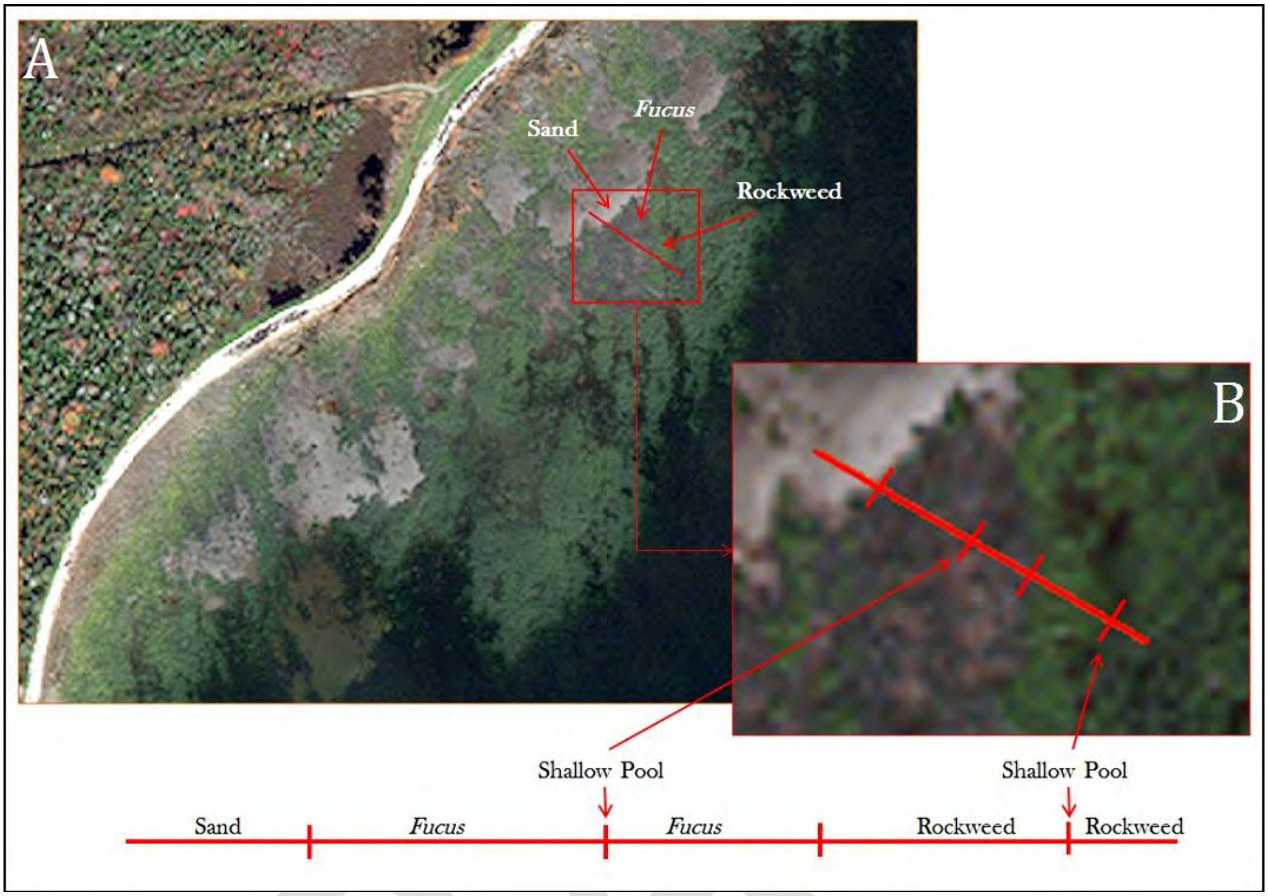

Figure 9. The location of the profile to assess the spectral reflectance difference between Fucus and Ascophyllum vegetation, larger scale (A) and zoomed in (B). The profile along the bottom shows the line through different features on a true colour composite image.

The results of the spectral profiles were analyzed. The bands that provided the greatest spectral reflectance difference between coastal vegetation types were chosen to proceed with classification.

2.4 Classification

2.4.1 Coast removal

The classification process groups input multispectral data into user-defined groups based on spectral means and standard deviations. Unnecessary spectral information in an image can make it more difficult to extract the desired features from the undesired features if they possess a similar spectral response. Removal of unnecessary spectral information in an image before classification has proven effective in salt marsh classification (Silva, 2011). In this case, as a type of vegetation, rockweed exhibits a similar spectral response as trees and other vegetation. Rockweed exists exclusively along the coast so removing all inland information would make the process of extracting rockweed from the remaining coastal vegetation more effective and eliminate commission errors.

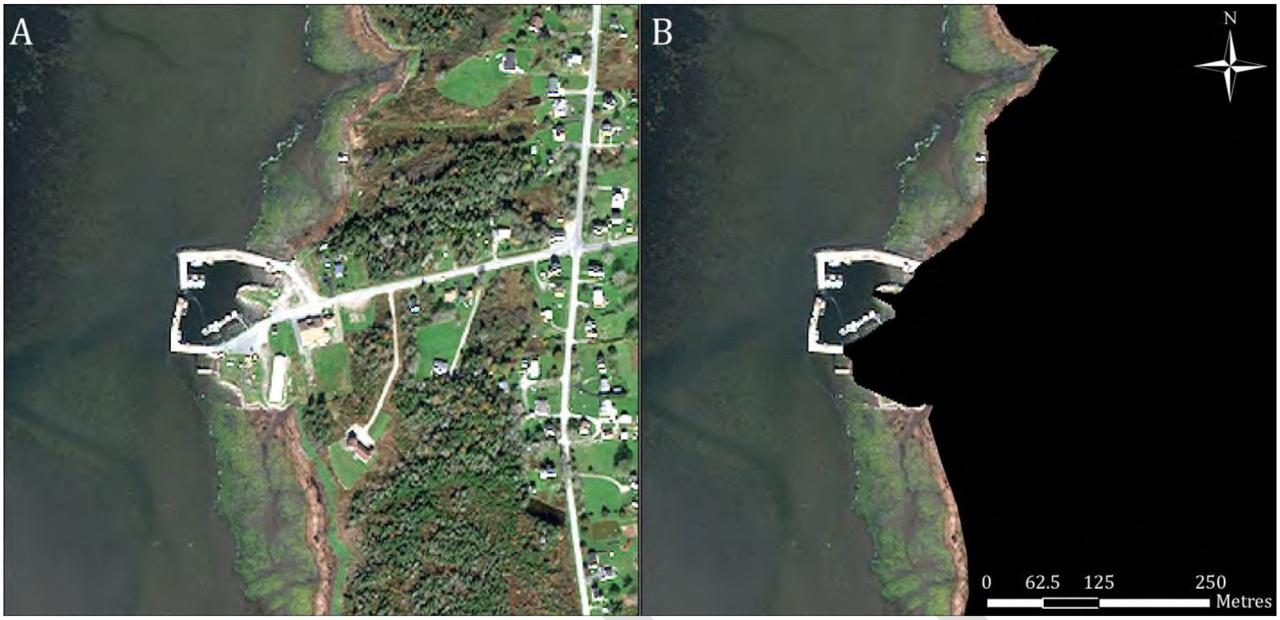

Figure 10. An area within the Wedgeport image shows a wide variety of land and coastal vegetation (A). The land data covered by the black coastline polygon (B) was removed to expose only the coastal area of the image.

A provincial coastline dataset obtained from the Nova Scotia Topographic Database was edited to ensure conformity between the coast polygon and the coast in each image. A series of raster calculations were executed to remove the land data from all spectral channels (Figure 10).

2.4.2 Unsupervised

As detailed in Section 1.0 Introduction, unsupervised classification requires the user to define the desired input spectral bands and appropriate classification algorithm, as well as the chosen number of output clusters, or classes. The software compares the various input bands and computes a mean digital number (DN) for each class, the number of which was previously defined by the user and classifies the image by iteratively examining and defining clusters in spectral space. The user visually assesses each class to interpret the feature the class represents.

The 8-band satellite image of the Wedgeport area (Appendix A) shows many offshore islands and coastlines ranging from rocky to muddy substrata. It was deemed the image most representative of complex shorelines, as well as the only image acquired with the extra four bands, and was thus chosen to experiment with various classification methods and algorithms to determine the best method for classifying rockweed.

2.4.2.1 Wedgeport

Unsupervised classification was executed on the Wedgeport image using various combinations of input bands, algorithms, and output class numbers. In addition to the 8 original MS bands, both NDVI and PCA results were included in the various input combinations. PCA was executed twice – once on all 8 original MS bands and once on just visible (R, G, B) and NIR – and the 3 most vital PCA results from each were included.

The results of the classification are polygons and values representing different classes. The classes were visually assessed to determine which feature each represented. Ideally, only one feature should be included within the polygon, and all of that feature present in the image should be within the polygon. So, one class should represent all the rockweed in the image, and not include any other features such as sand, water, or rocks. For visual assessment, the results of the different attempts at classification were compared with a true colour composite and an NIR-G-B composite and with previously ground-truth and photographed areas, such as in Figure 7 and Figure 8.

2.4.2.2 Other Areas

Worldview-2 images of the Cape Sable Island and Kelleys Cove areas, as well as the Quickbird image of Kelleys Cove, underwent unsupervised classification (7-class, K-Means algorithm) using various input bands (including NSVI and PCA results) and using NIR-G-B composite to interpret the results. For the results for each area, the single class representing rockweed the most successfully was extracted, and the surface area was calculated.

2.4.3 Supervised

As detailed in the introduction, supervised classification requires an additional training step before classification to outline pure areas of each desired feature to be classified. The supervised algorithms compare the spectral response of each constructed training area to determine various parameters whose thresholds may be manipulated iteratively and combined with visual analysis to obtain the most accurate classification with the least omission and commission.

2.4.3.1 Wedgeport

Supervised classification was executed on the Wedgeport image and compared to the unsupervised classification and ground truth data. Training areas (TA), or areas representative of one feature only, were created. Six distinctly different coastal features were identified in the Wedgeport image- rockweed, *Fucus*, rock/sand, mud, vegetated mud flat, and urban (such as wharves). The spectral reflectance range of rockweed alone necessitated the creation of sub-rockweed classes – submerged (underwater, barely any reflectance), wet (light, dim reflectance), dry dark (moderate reflectance), and dry bright (strong reflectance). In total, TA for nine classes were manually created by visually assessing a true colour and NIR-G-B composite of previously ground-truthed and photographed areas. Figure 11 shows an example of TA for non-seaweed features (A, C) on a true colour composite of the Wedgeport image. It also shows the spectral reflectance variation between *Fucus* and rockweed (B) and within rockweed classes (D).

Figure 11. An R-G-B composite of the Wedgeport image showing training areas for mud and rock (A) and urban (C, a wharf). It also shows the spectral reflectance variation between *Fucus* and rockweed (B) and within rockweed classes (D).

A maximum likelihood algorithm was chosen to perform supervised classification. This algorithm analyzes the spectral response of each TA to determine its mean, standard deviations, variance and co-variance. The algorithm then evaluates each pixel in the image to identify what TA to which it is most similar. If it is equally similar to more than one class, the algorithm places it in the class where it belongs to the lower standard deviation value. The user is able to manipulate the standard deviation values (the default SD value is 3), thus can fine-tune the classification of a particular feature by allowing a narrower or broader interpretation of pixels by decreasing or increasing the SD value (respectively). The purpose of this classification is to classify only the rockweed, thus accurate classification of all other non-rockweed pixels is secondary. To improve classification of rockweed, a NULL class was permitted in the maximum likelihood algorithm. If a pixel in the image does not fit into the user-defined SD values for one of the classes, it will be placed into the NULL class instead of forcing it to fit into an existing class which could potentially make the classification less accurate.

The SD thresholds were modified and the resulting classification visually analyzed in an iterative process until the rockweed was appropriately classified.

2.4.3.2 Other Images

The remaining images were classified in a similar manner. The pansharpened NIR-G-B composite with the same classification algorithm used in Wedgeport was used for each other image. Some sand and other non-rockweed related classes were eliminated as they were deemed unnecessary. Submerged rockweed was not as visible as its own class in the other three images as it was in Wedgeport, so this class was also eliminated from further classification procedures. Otherwise, the rockweed class structure used for supervised classification of Wedgeport was applied to Cape Sable Island and both Kelleys Cove images.

During each process, SD thresholds were iteratively modified to achieve the best results. In addition, densely vegetated mud flat areas scattered throughout the Kelleys Cove August QB image were outlined and removed from classification in the manner previously described for land data removal.

The resulting classification rasters were visually analyzed for omission/commission errors before further analysis.

2.4.4 Area Calculations

For each image, the resulting unsupervised and supervised classification rasters were converted to point and polygon shapefiles within ESRI's ArcGIS. A new field was added to the polygon attribute table to calculate the area of the desired class.

2.4.5 NDVI Analysis

To examine the relationship between NDVI, vigour, and biomass, the point classification shapefile for each area was used to extract and analyze the NDVI values for each class in that area. The mean NDVI and standard deviation values for each class were calculated and analyzed. The results were then compared with each of the other areas to determine any trends.

2.4.6 Sector Area Comparison

Surface area of available rockweed, aggregated by sector, was provided by ASL for various sectors across three of their leased areas. Totals for surface area of available rockweed (in hectares, ha) provided by ASL were compared with classification derived surface areas. As the sector is the smallest unit of aggregation provided, this comparison was completed only for sectors where classification results exist for the entire coastline (Figure 12).

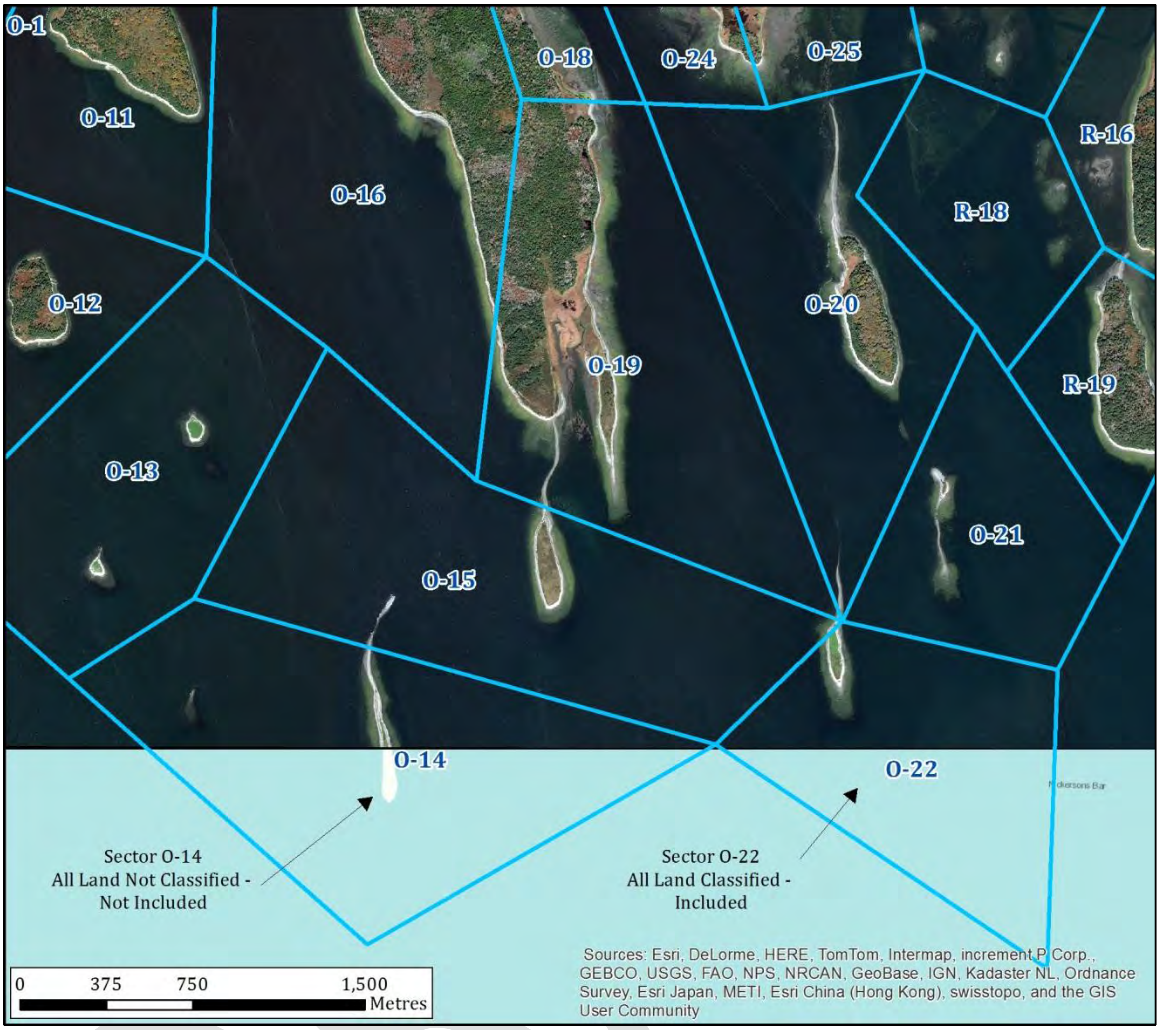

Figure 12. Sectors (blue lines) along the southern extent of the Wedgeport image, lain over a ESRI World Imagery basemap backdrop, shows sector O-14 contains coastline not included in the Wedgeport satellite image and thus was not included in the sector analysis. Conversely sector O-22 contains no additional coastline and thus was included in the Sector Analysis.

3.0 Results

3.1 Profiles

3.1.1 Wedgeport

Two profiles intersecting various coastal features were created to analyze the reflectance values across all eight MS bands of the WV-2 Wedgeport image. This was done to determine which bands were most useful for classifying rockweed. The most useful bands were the ones that show a unique spectral response in areas of rockweed compared to other features.

Profile A (shown in Figure 7) sampled an area including wharf, rocks, rockweed, and water (Atlantic Ocean). Figure 13 shows the profile spanning a true colour composite of the image, in which the wharf, rocks, rockweed, and water are visible. Rockweed shows a particularly strong and similar response in both NIR and NIR2 compared to all other bands (Figure 14). Rock shows a similar response in all bands with a slight exception in the green band, where a slight increase relative to the other bands is observed. Water exhibits a low reflectance that is similar in all 8 bands. The red edge band showed a moderate reflective response to rockweed, but showed a similar response to the wharf (DN≈60).

Figure 13. Profile (red line) of Wedgeport wharf, spanning features from wharf, rock, rockweed, to water. Profile in the direction of the arrow.

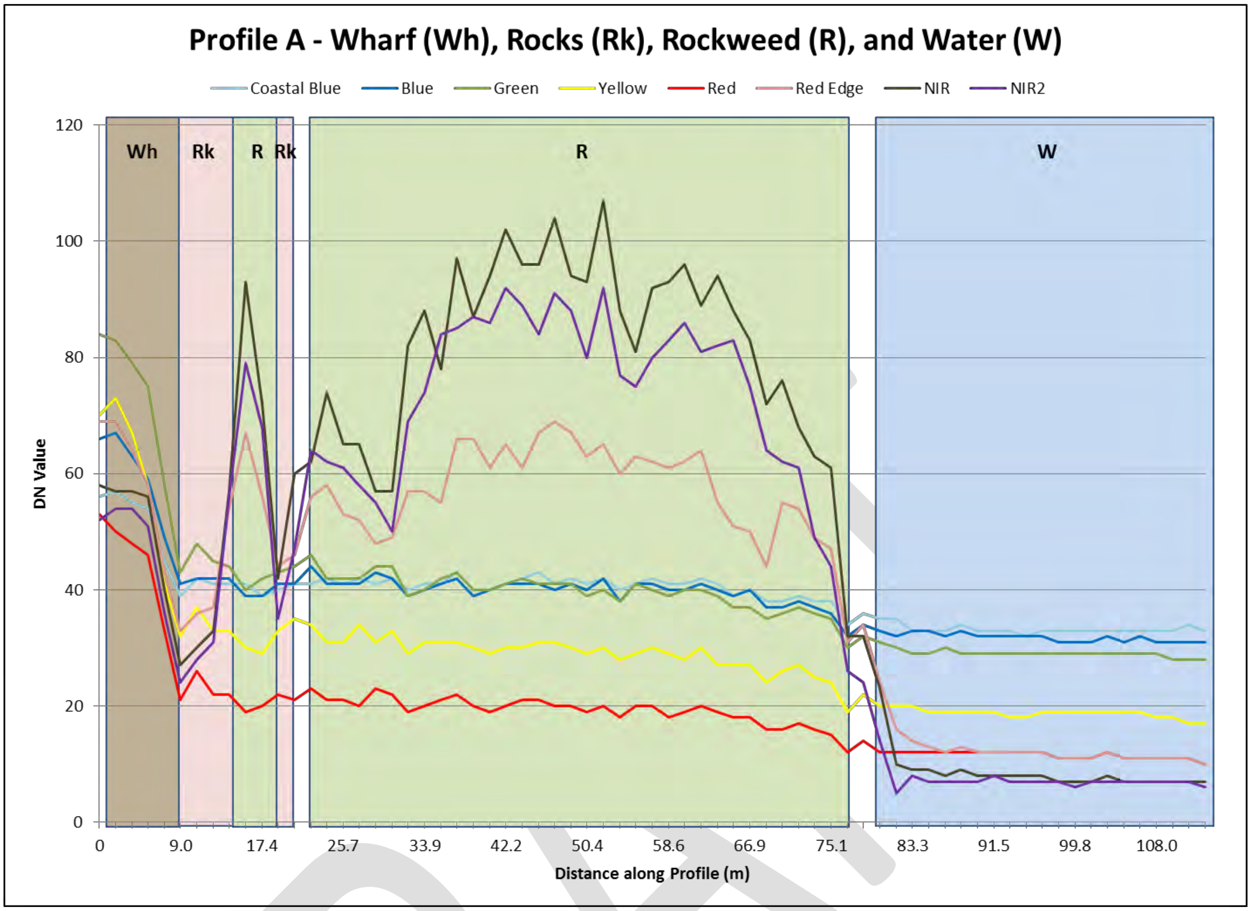

Figure 14. Spectral profile of 8 multispectral bands (coloured lines) in the Wedgeport WorldView-2 image. The profile intersects 4 features - a wharf (Wh, orange stripe), rockweed (R, green stripes), rocks (Rk, pink stripes), and water (W, blue stripe).

A second profile (Figure 15) included similar features plus a large patch of *Fucus*, a competitive species of seaweed, to determine if its spectral reflectance differed from that of rockweed. Figure 15 shows the profile spanning an NIR-G-B composite of the image, in which the sand, *Fucus*, rockweed, and water are visible.

Figure 15. Profile (red line) of Wedgeport Fucus area. The profile, shown on a true colour composite, spans sand, Fucus, rockweed, and water, with a few shallow pools of water.

Similar to Profile A, the most distinctive bands throughout sections of rockweed are NIR and NIR2 which show strong reflectance, and to a lesser extent the red edge band (Figure 14). The *Fucus* patch was easily identifiable using both NIR and NIR2, having a moderate reflectance (DN≈60) but not reaching the reflectance levels seen in areas of rockweed (DN≈80). The red edge band showed a slight increase in reflectance in the *Fucus* patch, but a similar magnitude response was seen in the adjacent sand patch as well. Similar to Profile A, water exhibits a low reflectance in all 8 bands.

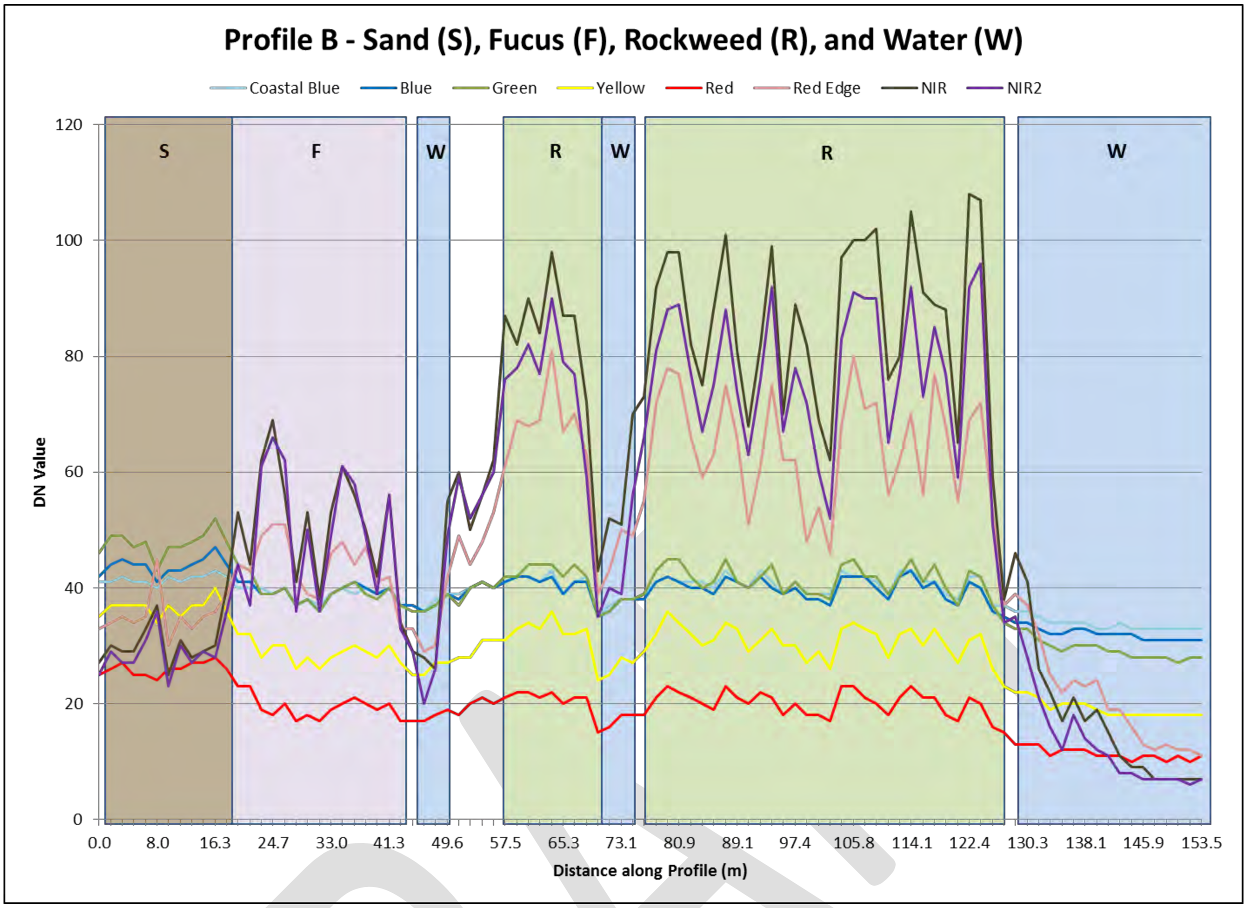

Figure 16. Spectral profile of 8 multispectral bands (coloured lines) in the Wedgeport WorldView-2 image (Figure 13). The profile intersects 4 features - sand (S, orange stripe), Fucus (F, purple stripe), rockweed (R, green stripes), and water (W, blue stripes).

3.1.2 Cape Sable Island

The profile of the Cape Sable Island image (Figure 17) intersected areas of land, water, rocks, rockweed and submerged rockweed. The areas of rockweed are especially visible in the NIR band of the image (Figure 18), especially when compared with the remaining image channels – red, green, and blue. In areas of rockweed the NIR reflectance is much higher than the reflectance of any other band.

Figure 17. Profile (red line) of Cape Sable Island on a true-colour composite image. The profile spans land, rockweed, and water in the direction of the arrow

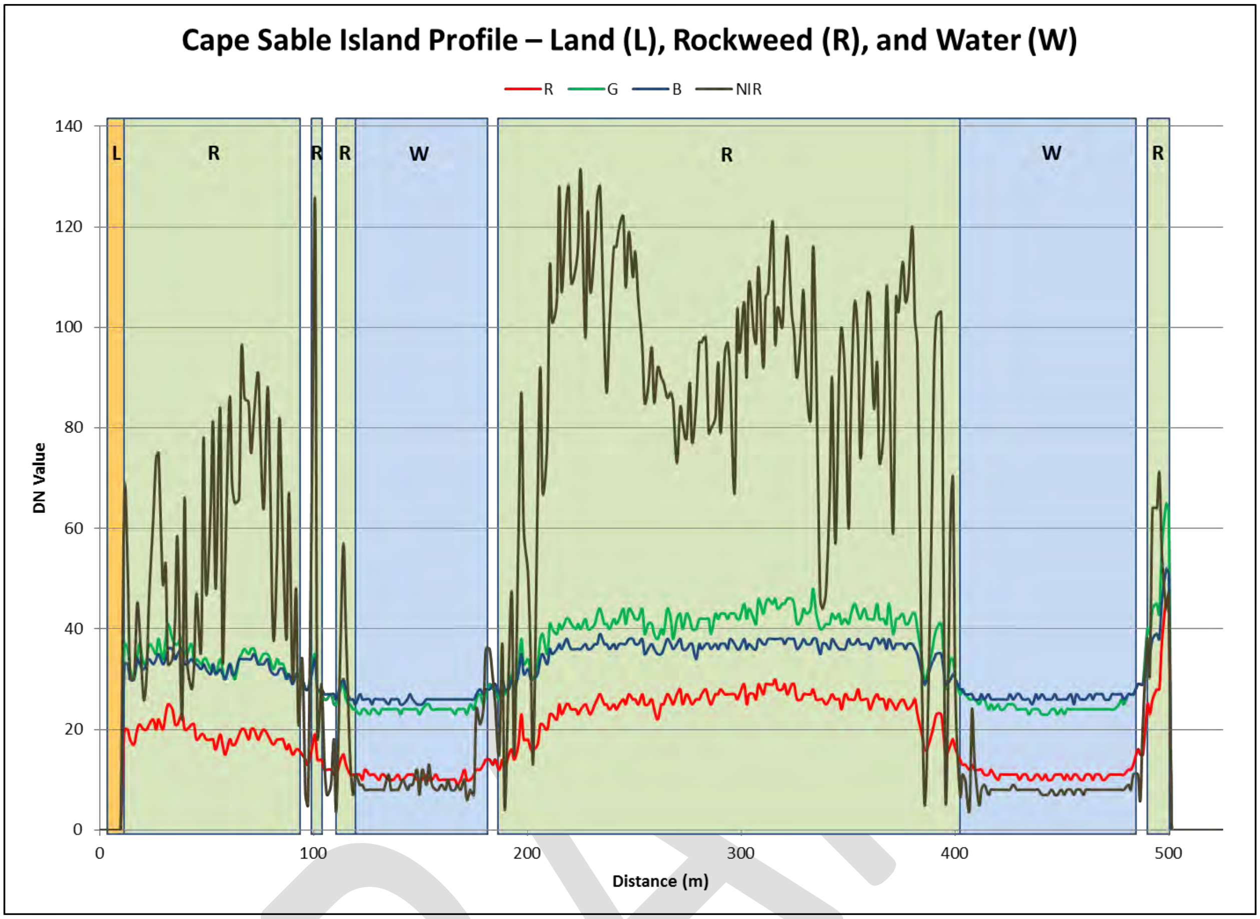

Figure 18. Spectral profile of 4 multispectral bands (coloured lines) in the Cape Sable Island WorldView-2 image (Figure 15). The profile intersects 3 features - land (L, orange stripe), rockweed (R, green stripes), and water (W, blue stripes).

3.2 Classification Results

The areas of known rockweed in the images were visually assessed to determine if the rockweed had any spectral differences within it that would affect the classification process. The coastline (such as in Figure 2) on a NIR-G-B composite was analyzed next to a true colour image and rockweed was visually split into 3-4 groups based on the brightness of its spectral response (Figure 19). Generally, rockweed closest to the land appeared brightest, and gradually became darker the closer the rockweed came to the waterline. This range was visually divided into bright, light, and dark rockweed. Typically, bright rockweed was found directly adjacent to the land and dark directly adjacent to the water, and was interpreted to represent different degrees of moisture in the rockweed. In addition, submerged rockweed was detected in shallow water areas in the Wedgeport image only, and thus 'submerged rockweed' was a 4th class of rockweed for that area only.

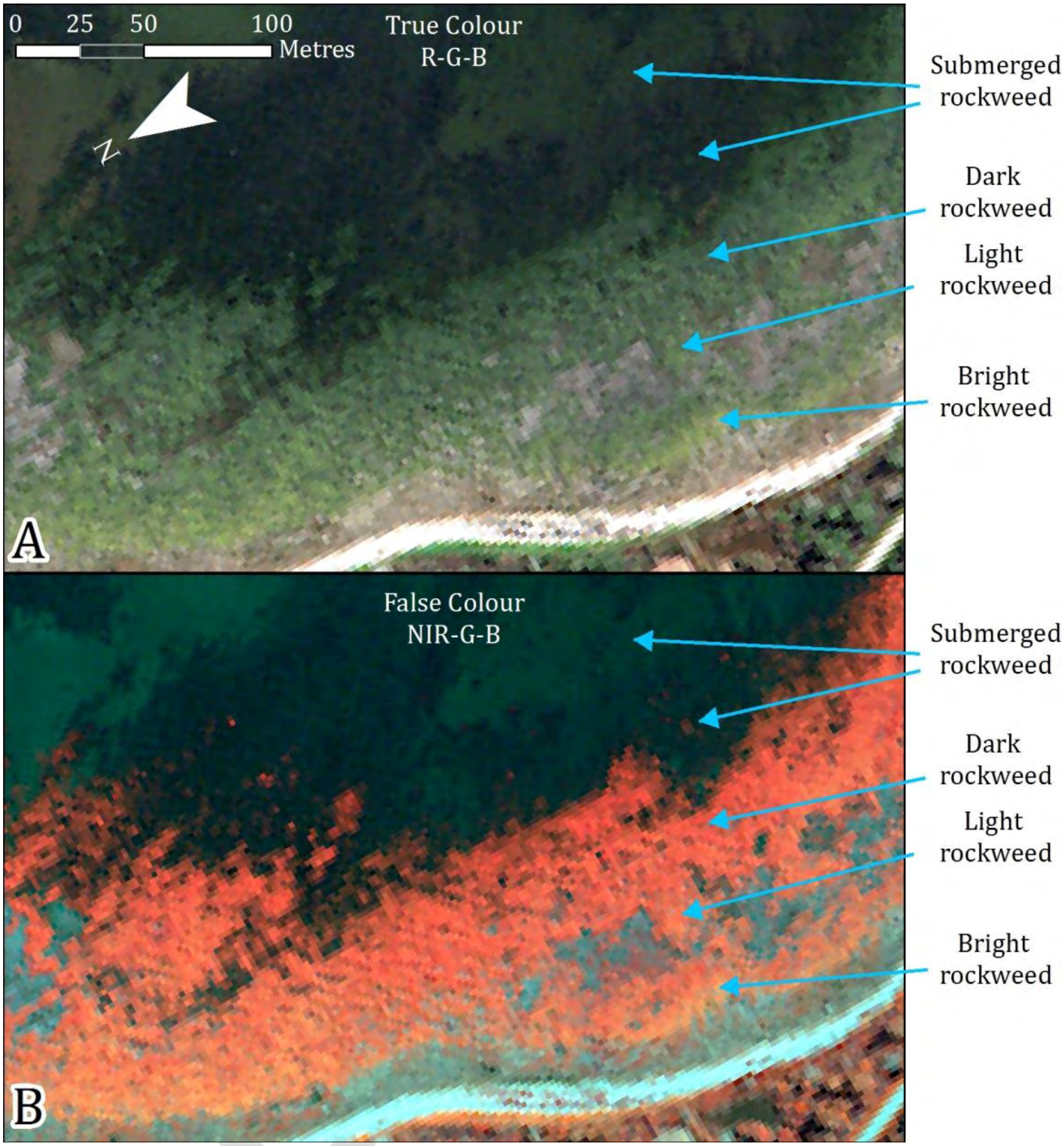

Figure 19. Examples of reflectance differences between the bright, light, dark, and submerged coastal rockweed on both an R-G-B composite (A) and NIR-G-B composite (B).

3.2.1 Wedgeport

The WV-2 Wedgeport image is defined by a multitude of offshore islands in addition to narrow points of mainland that jut into the ocean, thus forming a complicated, extensive coastline. On a true-colour composite (Figure 20), a greenish strip is seen in the intertidal zone along a large portion of the coastline, including the islands. Field validation confirmed the strip as primarily *Ascophyllum nodosum* (rockweed), with areas of sea-grass interspersed nearest the coast (Figure 2) and interspersed patches of undesirable *Fucus* sp. (Figure 8).

Figure 20. A complex shoreline with many offshore islands is characteristic of the Wedgeport study area, shown here on a true colour composite. The greenish strip prevalent along most coastlines has been identified by validation as primarily rockweed (A and B), while mudflat vegetation occupied other areas of coastline.

In addition to the predominantly rocky coastline host to ample rockweed, some sections of coastline are defined by variably vegetated mud flats which extend out far into the water (Figure 20C). These variably vegetated mud flats are submerged at different depths so they appear highly variable. Also, suspended sediment can be seen in some areas of the image (Appendix A).

3.2.1.1 Unsupervised

The WorldView-2 satellite image of the Wedgeport area was classified using various combinations of input channels which included 8 MS channels, NDVI, and PCA rasters. All classification runs, each using a K-Means classification algorithm, were visually analyzed to interpret intertidal features for the resulting classes. Regardless of input channel combination or the number of output classes, results always produced at least one class that mixed rockweed and non-rockweed features, thus necessitating an additional classification process to re-classify the mixed class. The results of that classification would also contain at least one mixed class of rockweed, thus confusion exists that the classifier could not resolve. However, the best classification was derived from a NIR-G-B composite.

In a NIR-G-B composite image vegetation appears in shades of red (due to the high NIR-reflectance of vegetation) while non-vegetated areas such as sand or rocks appear as blue or turquoise due to the NIR absorption. Figure 17 shows the results of the mixed class for each 8-band classification run draped over a NIR-G-B image (A). In each of the mixed classes (B, C, and D) both reddish pixels (identified as intertidal vegetation) and blue pixels (sand, rock) can be seen.

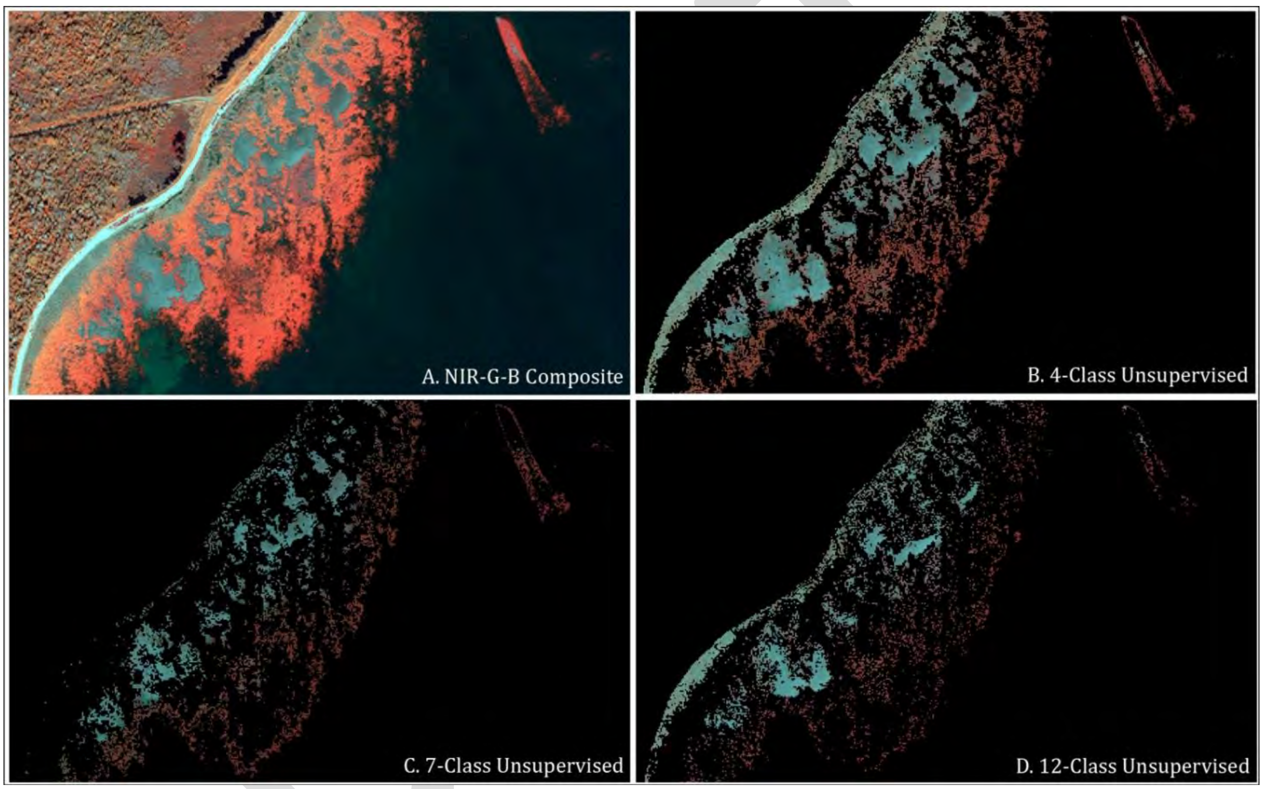

Figure 21. (A) A NIR-G-B false colour composite shows coastal vegetation in bright reddish hues and sandy or rocky areas in blueish hues. (B) A mixed class resulting from unsupervised classification with a 4-class output, (C) a 7-class output, or (D) a 12-class output.

The rockweed classified as the pure rockweed class covered 136.13 hectares (ha) which is considered an underestimation of true ground conditions, while the area of both the pure rockweed class and the mixed rockweed class amounted to 255.35 ha and is considered an overestimation. These estimates were compared with the supervised results and sector information provided by ASL in later sections.

3.2.1.2 Supervised

Supervised classification using a 'Maximum Likelihood with NULL class' algorithm was applied to various band combinations of the Wedgeport image. The standard deviation (SD) thresholds were iteratively modified to obtain the best results as compared to ground truth and interpretation of the image composites. In the end, the most successful classification was on a NIR-G-B combination (red was excluded), and the SD thresholds were increased for two classes (bright and dark rockweed) and decreased for two classes (light rockweed and *Fucus*) to achieve optimum results (Table 4).

Table 4. Standard deviation thresholds were utilized in the maximum likelihood with NULL class classifier. Standard deviation thresholds were increased for 2 classes and decreased for 2 classes while the others were left at the default value of 3.00.

Name	Threshold*
Bright Rockweed	4.00
Dark Rockweed	6.00
Light Rockweed	2.80
Rock	3.00
Mud	3.00
Mud Flat	3.00
Urban	3.00
Fucus	2.00
Submerged Rockweed	3.00

*Number of standard deviations from the mean

Figure 22 shows a portion of the Wedgeport image, including a patch of *Fucus*, successfully classified. Very little rockweed remains on shore that has not been classified as dark, light, or bright rockweed. Visual analysis revealed a very narrow strip fringing the submerged rockweed class that was classified as mud flat (Figure 23B). This strip is likely deeply submerged rockweed but has a similar spectral signature as mud flat areas. Consequently, threshold manipulation resulted in either overclassification of submerged rockweed (mud flat commission) or underclassification of submerged rockweed (omission) by excluding this very narrow strip in addition to all real mud flats in the image. The final classification excluded the narrow strip, a very small surface area of rockweed by comparison, in favour of a more realistic classification of available rockweed in other larger areas.

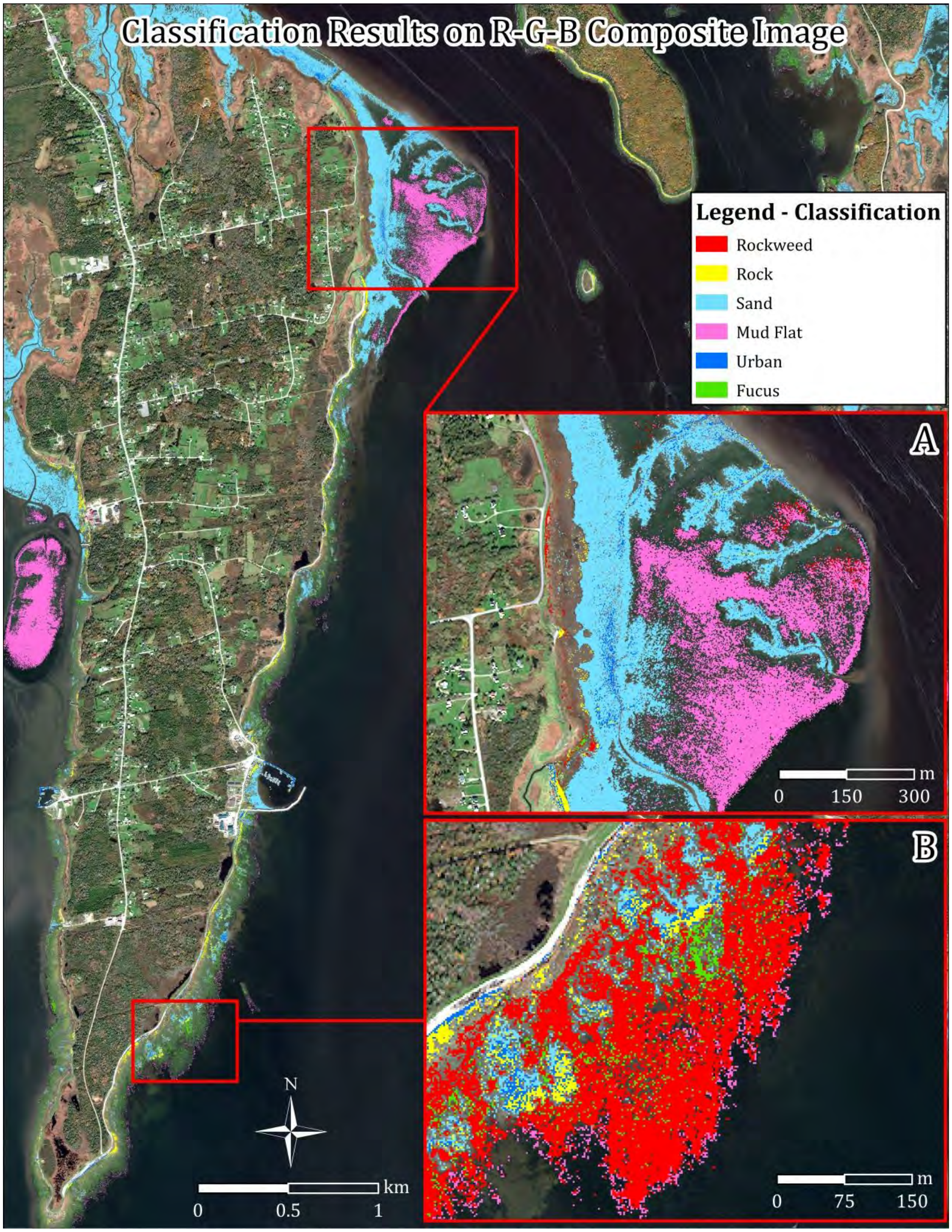

Figure 22. Wedgeport true colour image with supervised classification results showing correctly classified mudflats in A, and submerged rockweed incorrectly classified as mudflat fringing the red classified rockweed (B).

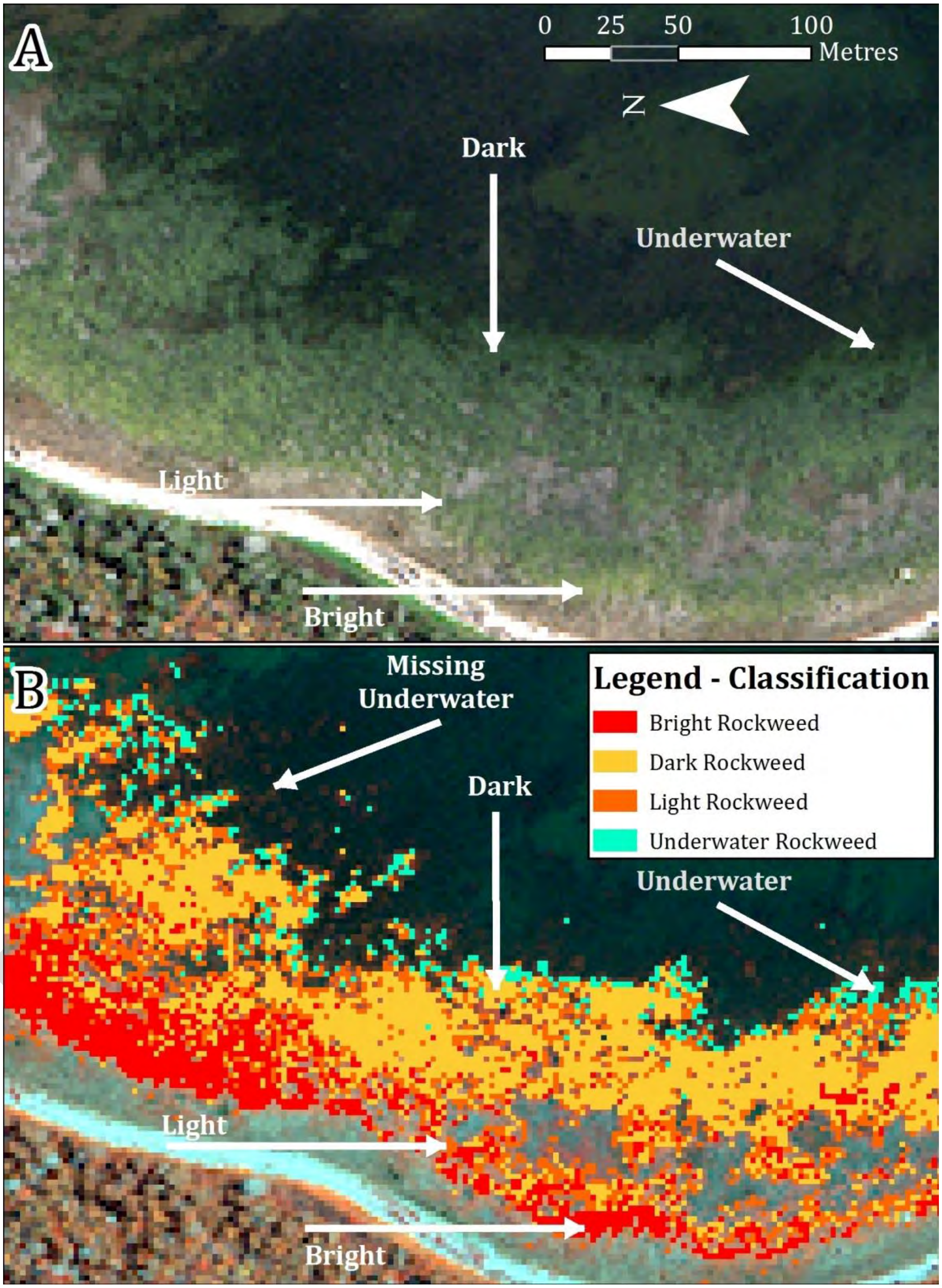

Figure 23. Four classes contained all rockweed in the image except odd scattered pixels of potential submerged rockweed (B).

The largest class (by surface area) is dark (damp, dimly reflective) rockweed, followed by light (slightly wet) rockweed, bright (dry, highly reflective) rockweed, and then submerged (barely reflective) rockweed. The results of the supervised classification produced a larger combined area of rockweed than the unsupervised approach (Figure 24).

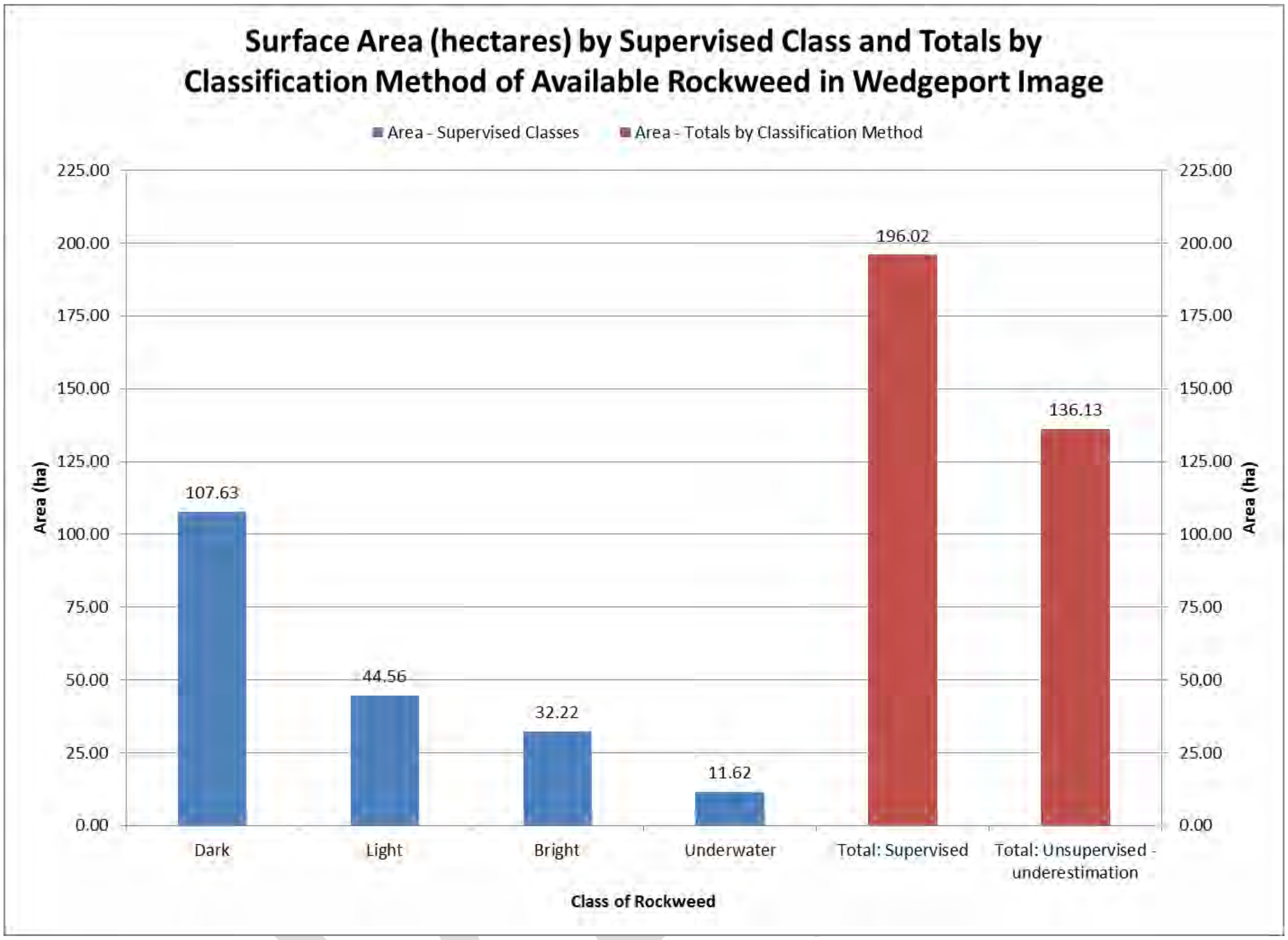

Figure 24. Surface area of available rockweed (by class for supervised classification, in blue) and total area for supervised and unsupervised processes (red). Compared to unsupervised, the supervised classification resulted in 44% more available rockweed.

3.2.2 Cape Sable Island

The WV-2 image of the Cape Sable Island coastline combines typical rock and rockweed within the intertidal areas with large lagoons full of vegetation (Figure 24). More non-rockweed vegetation exists along portions of the coast than in the Wedgeport area. Numerous wharves and breakwaters extend into the water, and shallow submerged sandy areas appear throughout the image.

3.2.2.1 Unsupervised

Unsupervised classification using a K-means algorithm was executed on various band combinations of the Cape Sable Island image. This method classified the image into seven classes, and classification of a NIR-G-B combination (or, excluding the red band) was successful in producing one pure rockweed class. Visual analysis of the rockweed class determined the inclusion of an acceptable portion of visible rockweed in the image, while all non-rockweed features were excluded (Figure 25). The results of the classification were deemed acceptable, so no further unsupervised classification was attempted for this image.

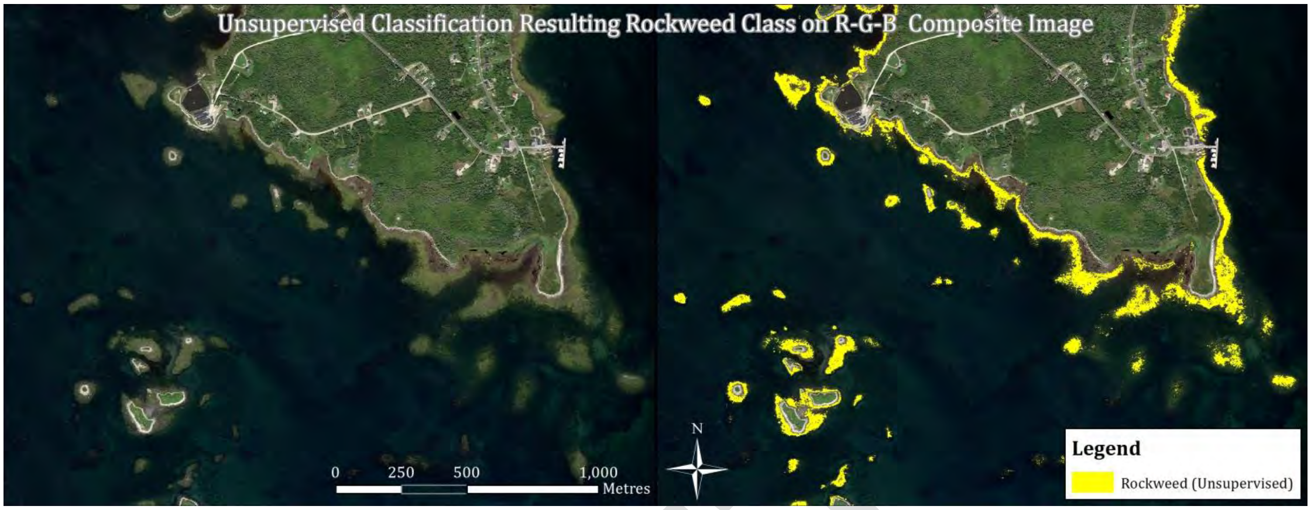

Figure 25. A true colour section of the WV-2 Cape Sable Island image (on left) showing green rockweed along the coast and surrounding small islands. Pure rockweed class (on right, in yellow) resulting from unsupervised classification.

3.2.2.2 Supervised

Supervised classification was executed on various band combinations of the Cape Sable Island WV-2 image and standard deviations were iteratively modified to obtain the best classification. Initially, classification was completed with a submerged rockweed class, but despite dropping the SD threshold to 1.00 for that class, the results were mixed with other features. Consequently, supervised classification continued with no submerged class, and submerged rockweed was incorporated into the darker classes.

Table 5. Standard deviation thresholds for maximum likelihood with NULL class supervised classification process. Standard deviation thresholds were modified for 2 classes – increasing for light rockweed and decreasing for dark rockweed, while all others left at the default value of 3.00.

Name	Threshold
Dark rockweed	2.00
Light rockweed	4.25
Bright rockweed	3.00
Dark non-rockweed vegetation	3.00
Light non-rockweed vegetation	3.00
Submerged sand	3.00
Sand	3.00

The most successful supervised classification was applied to the NIR-R-G band combination of the image with modified standard deviations (Table 5). The dark rockweed threshold was reduced to 2.00 while light increased to 4.25, attempting to eliminate non-rockweed vegetation while incorporating as much submerged as possible. Regardless, a small portion of submerged rockweed remained unclassified.

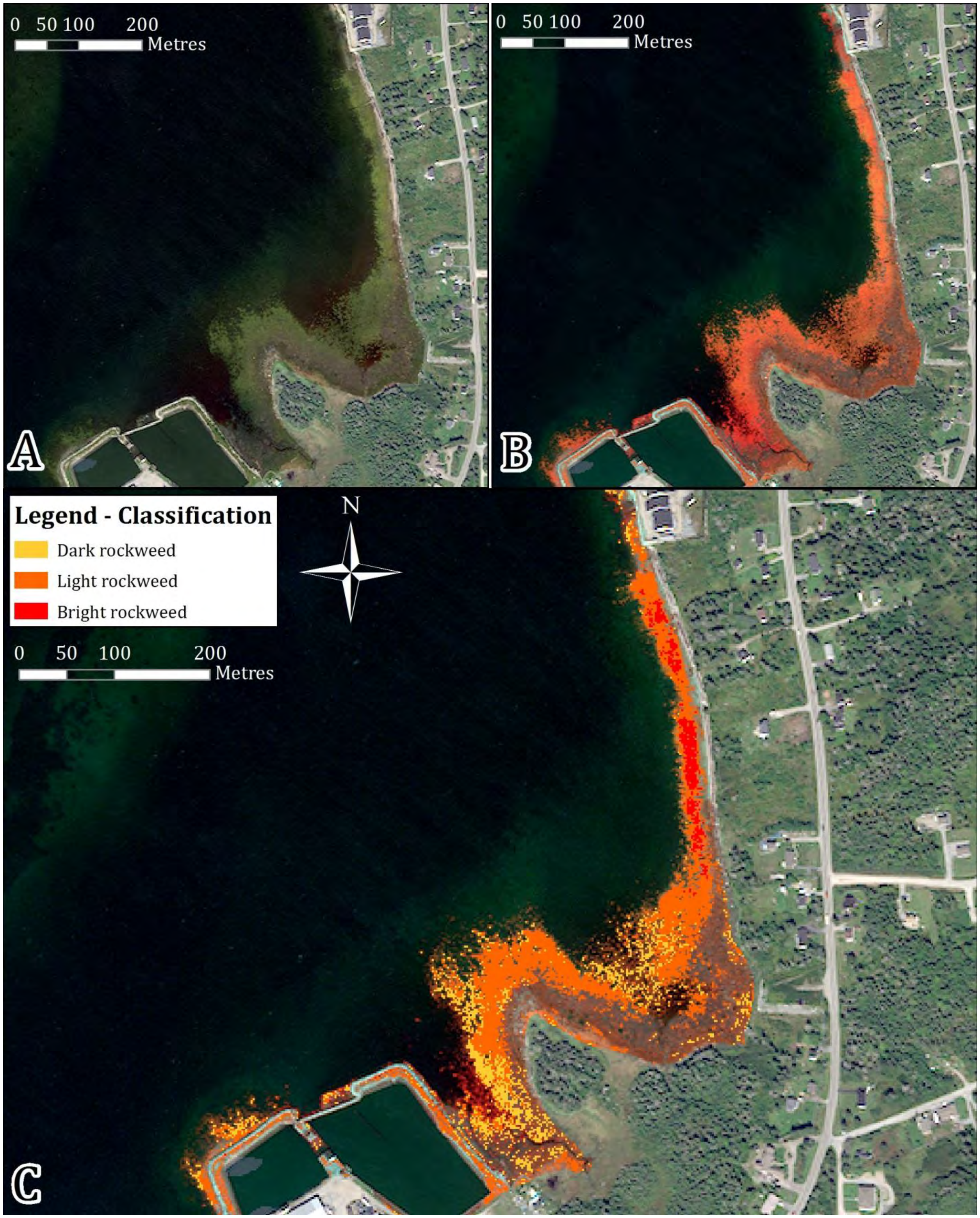

Figure 26. Area in Cape Sable Island in a true colour composite (A), NIR-G-B composite (B), and with final supervised rockweed classes (C).

The final rockweed classes in the image were classified as dark (damp, dimly reflective), light (slightly wet), and bright (dry, highly reflective) rockweed (Figure 26). The largest class (by area) is light rockweed, with dark second and brightest third, and the unsupervised classification produced a slightly larger total area than the combined supervised classes (Figure 27).

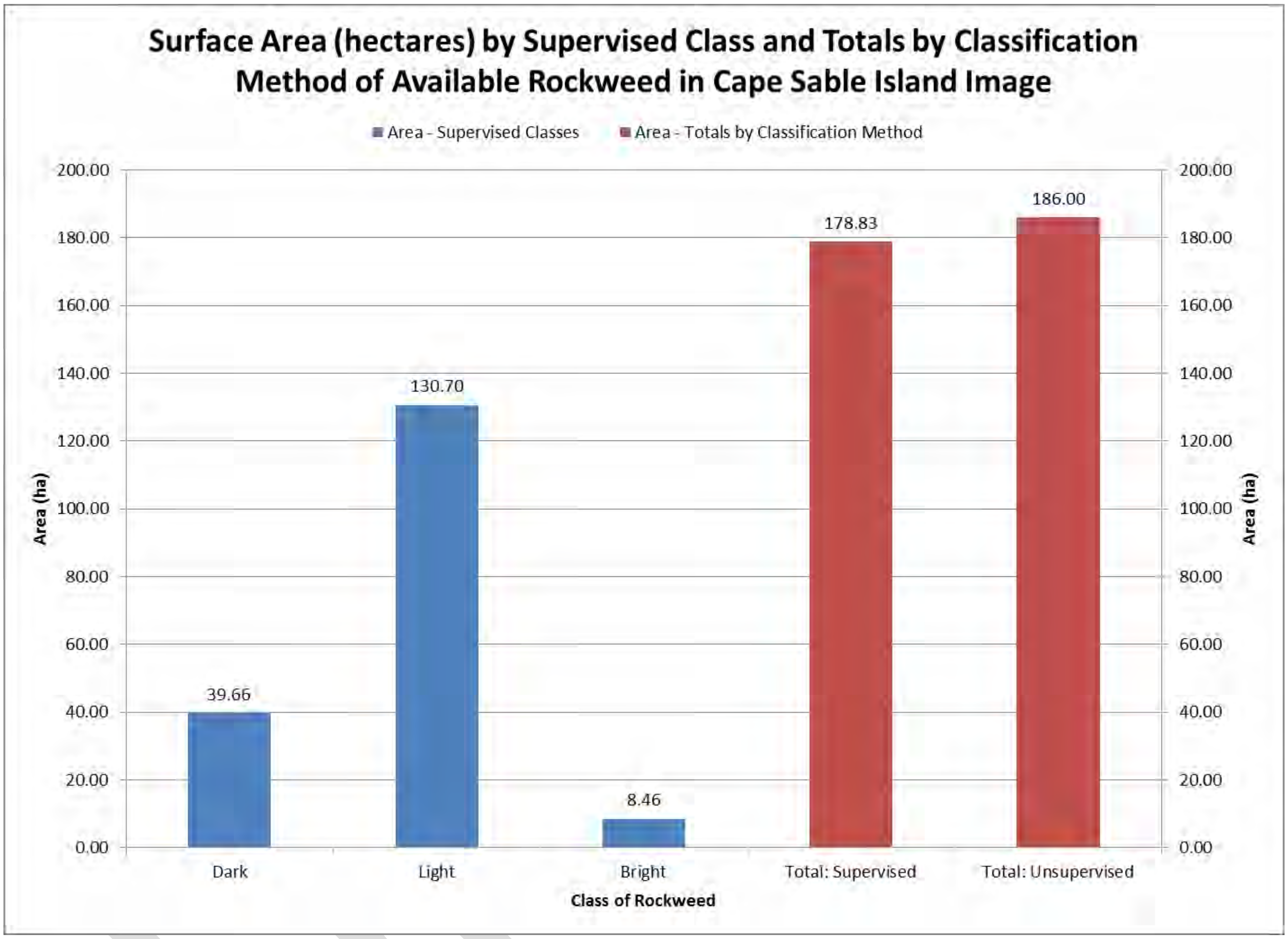

Figure 27. Surface area of available rockweed (by class for supervised classification, in blue) and total area for supervised and unsupervised processes (orange) for the Cape Sable Island WV-2 image. Unsupervised classification output roughly 10 ha more surface area than supervised.

3.2.3 Kelleys Cove – May 7, 2010

The WV-2 image of Kelleys Cove area is categorized by open, exposed coastlines in the northwest and southwest portions of the image, and a more sheltered area which is the entrance to Yarmouth Harbour. No offshore islands exist here, yet Yarmouth Harbour is bordered by mud flats that are vegetated with salt marsh. Numerous wharves and other urban features border the water across the image. Kelleys Cove itself is a sheltered cove in the south of the image and is identified in Appendix A.

Rockweed along the coast appears very dark in the true colour image, making it a visible brown strip compared to the surrounding features. In the NIR-G-B composite, the rockweed appears a bright pink-red hue that gets progressively darker the closer to the water as the moisture content of the rockweed increases. The exposed coastline is subject to waves that appear as white breakers, seen near the shore, which makes viewing any rockweed within the submerged near shore area virtually impossible.

3.2.3.1 Unsupervised

Unsupervised classification was executed on various band combinations of the WV-2 image using a K-Means classifier algorithm and various output classes. Similar to the Wedgeport image, a NIR-G-B combination was the most successful, and significant rockweed omission occurred regardless of the number of output classes.

3.2.3.2 Supervised

Training areas were constructed for four classes in the Kelleys Cove – May image. Dark, light, and bright rockweed classes were identified and one for non-rockweed vegetation representing salt marsh on the mud flats. SD thresholds were modified iteratively to achieve the best classification (Table 6) which was obtained on a NIR-G-B combination image.

Table 6. Standard deviation thresholds for maximum likelihood with NULL class supervised classification process. Standard deviation thresholds were modified for 3 classes – increasing for dark and bright rockweed classes and decreasing for light rockweed, while the last class was left at the default value of 3.

Name	Threshold
Light rockweed	4.20
Bright rockweed	4.60
Dark rockweed	1.50
Non-rockweed vegetation	3.00

The result of the supervised process was successful classifying all visible rockweed, including submerged rockweed as part of the 'dark' class. Rockweed virtually dominates the entire shoreline except in muddy areas where salt marsh and algae vegetation is more prevalent. However, isolated rockweed pixels can be found in the salt marsh areas and probably represent a commission error for rockweed (Figure 28). These small patches of bright rockweed found in areas of salt marsh were manually removed using the mud flat polygon (Figure 30).

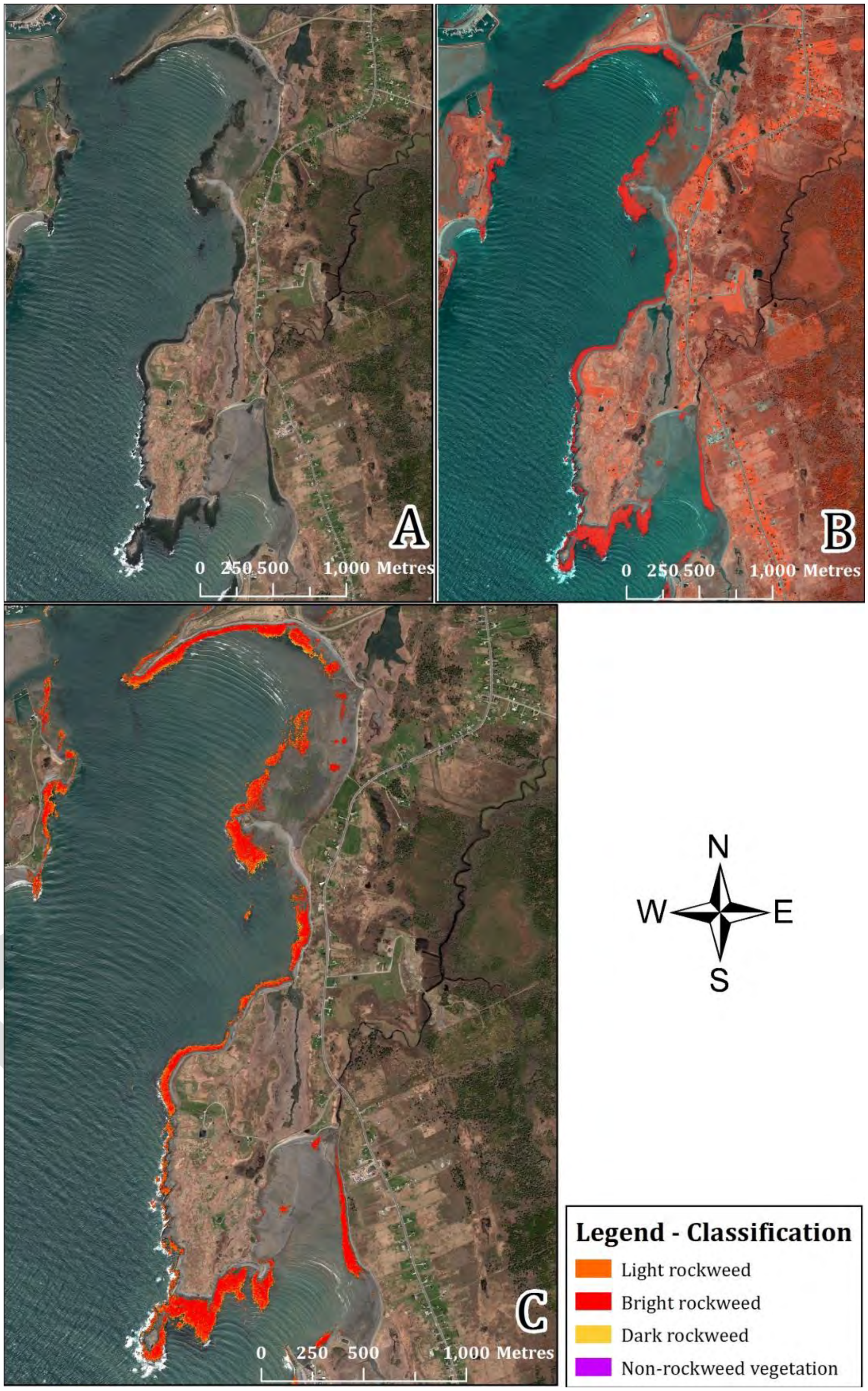

Figure 28. Worldview-2 images of Kelleys Cove, NS (taken May 2010) in a true colour composite (A), NIR-G-B composite (B), and with final supervised rockweed classes (C). Light (green) and bright (blue) rockweed is the dominant intertidal vegetation.

Bright rockweed was the largest class by surface area, followed by light then dark rockweed and the unsupervised classification produced about the same overall total area as supervised (Figure 29).

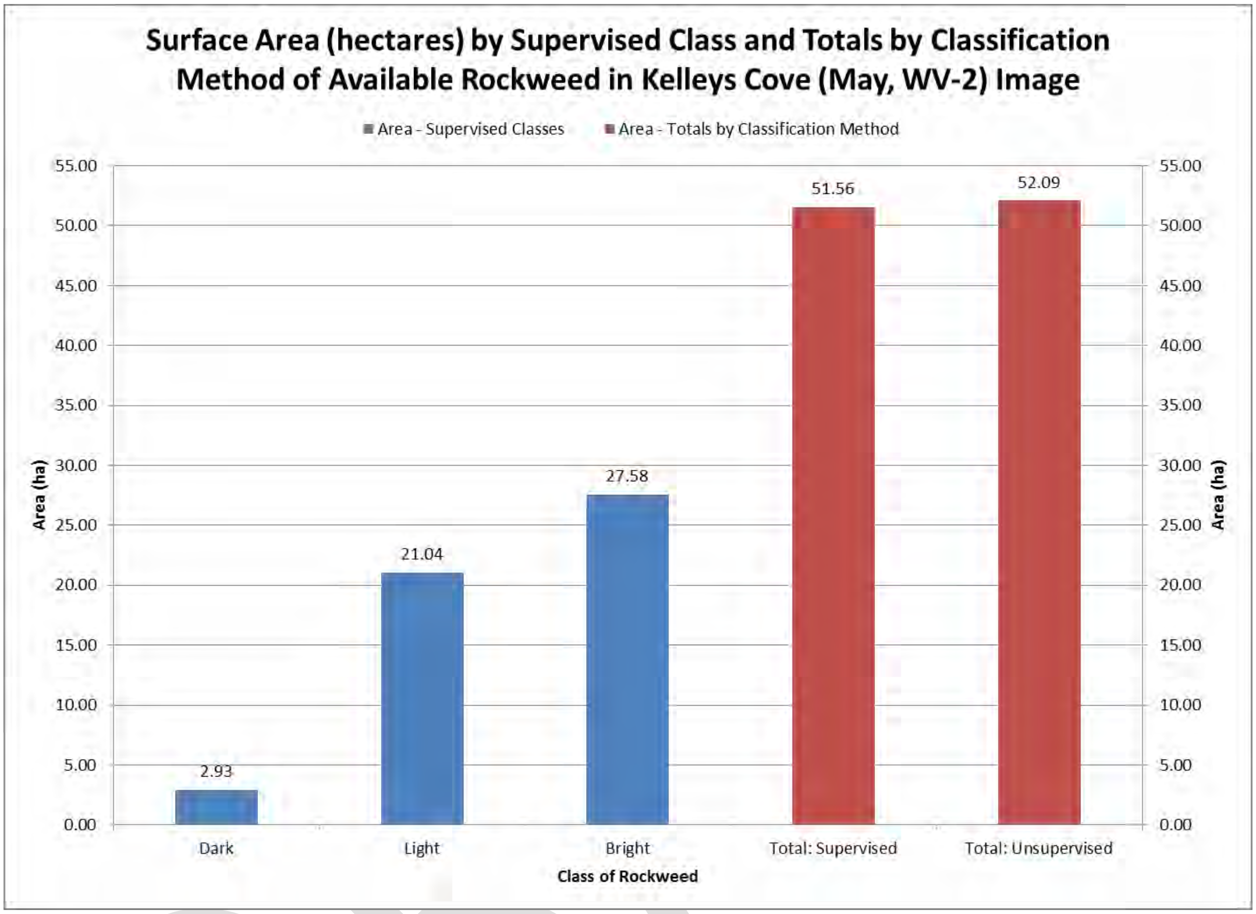

Figure 29. Surface area of available rockweed (by class for supervised classification, in blue) and total area for supervised and unsupervised processes (orange) for the Cape Sable Island WV-2 image. Supervised and unsupervised processes output roughly the same surface area of available rockweed.

3.2.4 Kelleys Cove – August 19, 2010

The Quickbird image taken on August 19, 2010 of the Kelleys Cove area shows a physical coastline similar to that of the May WV-2 image, but with subtle changes.

The water in the August image has less wave action than in the May image, allowing seafloor features to be seen more clearly. The rockweed in the image is visually much lighter in the true colour composite, appearing more yellowish-green than brown. For this reason, the rockweed blends in with the surrounding features more than in the May image. In addition, having been taken later in the summer there is significantly more salt marsh vegetation than in the May image, and the salt marsh appears to have a large variation in the intensity of its response (NIR-G-B composite) which is a potential issue for classification.

3.2.4.1 Unsupervised

Unsupervised classification was executed on various band combinations of the QB image using a K-Means classify algorithm and various output classes. As with the May image, a NIR-G-B combination was the most successful, significant rockweed omission occurred regardless of output class number, and one or more mixed classes resulted.

3.2.4.2 Supervised

Training classes were produced for the same categories as the WV-2 image of the same area – dark, light, bright rockweed and non-rockweed vegetation. Despite getting its own class, mud flat vegetation caused complications when classifying dark rockweed in this image. Along sections of coastline with large, vegetated mud flats, some rockweed exists on large rocky substrata often found close to the high tide water mark. Regardless of band combination, parameter and training area modifications, these vegetated mud flats consistently classified as dark rockweed. Consequently, the obvious mud flat areas were selected and removed from classification (Figure 30), while any final mud flats which were classified were manually removed post classification.

SD thresholds were modified iteratively. To achieve a suitable classification, rockweed classes were increased SD thresholds, while that of non-rockweed vegetation was lowered (Table 7). The most successful classification was executed on a NIR-G-B combination.

Table 7. Standard deviation thresholds for maximum likelihood with NULL class supervised classification process. Standard deviation thresholds were modified for all 4 classes – increasing for all 3 rockweed classes and decreasing for non-rockweed vegetation.

Name	Threshold
Dark rockweed	3.25
Light rockweed	6.00
Bright rockweed	3.25
Non-rockweed vegetation	1.50

Figure 30. Densely vegetated mud flat areas (outlined in red) that were removed from the supervised classification due to their spectral similarity to dark rockweed.

The supervised process succeeded in classifying all visible rockweed, including submerged rockweed as part of the 'dark' class. Rockweed virtually dominates the entire shoreline (Figure 31).

Rockweed can mostly be found in large patches that appear at low tide. Some rockweed is found nearer the high tide mark and would be accessible if the mud flats were submerged. Some rockweed can be found attached to the side of wharves and other manmade features, particularly in Yarmouth Harbour.

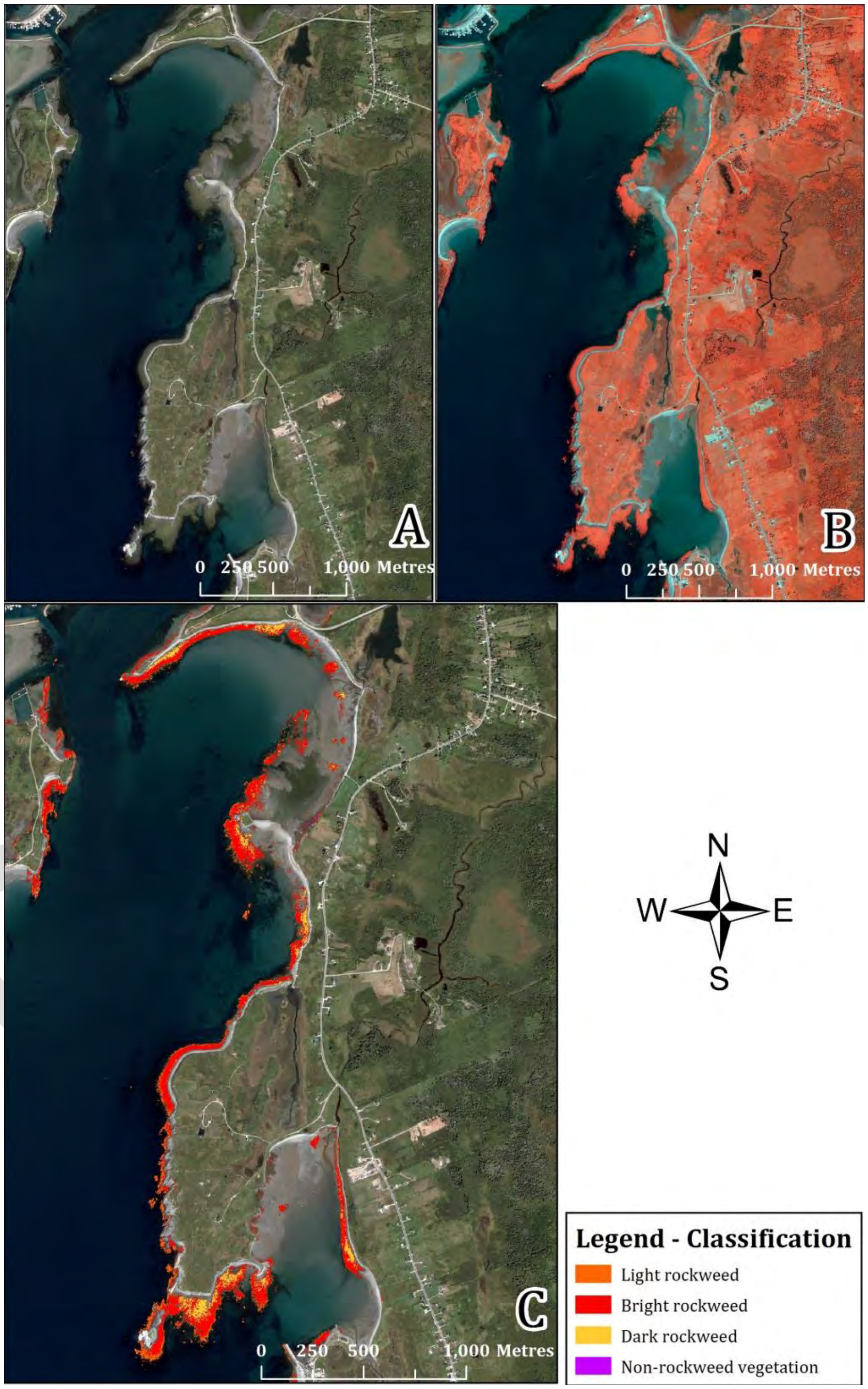

Figure 31. Quickbird images of Kelleys Cove, NS (taken August 2010) in true colour composite (A), NIR-G-B composite (B), and with final supervised rockweed classes (C).

Light rockweed was the largest class by surface area, followed by bright and dark rockweed in roughly equal amounts and the unsupervised classification produced about the same overall total area as the supervised classes (Figure 32).

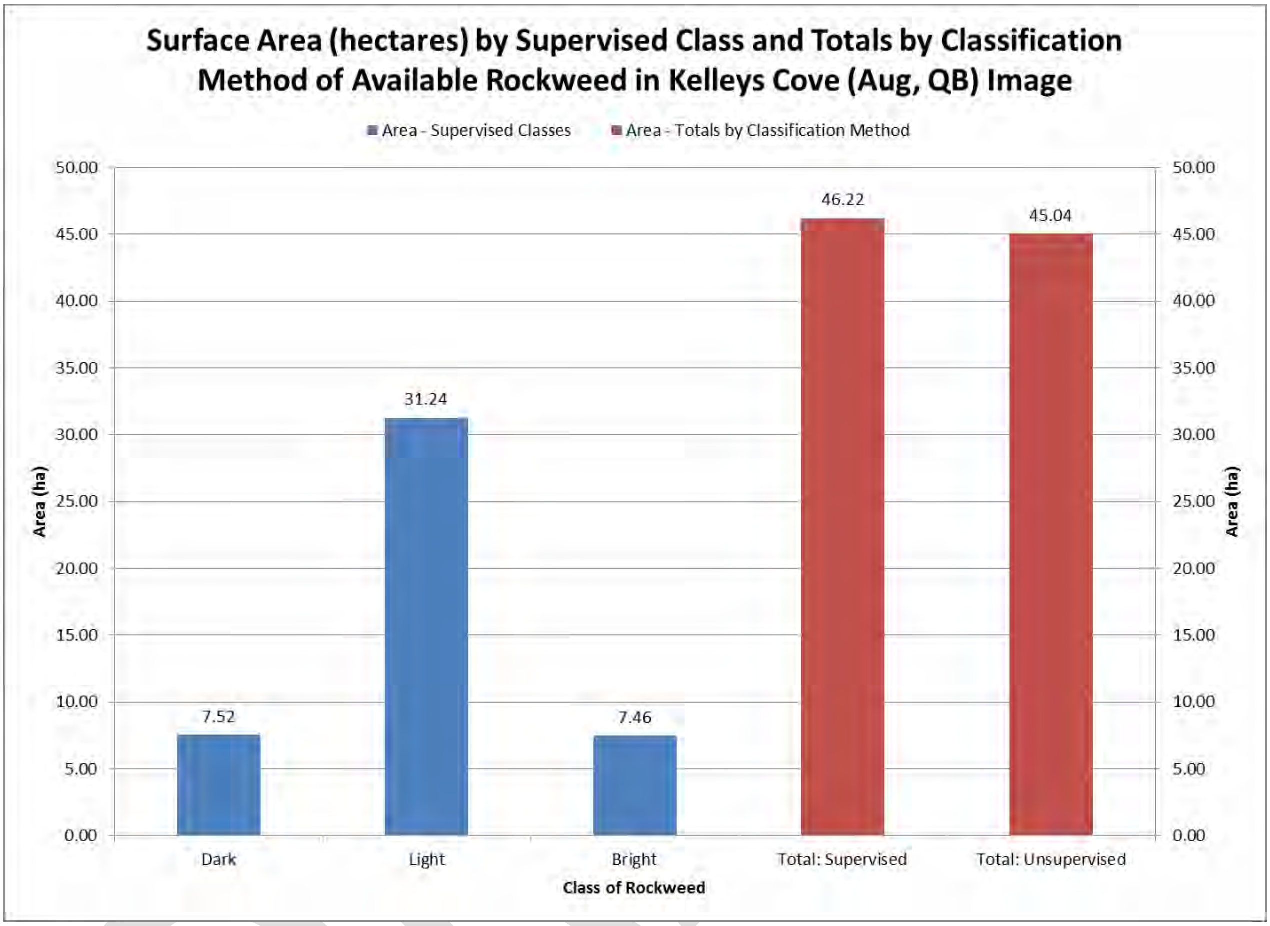

Figure 32. Surface area of available rockweed (by class for supervised classification, in blue) and total area for supervised and unsupervised processes (orange) for the Cape Sable Island WV-2 image. Supervised and unsupervised processes output roughly the same surface area of available rockweed.

3.2.5 NDVI Analysis

Normalized Difference Vegetation Index (NDVI) is an indicator of vegetative health ranging between 0 -1. The NDVI was determined for the overall exposed rockweed area as well as each rockweed class (dark, light, or bright plus submerged for Wedgeport) for each satellite image (Table 8). Although some variability exists in the dark and light classes, overall exposed rockweed (dark, light, and bright rockweed classes) exhibited similar mean NDVI values (0.57-0.58) in three of four images - Wedgeport, Cape Sable Island, and the August image of Kelleys Cove. The May image of Kelleys Cove resulted in different NDVI values across each class of exposed rockweed, resulting in a higher mean NDVI value for the May image of Kelleys Cove (0.66) than for any other image. Submerged rockweed was only classified in one image so it was excluded from overall mean calculations.

NDVI increased with increasing class brightness for the springtime Kelleys Cove (May) image. This effect was not seen in any other image. Indeed all rockweed classes from the Cape Sable Island image elicited a similar NDVI (Table 8).

Table 8. Mean NDVI values for each supervised class of rockweed as well as all classified rockweed (except submerged) for each image.

	Wedgeport NDVI Mean	Cape Sable Island NDVI Mean	Kelleys Cove May NDVI Mean	Kelleys Cove August NDVI Mean
Imagery Date	October 24, 2012	September 11, 2011	May 7, 2010	August 19, 2010
Dark	0.61	0.59	0.29	0.53
Light	0.52	0.58	0.66	0.59
Bright	0.57	0.57	0.72	0.58
Submerged*	0.46			
Overall Mean*	**0.57**	**0.58**	**0.66**	**0.58**

*Submerged rockweed not included in 'Overall Mean'

3.2.6. Sector Area Comparison

Overall, classification derived surface area (in hectares, ha) was compared to ASL determined surface area for 25 sectors, all in the Wedgeport study extent (Figure 33). Classification derived surface areas exceeded ASL determined surface areas for half (13/25) of the sectors, with the largest difference seen in sector O-3 of over 8 ha surplus rockweed. The difference between classification derived surface areas and ASL determined surface areas results in 16.47 ha more surface area of available rockweed found through classification than was determined by ASL (Table 9).

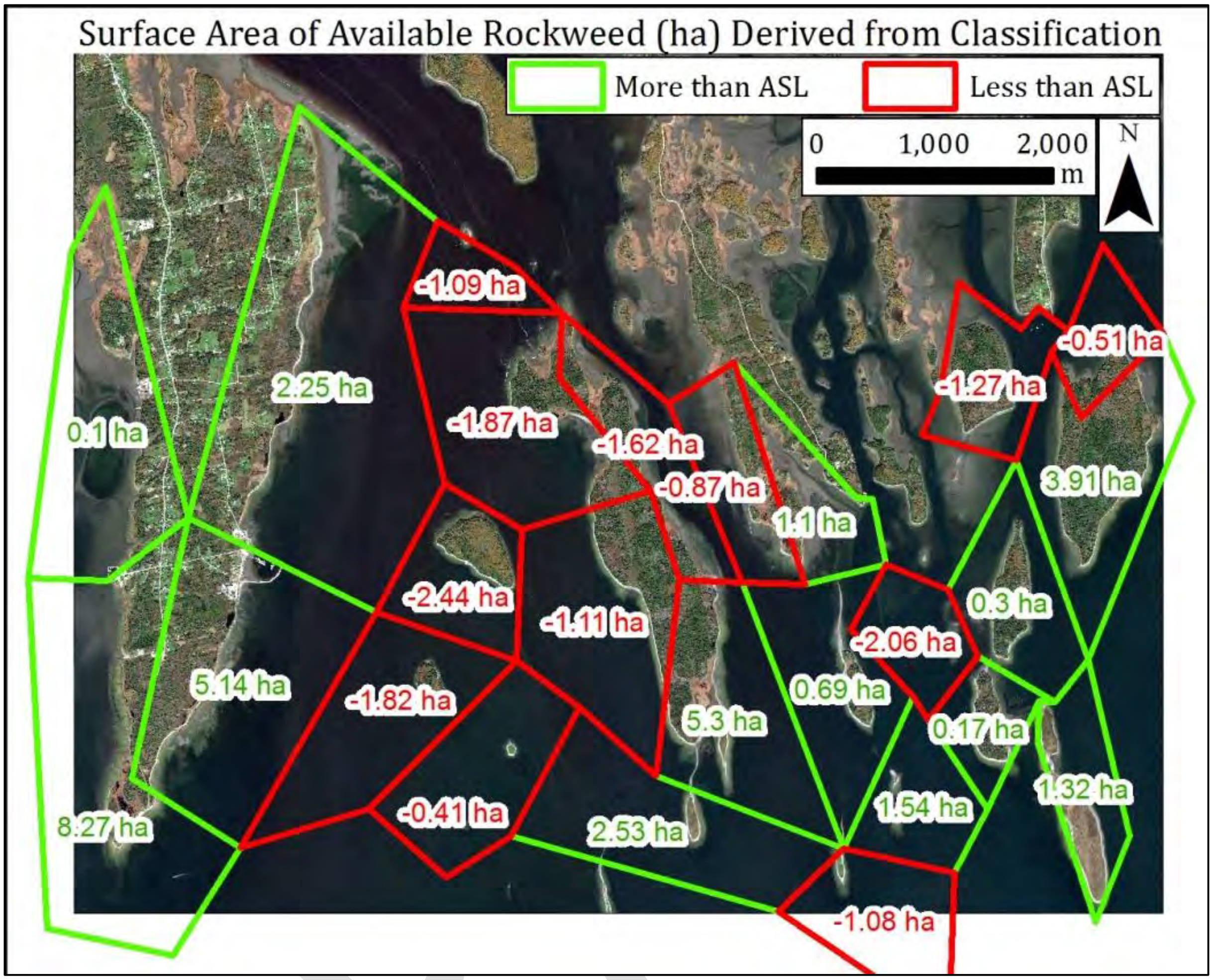

Figure 33. Sector analysis of measured and derived surface areas of available rockweed. Green sectors indicate more rockweed surface area was classified than was measured by ASL (positive values in green) whereas red sectors indicate less classified rockweed than measured (negative values in red).

Table 9. Surface area totals for 25 sectors in the Wedgeport study area show classification derived surface area of available rockweed exceeding measured quantities by 16.47 ha.

	ASL Determined	Classification Derived	Difference (Derived - ASL)
Total Surface Area (ha)	119.02	135.49	16.47

4.0 Discussion

4.1 Satellite Image Quality

Archived satellite images were investigated with various criteria: recently acquired (within the last 5 years), high resolution, low tide, calm water, cloudless conditions, and taken between mid-June and mid-September. Despite the abundance of available archived imagery, finding ideal images that met all criteria for every area was still not possible (Table 1) and two timeframe exceptions had to be made. The Wedgeport image and one Kelleys Cove image were taken outside the ideal time frame (October and May, respectively) but were deemed exceptional due to their clarity and low tide conditions. The Kelleys Cove May 2010 Worldview-2 image provides a temporal and sensor comparison to the Kelleys Cove August 2010 Quickbird image, as well as providing the ability to observe the spectral response of *Ascophyllum* during its fruiting season (May). The Wedgeport image was taken on such a clear, calm day that submerged rockweed was visible and classification of this feature investigated. Wedgeport is the only image in which submerged rockweed could be classified.

The Worldview-2 image of the Wedgeport area was purchased with 4 new bands – coastal blue, yellow, red edge, and a second near-infrared. Profiles of key intertidal features show rockweed responding strongly in the red edge, NIR, and NIR2 channels, making these potentially suitable bands for rockweed identification. However, the strong response from the red edge band was not unique to rockweed, as flat, man-made features such as wharves also exhibited a strong response, reducing the effectiveness of this channel. Furthermore, the strong responses from both NIR bands, though unique to rockweed, were very similar to each other, and thus only one of these bands is required. Considering the NIR2 band must be purchased as part of the more expensive 8-band package, it does not provide any apparent useful information, at least using our methods, that is not already provided in the less expensive 4-band package. Thus, purchasing imagery with red, green, blue, and near-infrared bands appears to be sufficient for classification of rockweed.

4.2 Classification

Several spectral profiles indicated the most useful band(s) for identifying rockweed are NIR and NIR2, the former costing much less than the latter. The profiles also showed bands green or blue both produced a similar, low response to *Fucus* and rockweed, though the response to *Fucus* was less than that of rockweed, while showing subtle differences in their responses to sand and water – green showing stronger in sand and weaker in water. Conversely, profiles showed the red band produced a low response to all features, with no observable difference in its response to sand and water.

In addition, classification was executed with many combinations of input bands, and the results analyzed, with the same conclusion – NIR and NIR2 provide the similar value for classification, and when combined with blue and green, rockweed can be successfully classified from the imagery. This conclusion confirms the usefulness of the NIR-G-B combination for classifying intertidal features outlined in Pauly (2011).

Unsupervised classification proved to be an inconsistent method of classifying rockweed from multispectral imagery as rockweed omission and/or commission of other features (primarily vegetated mud flats) consistently occurred. The spectral reflectance of submerged vegetation (rockweed, kelp, mud flat grass, etc.) is more similar spectrally to exposed wet sandy areas than it is to above water rockweed, and thus is consistently assigned to a class with those non-rockweed features. This effect was seen in the unsupervised results for all images; however, this effect was especially visible in the Wedgeport results, where the supervised classification detected 44% more rockweed than the unsupervised method. This is possibly due to exceptional water clarity (low wave action) combined with the near-shore bathymetry, in that Wedgeport is the only image in which submerged rockweed was detectable enough to warrant a separate supervised class.

Supervised classification of rockweed into visually bright, light, dark, and submerged classes based on a NIR-G-B combination proved most effective for extracting rockweed from the satellite images, which are consistent with the conclusion that successful classification of intertidal features using a NIR-G-B false colour composite image is possible (Pauly, 2011). The various shades of 'brightness' exuded by the rockweed in the NIR-G-B composite is interpreted to be caused by relative surface wetness. Generally, the 'brightest' class tended to be furthest from the low tide water line in the image - presumably the rockweed that has been out of the water the longest and thus the driest. An investigation comparing mean NDVI of each supervised class revealed no definitive correlation between NDVI values and classes based on visual brightness (Table 7), though an increase of NDVI with increasing class brightness was seen on the only springtime image (Kelleys Cove – May) .

Differentiation between *Ascophyllum* and *Fucus* seaweeds using traditional air photo methods is difficult at best due to the nature of the *Fucus* bring interspersed among *Ascophyllum*. Supervised classification was successful in differentiating between the two kinds of seaweed, as the *Fucus* elicits a different response in the NIR than does rockweed. This was determined in areas where *Fucus* was observed during ground truthing and thus could be observed on the satellite image in NIR.

4.3 NDVI Analysis

As the preferred index for global vegetation monitoring, NDVI is a typical measure of vegetation health and vigour (Lillesand, 2008). The mean NDVI of the rockweed in each image was found to be between 0.57-0.58 for 3 of the 4 images, and 0.66 for the remaining image. The outlying NDVI value (Table 10) belongs to the image of Kelleys Cove taken in May, during rockweed's fruiting season. It stands to reason that rockweed would be especially healthy and vigorous during reproduction. During its fruiting season, rockweed produces small vesicles which add to the biomass of the plant. Without performing concurrent spatially integrated ground transects that relate biomass to the satellite imagery, it remains postulation that this increased mean NDVI value is related to the increased biomass of the rockweed. However, this interpretation is consistent with an overall increase in the area of rockweed classified from the May image compared with the August image (Figure 34).

Table 10. Month imagery was captured and the mean NDVI of the rockweed from that image.

	Wedgeport	Cape Sable Island	Kelleys Cove (WV2)	Kelleys Cove (QB)
Month Imagery Captured	October	September	May	August
Mean NDVI of Rockweed	0.57	0.58	0.66	0.58

The intention to use NDVI as a predictor of biomass was unable to be accomplished at this stage. We were provided determined biomass (kg/m^2) values by ASL, though measured transects are not spatially related and resulting biomass measures are spatially aggregated to the sector. A sector is too large an area to develop a NDVI-biomass relationship, thus no relationship could be determined at this time.

4.4 Kelleys Cove – Temporal/Sensor Comparison

Two images of Kelleys Cove were obtained – one a 4-band Worldview-2 image taken in May 2010, the other a 4-band Quickbird image taken three months later in August 2010. For both images, the difference between surface area for supervised and unsupervised rockweed was less than 1.5 ha (Figure 34). The May image showed ~5 ha more rockweed than that of August, which could be a result of the tidal stage during image capture or fruiting rockweed. The August image capture occurred approximately 20 minutes before low tide, whereas the May image was captured precisely at low tide, demonstrating the requisite to obtain direct low tide imagery. As previously discussed, further ground truthing is required to fully attribute the differing NDVI values to biomass or vigour. The differing spatial resolution between Quickbird (2.4 m) and Worldview-2 (2.0 m) did not appear to have any impact on classification in this instance.

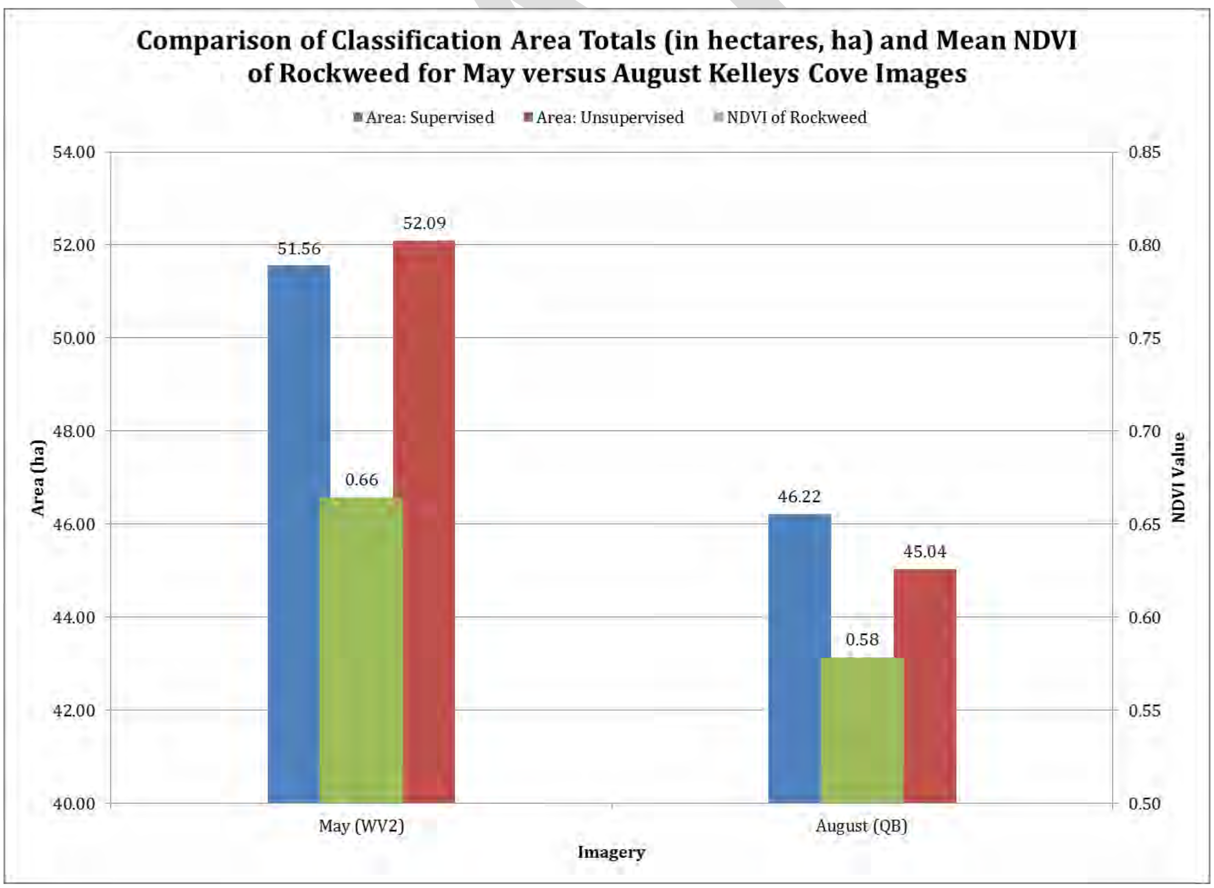

Figure 34. Comparison of classification area totals (in hectares, ha) plus mean NDVI of the classified rockweed for May and August, 2010 images of Kelleys Cove.

4.5 Sector Area Calculations

The surface area of available rockweed (classification derived vs. ASL determined values) was analyzed for 25 sectors in the Wedgeport area. Half of the sectors revealed more available surface area from classification than was determined by ASL in 2012, while the other half displayed less surface area than was determined by ASL (Figure 35). Overall, the surface area of available rockweed derived from supervised classification detected 16.47 ha more than the determined amount by ASL.

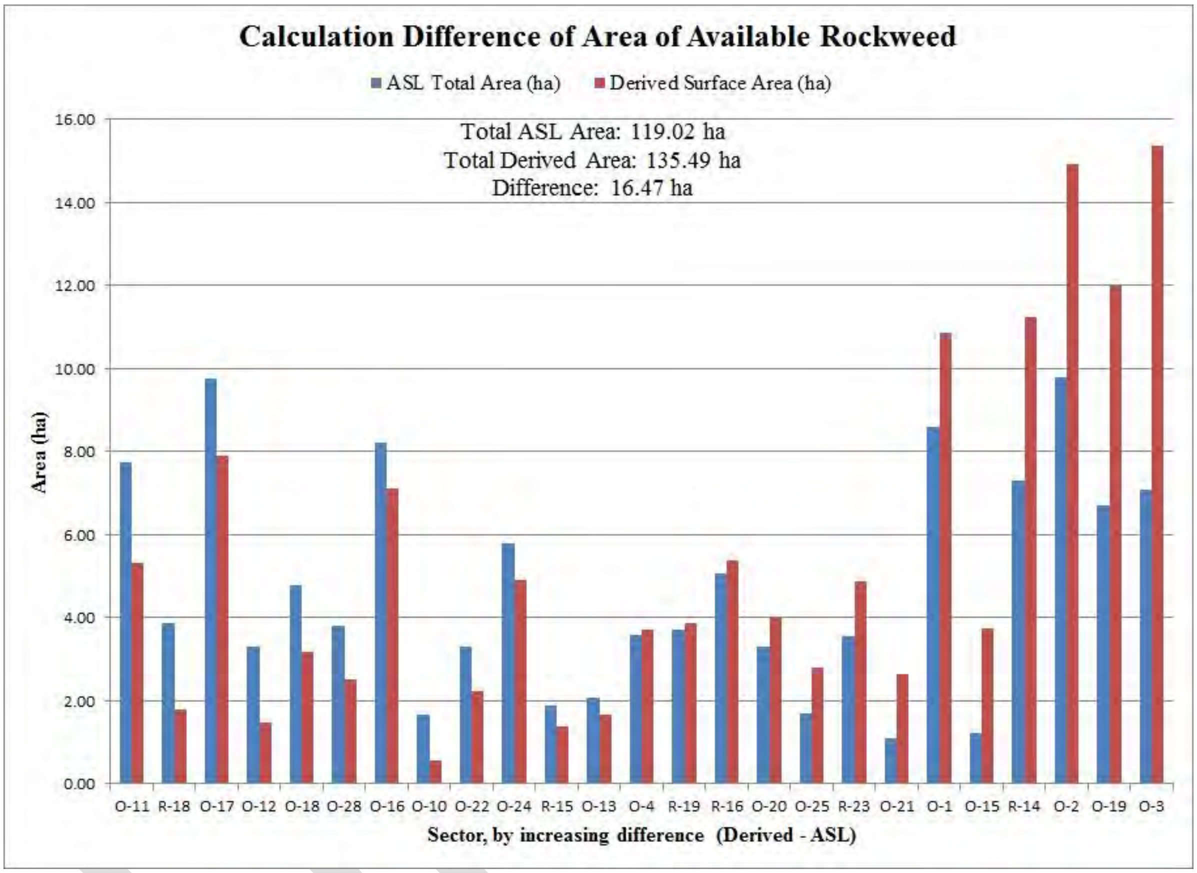

Figure 35. Classification derived rockweed surface area (ha, in red) minus ASL measured rockweed surface area (ha, in blue) results in classification deriving 16.47 ha more surface area of available rockweed than measured by ASL.

It isn't likely that the surplus can be accounted for temporally, as the values provided by ASL were updated in 2012, the same year the imagery was captured. An additional partial explanation is that submerged rockweed, which was classified and included in the totals above, was not measured by ASL due to its submerged state and thus was not included in the totals. However, the surface area of submerged rockweed is much less than the overage measured (Table 11) and thus is not the only explanation.

Table 11. Surface area of submerged rockweed (in ha) for 3 sectors in Wedgeport.

Sector	Difference (Derived - ASL)	Area Submerged Rockweed (ha)
O-1	2.25	0.72
O-2	5.14	1.21
O-3	8.27	0.62

5.0 Conclusion

Four high resolution archived satellite images were obtained for 3 areas in Southwest Nova Scotia. Three of the images were WorldView-2 (2.0 m MS, 0.5 m Pan), with one of the images containing 8 bands and the remaining image containing 4 bands (R, G, B, NIR). The final image was a 4-band Quickbird image (2.4 m MS, 0.6 m Pan) of the same geographic extent as one of the 4-band MS images but taken 3 months later for a temporal comparison. Each image was pansharpened (80% MS, 20% Pan) and spectral profiles were created to gain an understanding of the spectral behaviour of key coastal features such as rocks, rockweed, sand, and water. Land data within a modified coastline polygon was removed so just the coastal region remained for classification. Both supervised and unsupervised classification methods were applied to various combinations of input bands, including derivatives such as NDVI and PCA. Supervised classification results were compared with unsupervised results and available rockweed areas provided by ASL. In addition, a temporal/sensor comparison was completed between a springtime WV-2 and summertime QB image.

Classifying high resolution multispectral satellite imagery is an effective and efficient method of determining the presence and distribution of *Ascophyllum nodosum* in the intertidal zone of Atlantic Canada. For successful classification, critical parameters must be used to restrict the selection of coastal satellite images. The images must be taken during summer, particularly between June and September, at low tide on clear, calm days to expose the intertidal rockweed and reduce cloud and ocean wave action. Multispectral image bands essential for superior classification include red, green, blue, and a near-infrared, while newer satellite bands (coastal blue, red edge, yellow, and an additional near-infrared) were shown to add little value for the added cost. Both supervised and unsupervised classification approaches successfully classified rockweed from each image, supervised classification appeared to be slightly more accurate than unsupervised, particularly in areas with exceptionally calm waters in which submerged vegetation can clearly be seen. Supervised classification allowed for the exclusion of fucoid seaweeds undesirable to ASL by creation of a separate class which was successful in classifying at least some of the known unwanted seaweed patches from the images. Noteworthy differences in mean NDVI values and surface areas of available rockweed were recorded between the May 2010 and August 2010 images, indicating the springtime fruiting season is recognizable via satellite imagery and classifying such images will lead to an overestimation of available rockweed. Data updated in 2012 provided by ASL regarding the surface area of available rockweed, aggregated to the sector, was compared with similarly aggregated surface areas derived from classification of the Wedgeport area. For 25 sectors overall, classification derived surface area exceeded ASL values by 16.47 hectares, all of which cannot be contributed to classification of submerged rockweed. Atmospheric and ground conditions at the moment of image acquisition proved to be more important factors contributing to successful classification of rockweed than sensor type or season, and if the water in the images is clear enough it is possible that submerged rockweed may be classifiable. The smallest spatially integrated unit of biomass provided by ASL was the sector, which is too large an area to determine a relationship between NDVI and biomass, thus further small-scale, spatially integrated ground sampling is required to possibly relate NDVI values to rockweed biomass for the purposes of biomass quantification via satellite imagery.

6.0 References

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Appendix A- Wedgeport

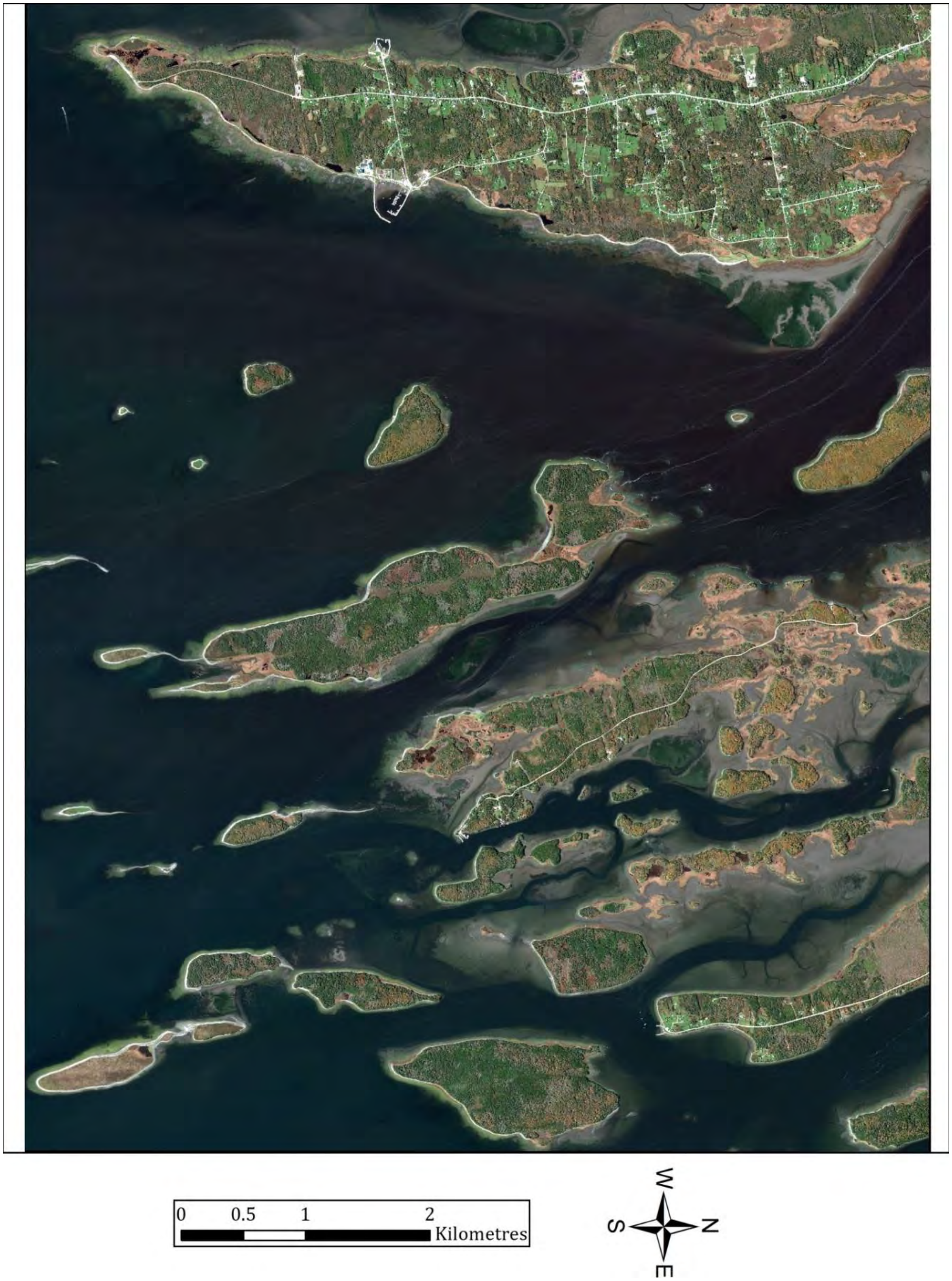

Figure 36. True colour composite of Wedgeport, NS. Worldview-2 image taken October 24, 2012.

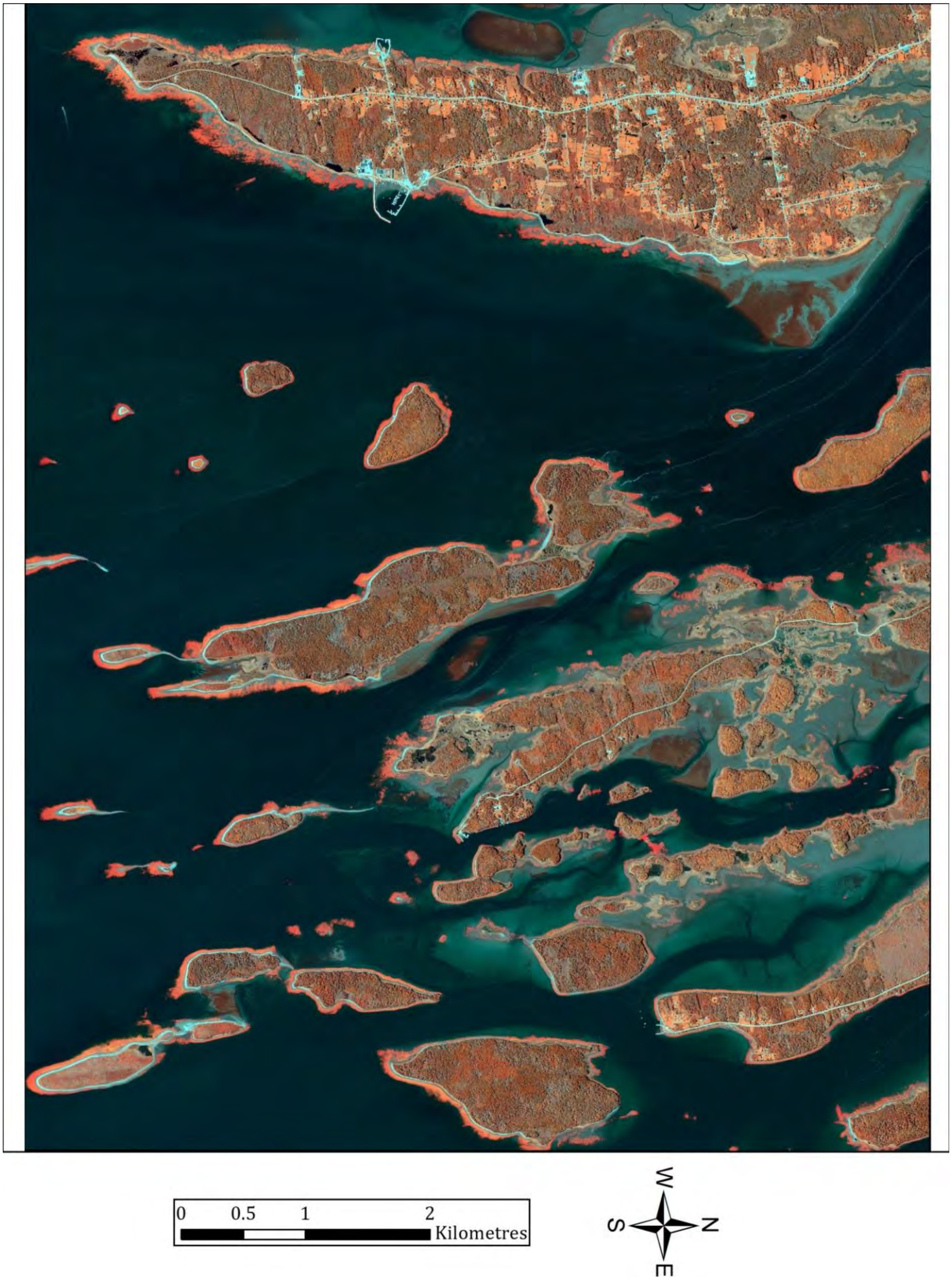

Figure 37. Near-infrared, green, blue (NIR-G-B) composite of Wedgeport, NS. Worldview-2 image taken October 24, 2012.

Figure 38. Supervised classification results shown on a true colour composite of Wedgeport, NS. Worldview-2 image taken October 24, 2012.

Appendix B - Cape Sable Island

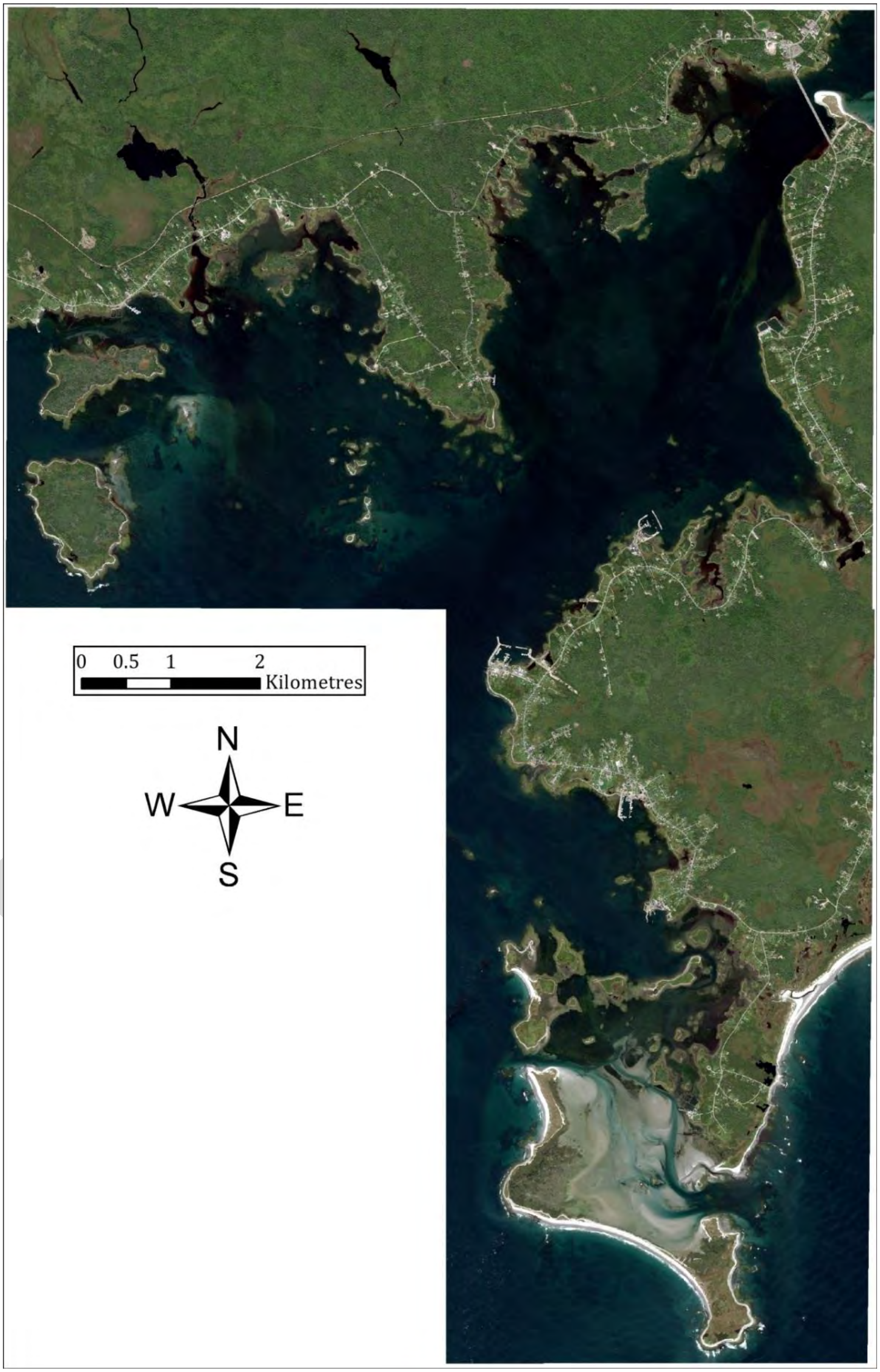

Figure 39. True colour composite of Cape Sable Island, NS. Worldview-2 image taken September 11, 2012.

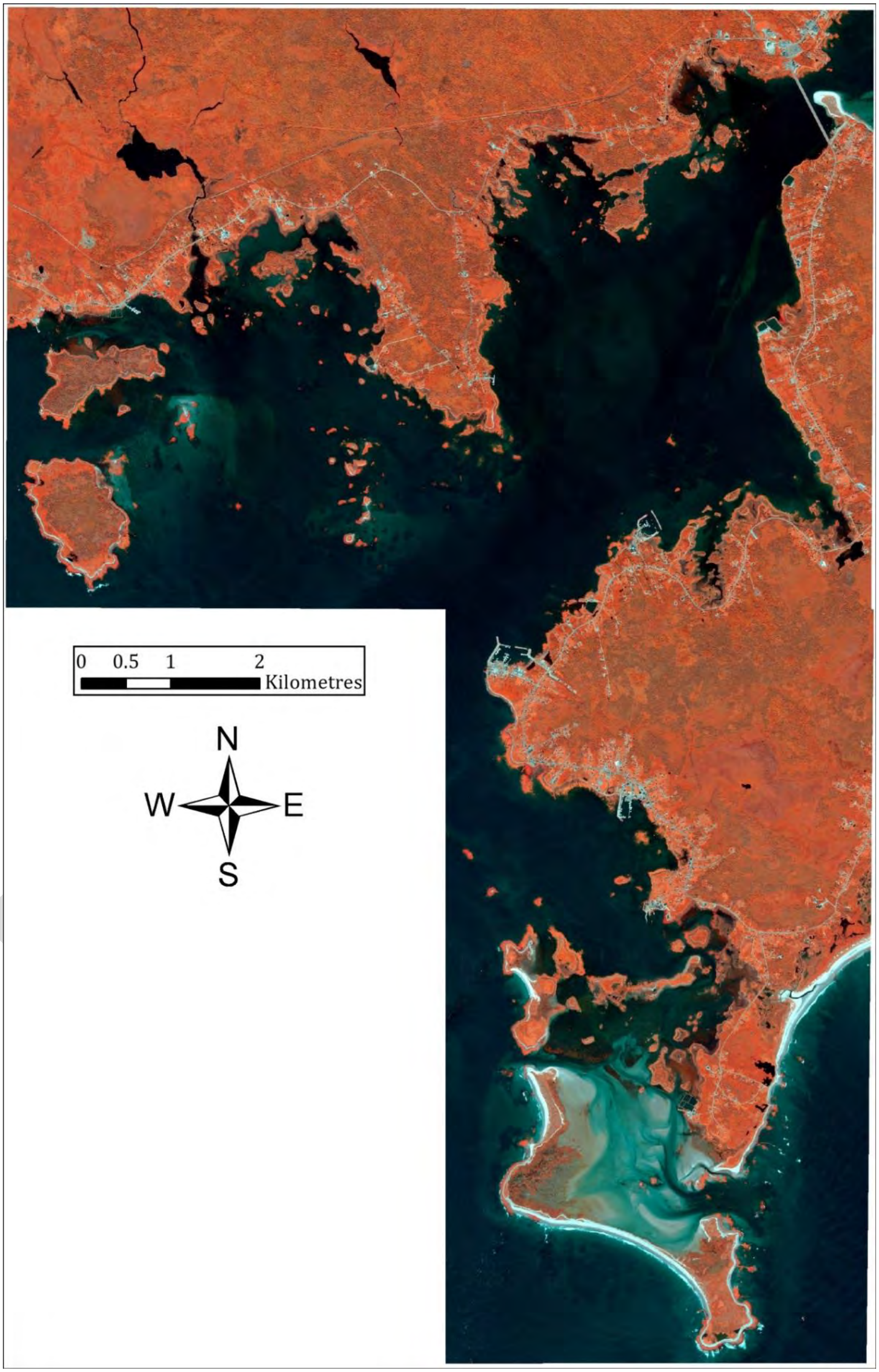

Figure 40. Near-infrared, green, blue (NIR-G-B) composite of Cape Sable Island, NS. Worldview-2 image taken September 11, 2012.

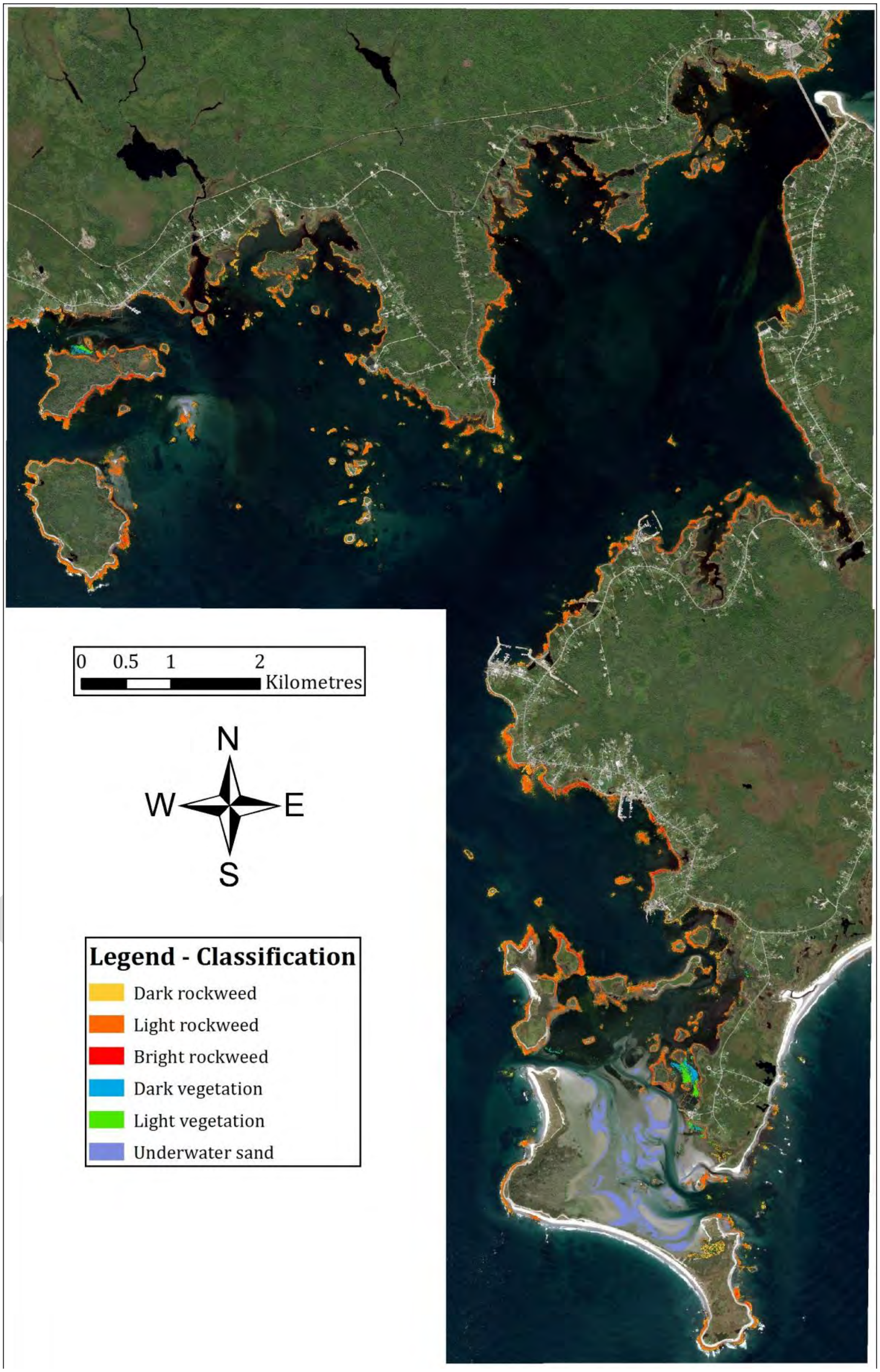

Figure 41. Supervised classification results shown on a true colour composite of Cape Sable Island, NS. Worldview-2 image taken September 11, 2012.

Appendix C - Kelleys Cove – May 7, 2010

Figure 42. True colour composite of Kelleys Cove, NS. Worldview-2 image taken May 7, 2010.

Figure 43. Near-infrared, green, blue (NIR-G-B) composite of Kelleys Cove, NS. Worldview-2 image taken May 7, 2010.

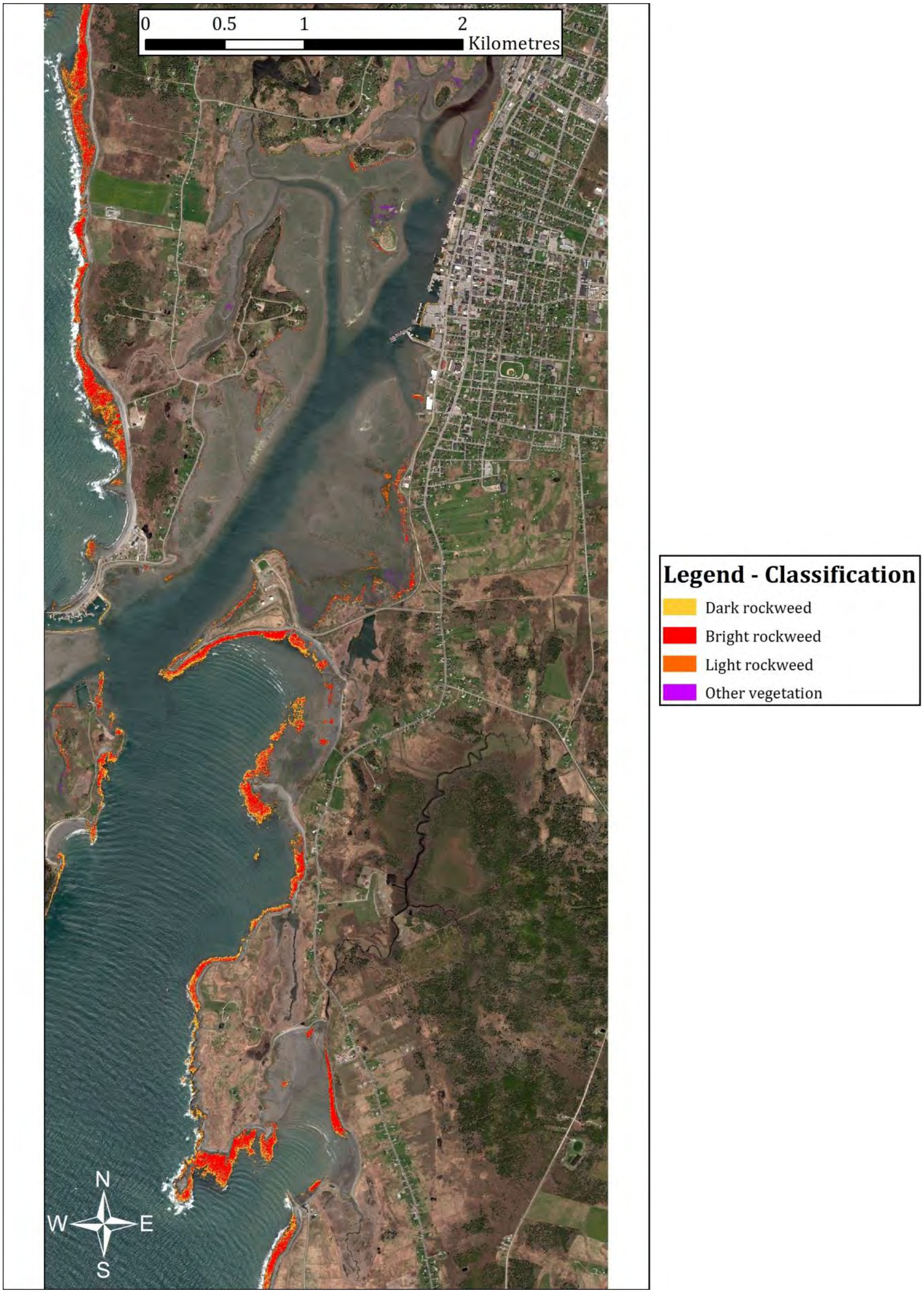

Figure 44. Supervised classification results shown on a true colour composite of Kelleys Cove, NS. Worldview-2 image taken May 7, 2010.

Appendix D - Kelleys Cove – August 19, 2010

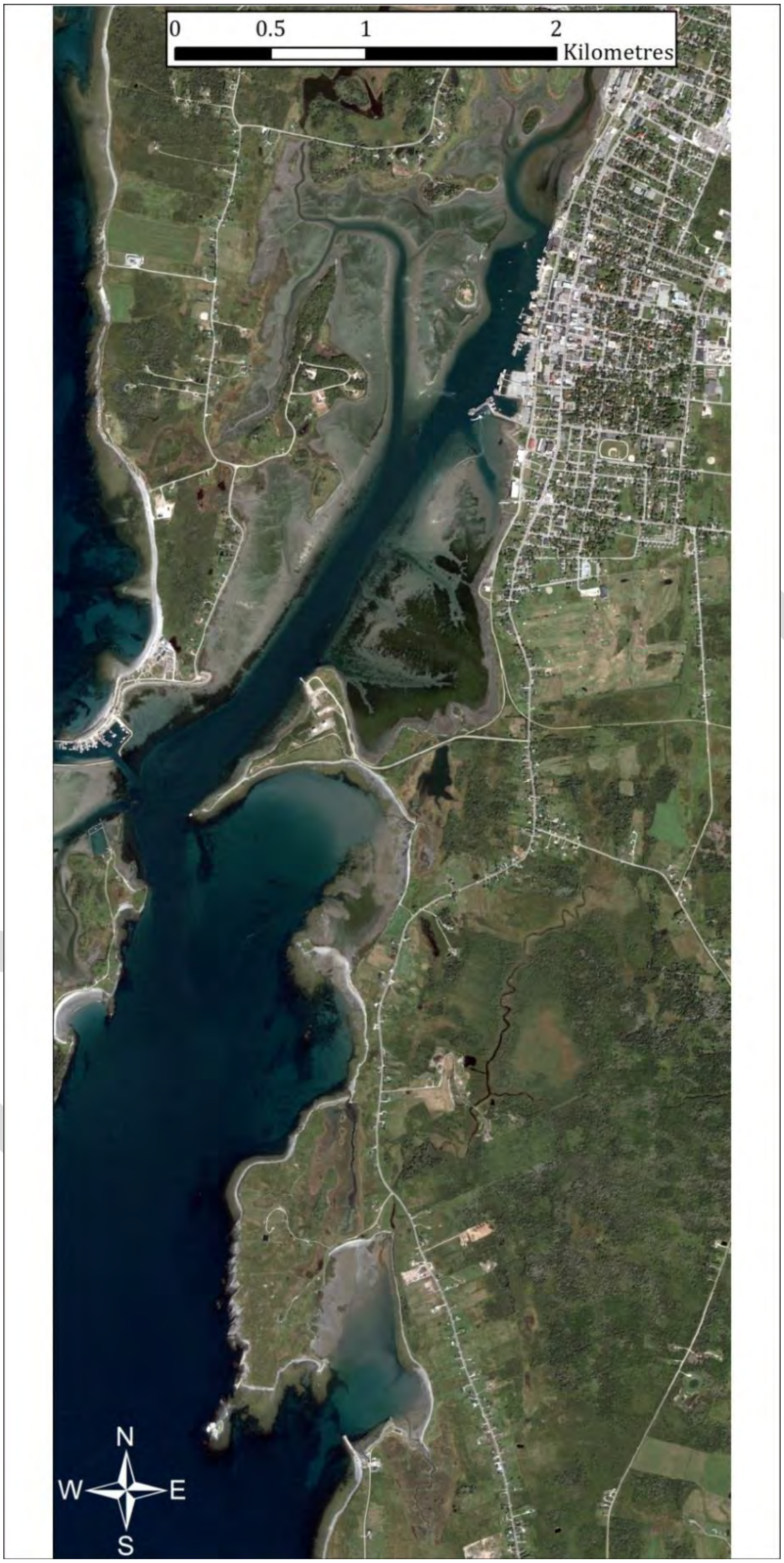

Figure 45. True colour composite of Kelleys Cove, NS. Quickbird image taken August 19, 2010.

Figure 46. Near-infrared, green, blue (NIR-G-B) composite of Kelleys Cove, NS. Quickbird image taken August 19, 2010.

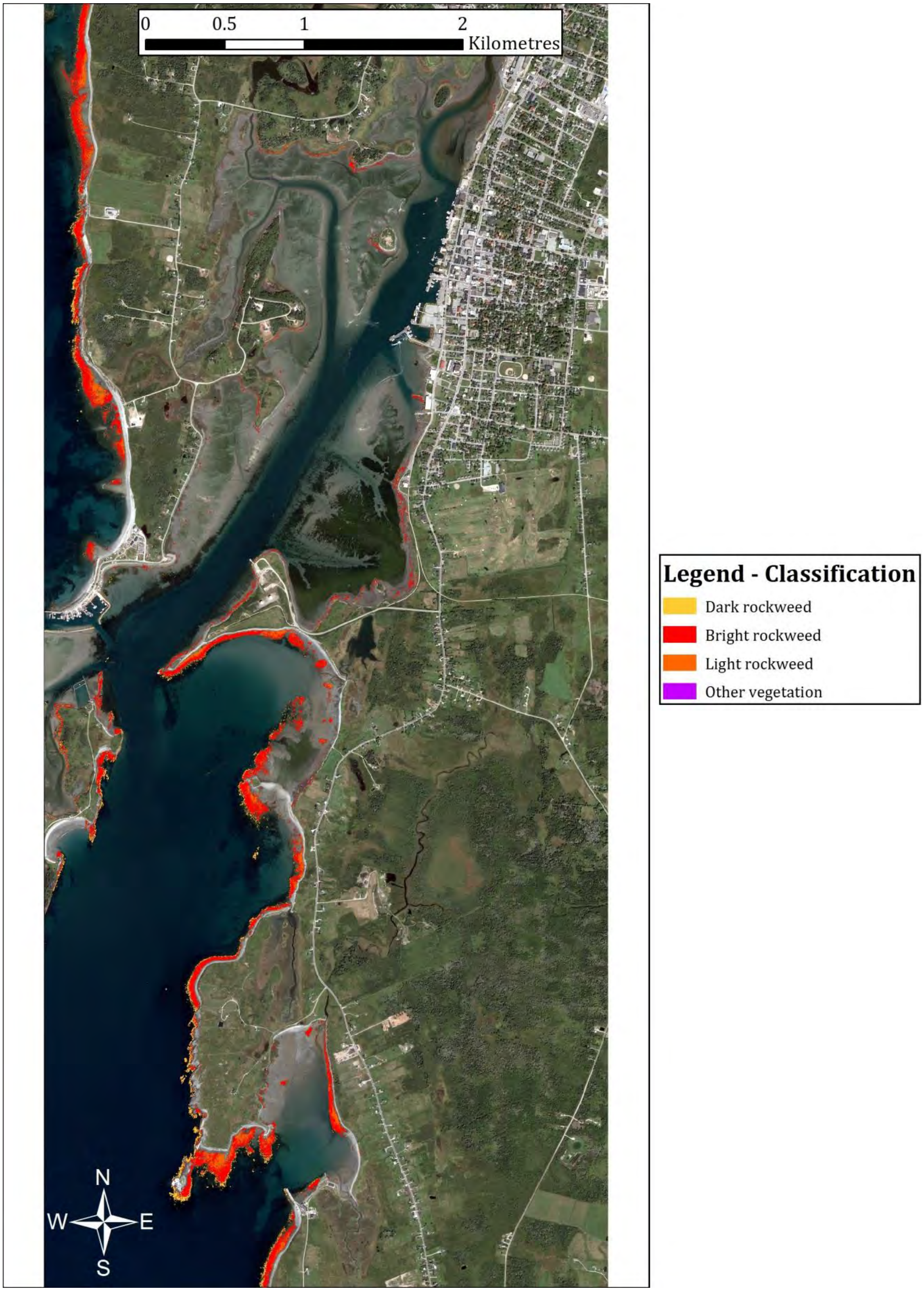

Figure 47. Supervised classification results shown on a true colour composite of Kelleys Cove, NS. Quickbird image taken August 19, 2010.