Evaluating satellite imagery for Atlantic walrus (*Odobenus rosmarus rosmarus*) stock assessment – a pilot study

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ABSTRACT

Matthews, C.J.D., Dispas, A., and Mosnier, A. 2022. Evaluating satellite imagery for Atlantic walrus (*Odobenus rosmarus rosmarus*) stock assessment – a pilot study. Can. Tech. Rep. Fish. Aquat. Sci. 3492: v + 25 p.

The recent development of very high-resolution (VHR) satellite imagery allows for unprecedented detection and identification of animals. This report outlines a pilot study in which satellite images of one of the primary terrestrial walrus (*Odobenus rosmarus rosmarus*) haulout sites in the eastern Canadian Arctic was evaluated as an alternative to conventional methods of stock assessment. Visual assessment indicated the 30-cm on-the-ground spatial resolution was insufficient to identify individual walruses in both panchromatic and pansharpened 4-band (red, blue, green, and near-infrared) images, in particular where hauled out walruses were clumped. A supervised classification algorithm showed promising results, but required manual adjustments based on visual assessment. Classification errors may have stemmed from overlap between the spectral profiles of walruses and background rock. Nevertheless, abundance estimates calculated as the product of the area covered by walruses identified by the classification algorithm and walrus densities determined from aerial survey photographs taken in 2017 were comparable to survey counts. While satellite imagery is currently sufficient for applications requiring presence/absence information, we caution that proper validation comparing satellite image-derived estimates and aerial counts from the same time is required before satellite images can be used in quantitative walrus stock assessment. We also stress that cloud-free images were only obtained on a single day out of several weeks of tasking, potentially constraining its use in Arctic environments, particularly for applications requiring high temporal resolution.

RÉSUMÉ

Matthews, C.J.D., Dispas, A., and Mosnier, A. 2022. Evaluating satellite imagery for Atlantic walrus (*Odobenus rosmarus rosmarus*) stock assessment – a pilot study. Can. Tech. Rep. Fish. Aquat. Sci. 3492: v + 25 p.

Le développement récent de l'imagerie satellitaire à très haute résolution permet une détection et une identification sans précédent des animaux. Le présent rapport décrit un projet pilote dans lequel les images de l'un des principaux sites d'échouerie terrestres des morses (*Odobenus rosmarus rosmarus*) dans l'est de l'Arctique canadien ont été évaluées afin de tester une alternative aux méthodes conventionnelles d'évaluation des stocks. L'évaluation visuelle a indiqué que la résolution spatiale au sol de 30 cm était insuffisante pour identifier les morses à l'échelle individuelle sur les images panchromatiques et multispectrales affinées («pan-sharpened») à 4 bandes (rouge, bleu, vert et infrarouge), en particulier lorsque les morses échoués étaient regroupés. Cependant, un algorithme de classification supervisé a donné des résultats prometteurs, mais des ajustements basés sur une évaluation visuelle ont été nécessaires. Les erreurs de classification pourraient provenir de ressemblances entre les profils spectraux des morses et les rochers en arrière-plan. Néanmoins, les estimations d'abondance calculées comme le produit de la superficie des zones identifiées par l'algorithme de classification et des densités de morses déterminées à partir de photographies aériennes prises lors de relevés aériens en 2017 étaient comparables aux dénombrements obtenus lors du relevé. Bien que l'imagerie satellitaire est actuellement suffisante pour les applications requérant des informations de présence/absence, nous mettons toutefois en garde qu'une validation adéquate, comparant des estimations dérivées d'images satellitaires et des décomptes aériens réalisés au même moment, est requise avant que les images satellitaires ne puissent être utilisées dans l'évaluation quantitative des stocks de morses. Nous soulignons également que des images sans nuages n'ont été obtenues que lors d'une seule journée sur une période de plusieurs semaines. Cela révèle les limites potentielles de cette méthode pour examiner les patrons d'échouerie à relativement haute résolution temporelle (i.e., quotidienne) dans les environnements arctiques.

1. INTRODUCTION

Monitoring of animal populations, including regular assessment of population abundance and distribution, is essential for conservation and management, in particular for detecting and identifying drivers of population change (Holling 1978, Campbell *et al.* 2002). Atlantic walrus (*Odobenus rosmarus rosmarus*) are distributed in remote areas throughout the eastern Canadian Arctic, where they occur as two genetically distinct populations (Shafer et al. 2014). The largest population, numbering approximately 18,900 animals, is the Central Arctic population, which is found in Hudson Bay, Foxe Basin and Hudson Strait (Stewart 2008, COSEWIC 2017). The range of the High Arctic population, which numbers approximately 2,500 animals, includes Baffin Bay, Jones Sound, Penny Strait, and Lancaster Sound (Stewart 2008, COSEWIC 2017).

Fisheries and Oceans Canada (DFO), the federal agency responsible for co-management of walrus in Canada, uses aerial surveys by fixed-wing aircraft in walrus population assessments (Hammill et al. 2016, Mosnier et al. 2022). Surveys are timed to coincide with maximum numbers of walruses hauled out at terrestrial sites during the open-water period, and generally fly over known haulout sites and intervening coastline and islands to identify any new sites. Coastal aerial surveys have been primarily photographic, in which animals are later counted from RGB images taken using digital SLR cameras. Abundance estimates are derived from raw counts that have been adjusted by availability bias factors to account for animals at sea (and therefore not counted directly during the survey; Stewart et al. 2014, Hammill et al. 2016, Mosnier et al. 2021). Aside from the logistical difficulties and expenses associated with conducting aerial surveys over the large spatial scales occupied by walruses (for example, the DFO survey conducted in September 2017, which covered for the first time the entire area used by the Hudson Bay-Davis Strait stock, required three planes over a period of several weeks [Mosnier et al. 2022]), the highly clumped nature of walrus distribution makes them inherently difficult to enumerate (Hammill et al. 2016). Movement between haulout sites and uncertainty in the proportion of animals hauled out during the survey make replicated surveys desirable to assess count variability, although concurrent tracking of animals with satellite tags and ground-based time-lapse photographs of the haulout site can help address these issues. Walruses are also prone to disturbance at haulout sites, including from aircraft flying at typical aerial survey altitudes (~300 m; DFO 2019), so a non-invasive method of population assessment is desirable.

With improvements in spatial resolution over recent decades, satellite imagery has become a practical means of studying terrestrial and marine animal abundance and distribution. Earlier applications of satellite imagery in animal ecology studies used images with resolution on the order of tens of meters, and thus relied on indirect cues to infer animal presence (such as the area extent of fecal staining at penguin colonies; Schwaller et al. 1989, Fretwell et al. 2012). Recent advances in resolution of commercially available images taken by satellites such as WorldView-3 have allowed for direct detection and counting of individual animals. Very high-resolution (VHR) images with under 1-m and as good as 30-cm on-the-ground resolution have allowed for expanded applications of satellite imagery to study abundance and spatial distribution of large-bodied animals such as baleen whales (Fretwell et al. 2014, Cubaynes et al. 2018) and polar bears *Urus maritimus* (Stapleton et al. 2014, LaRue and Stapleton 2018), but also of considerably smaller animals such as albatrosses *Diomedea exulans* and *D. sanfordi*

(Fretwell et al. 2017) and Whooper Swans *Cygnus Sanford* (Zhao et al. 2020) that had previously been impossible to discern in lower resolution images.

Recent studies have confirmed that satellite images can be reliably used in assessments of pinniped populations. LaRue et al. (2011) demonstrated acceptable correlations between satellite image and ground counts of Weddell seals *Leptonychotes weddellii*, and also demonstrated that satellite images could be reliably used to detect abundance trends. The dark bodies of Weddell seals against the Antarctic sea ice on which they were hauled out provided an ideal high-contrast situation in which to employ satellite imagery. McMahon et al. (2014) similarly reported strong correlations between ground and satellite image counts of individual elephant seals *Mirounga leonina* on Macquarie Island in the southwest Pacific Ocean, confirming that the method could also be employed in situations with reduced contrast between the animal and background elements (i.e., seals on land). Following these proof-of-concept studies, Ainley et al. (2015) compared historic ground counts (1959-1968) of Weddell seals to recent counts from high-resolution satellite images (2008-2012) of two major molting areas in Antarctica, and found a decrease in population abundance and/or a shift in distribution occurred in the interim period.

While resolution of commercially available satellite images does not yet rival that of images obtained during conventional aerial surveys, the method potentially offers some advantages over aerial survey methods. Satellites can cover large geographic areas, including remote sites that are difficult to access. Moreover, satellites often pass over the same sites at intervals of 1-2 days, allowing for repeated imaging with broad spatial coverage, which facilitates longitudinal studies of widely-distributed animal populations. Replicated coverage of haulout sites over short intervals could be particularly valuable in walrus stock assessment, as variation in proportions of hauled out walruses could be quantified to allow for more accurate adjustment of raw counts to derive abundance estimates (see Doniol-Valcroze et al. 2016). While costs associated with purchasing images over large spatial areas can be prohibitive and similar to aerial survey operational costs, images acquired via satellite require little logistical effort and pose no safety concerns to researchers. This method also has the added advantage of being completely non-invasive to animals and their habitats, which could be of particular value for studying abundance, spatiotemporal distribution, and behavior of disturbance-prone walruses at terrestrial (and sea ice) haulout sites (DFO 2019).

Few satellite image studies exist of walrus, a species that hauls out in masses on terrestrial substrate that can contrast little with their own coloration, both factors known to limit application of this technique in animal studies (see Fischbach and Douglas 2021). This report outlines findings of a pilot study designed to assess the feasibility of using very high-resolution satellite imagery as an alternative approach for counting walruses at terrestrial haulouts, as well as assess temporal variation in numbers of walruses hauled out. Objectives included determining whether commercially available satellite imagery is of sufficient resolution to detect and reliably count individual walruses, and if not, how satellite imagery might still be used in assessment of walrus haulout behavior (e.g., presence/absence) and relative abundance (e.g., proportions of animals hauled out at any given time).

2. MATERIALS AND METHODS

2.1 STUDY SITE

Walrus Island, one of the major walrus haulout sites in the eastern Canadian Arctic, is located in northern Hudson Bay just south of Southampton Island (63.2736 N, –83.6875 W; Figure 1). This site was selected for the pilot study because DFO aerial surveys consistently record the highest raw counts of walruses in the Canadian Arctic at this site (Hammill et al. 2016, Mosnier et al. 2022). The selection of Walrus Island is also relevant because of its proximity to shipping routes, which requires monitoring walrus numbers, distribution, and behavior to assess any impacts of shipping disturbance (DFO 2019).

2.2 SATELLITE IMAGES

The WorldView-3 satellite was tasked via Maxar Technologies (https://www.maxar.com) to take multiple images of Walrus Island over a 2-week period (Sept 1 to 15, 2020) when seasonal maximums of walruses are hauled out. Both panchromatic (grayscale) and pansharpened images (four bands – red, blue, green, and near-infrared; produced by merging a higher resolution panchromatic image with the corresponding lower resolution multispectral image to produce a very high-resolution colored image) were ordered to allow for comparison of the two image types for detecting walrus. Both types of images were 30-cm resolution and were orthorectified, which corrects imagery for terrain and provides the perspective of looking directly over the photographed objects. Archives were also searched for available images from previous years. In particular, we were interested in acquiring images during the most recent aerial survey (September 2017) to assess accuracy of satellite image counts via comparison with counts from higher resolution aerial photographs taken from survey aircraft. Unfortunately, no suitable archived images of Walrus Island were available from that period.

The two-week period was selected to provide sufficient time to acquire a series of suitable images (i.e., 0% cloud cover over the site) while accounting for typical overcast and foggy conditions at that time of year. Advanced commercial satellite image purchase required a minimum area of 100 km^2, which was more than enough to encompass the entire island, including several hundred meters of water extending in all directions from the coastline. We had intended to collect several images separated by an interval of several days within the allotted time period to allow for assessment of variability in numbers of hauled out walruses.

2.3 DATA ANALYSIS

Georeferenced panchromatic and pansharpened satellite images were processed in QGIS 3.16, an open-access geographic information system (GIS) software (QGIS Development Team 2021). Our general data analysis goals were to 1) determine whether individual walruses could be manually counted; 2) train a semi-automated detection algorithm on the spectral profile of walruses to classify and extract those pixels from other image elements (i.e., rock, water) and calculate area covered by walruses; and 3) estimate walrus numbers by multiplying the area covered by walruses in the satellite image by a range of walrus densities determined from previous aerial surveys of Walrus Island.

Manual detection and counts. Both panchromatic and 4-band pansharpened images were visually assessed by three different observers to determine whether individual walruses could be discerned and reliably counted (particularly those amassed in groups; Figures 2 to 5). Image enhancement included manipulating brightness, contrast, and saturation of both the panchromatic and pansharpened images, as well as varying the contributions of the four band components of the pansharpened image.

Supervised classification and detection. Supervised classification is commonly used to identify animals in satellite images (LaRue et al. 2014; Fretwell et al. 2014, Hollings et al. 2018). In this approach, the user manually defines pixels belonging to known elements (e.g., rock or water) to train the algorithm via maximum likelihood to identify the element's spectral profile, and to then use the mean and variance of the training data to classify remaining pixels in the image (Hollings et al. 2018). Supervised classification is potentially more accurate than unsupervised classification when classifiers have *a priori* knowledge of image components (Hollings et al. 2018), and we opted for this approach given our experience identifying walruses in aerial survey photographs of the same haulout site. A semi-automatic image classification tool called 'Dzetsaka' (Version 3.64; Karasiak 2020; available as a QGIS plugin) was used to assist with the identification of walruses. Of the available classification algorithms in 'Dzetsaka', we used the Gaussian Mixture Model classifier, which assumed that the distribution of the spectral signatures of each feature follows a normal distribution. Images were manually subdivided into different areas of interest (AOI) estimated to be representative of specific landscape elements: walrus, rock, terrestrial vegetation, sea water, and pooled surface water on the island (Figures 6 and 7), and the algorithm was trained to recognize the unique spectral combinations of each of those components. The mean and variance of the spectral signatures of the training data were then used to classify all remaining pixels in the image (see Fauvel et al. 2015), which allowed for identification of area covered by walrus vs. areas covered by all other features. After the classification was performed, a raster representing the predicted class of each image pixel was generated (Karasiak and Perbet 2018). The pixels classified as 'walrus' were then selected and converted (vectorized) to a spatial polygon shapefile from which we were able to estimate the area covered by this species.

The procedure outlined above was repeated using walruses from different areas of the image to train the classification tool, which had an important effect on results (see below). We retained two classification sets (1 and 2; Table 1, Figures 6 and 7) that, respectively, overestimated and underestimated the area covered by walruses (compared with visual assessment), and conducted an additional 'classification' in which the shapefile that overestimated the area covered by walruses was manually edited to remove wrongly identified areas and add missed individuals (Figures 8–10).

Archived georeferenced images from the last walrus aerial survey conducted by DFO in September 2017 (Mosnier et al. 2022) were used to estimate a range of densities of walruses hauled out on Walrus Island. Four zones corresponding to areas with walruses on both the satellite image and the aerial survey images were delimited (Figure 11). Walruses were counted on the aerial survey images within three small polygons per zone considered to be representative of the local variability in walrus density (Figure 12). Polygons were located in areas where the number of animals could be clearly estimated, and the boundaries of each polygon encompassed walruses that were within 30 cm of each other, mimicking the result of the classification algorithm on a 30-cm resolution satellite image.

Densities within each polygon were averaged to obtain a density for the respective zone, which were then tested for differences using ANOVA. Densities did not differ among zones (see below), so they were averaged and multiplied by the area of the island covered by walruses (as delineated by the classification algorithm) to estimate the number of walruses hauled out in the satellite image.

3. RESULTS AND DISCUSSION

Cloud-free satellite images of Walrus Island could not be obtained during the allotted two-week period, highlighting one of the downfalls in using this approach when specific windows for data collection are required, particularly during the Arctic open-water season characterized by persistent fog and cloud cover. However, suitably clear images of the island were obtained on September 25, 2020, 10 days after the allotted period (Figure 2). The end of September spans the open-water period when walruses can be found at Walrus Island, and groups of hauled out walruses were visible at several locations around the island (Figure 2). Without multiple images, however, our original objective of assessing variation in numbers or proportions of walruses that were hauled out on different days was not achievable. Our difficulty obtaining replicate images was similar to those of other researchers trying to acquire multiple satellite images in polar regions (e.g., LaRue and Stapleton 2018). This issue is not trivial, as numbers of walruses at haulout sites can vary significantly over periods as little as 24 hr (Mansfield and St Aubin 1991), so replicate images with relatively high temporal resolution are necessary to capture that variation. Near-future improvements in temporal resolution of satellite imagery are anticipated with the recent and planned launches of multiple new 30-cm resolution imaging satellites by companies such as Maxar Technologies and Airbus (https://www.maxar.com, https://www.airbus.com).

Visual inspection confirmed the 30-cm resolution of the WorldView-3 satellite images is insufficient to clearly and reliably count individual walruses that are massed together in groups (Figures 3 and 4). This is typical of satellite images of animals that occur in groups or flocks, thus making manual counting difficult or impossible, and requiring other quantification methods such as multiplying area covered by density estimates derived from other approaches (see below). Walruses that were more scattered, such as those more sparsely hauled out along the coast or those in water, were large enough to comprise several pixels on the image and were therefore visible (Figures 3 and 4), although, without the benefit of having multiple images, it was not possible to confirm objects were walruses and not other objects of similar size and shape (notably, rocks). Pansharpened images, with the additional spectral information in the four color bands, provided much better ability to discriminate walruses from background than the low-contrast panchromatic (grayscale) images (Figure 5).

Identification of the area covered by walruses based on their spectral signature using the image classification tool varied and was dependent on the initial selection of the walrus AOI used to train the algorithm. The first set of AOI definitions (classification set 1) provided reasonably good delineation (judged visually) of the total area occupied by walruses in the four zones (4541 m^2; Figure 8, Table 2). Some animals were missed in zones 1, 2, and 4; however, a larger sector in zone 3 that appears to have been previously used by walruses and therefore had coloration due to walrus feces was also classified as 'walrus', resulting in an over estimation of the area in this zone. In contrast, the second set of AOI definitions (classification set 2) clearly resulted in a large underestimation of the total area occupied by walruses in the four zones (2292 m^2; Figure 9, Table 2). The area estimated using the manual editing approach (see Methods) was slightly larger (4858 m^2) than the total identified using the first set of AOI definitions (Figure 10, Table 2). This was due to the removal of the overestimated area in zone 3 but the addition of larger areas of missed walruses in the other zones. We consider the manually adjusted area to be the most accurate of the three, but acknowledge some degree of observer error is typically present, which we have not quantified.

When applied at the scale of the entire island, the classification algorithm using the first set of AOI definitions clearly overestimated the area covered by walruses (9162 m^2), compared to the manually edited area (4865 m^2; Table 2). The large overestimation of the first approach was due to the misclassification of the landscape sharing part of the spectral signature of walruses, where walrus presence was visually ruled out. Classification of the entire island using the second set of AOI definitions still resulted in under-representation of the area occupied by walruses (2311 m^2; Table 2). Variability in supervised classification results (between the first and second set of AOI definitions) could reflect several factors, including variation in the initial identification of training data as well as the distinctiveness of the spectral profiles of walruses relative to other background elements (Hussain et al. 2013, Hollings et al. 2018). The larger manually defined walrus AOI in the first set of definitions likely included a greater number of pixels representing land (i.e., in between hauled out animals), while the smaller walrus AOI in the second set of definitions may not have included the full range of walrus pixels (Table 1, Figures 6 and 7). Both algorithms would have been impacted by overlapping spectral profiles of walruses and background elements (e.g., rock). These issues could potentially be addressed using 8-band images, although the greater amount of spectral data would come at the expense of lower spatial resolution. This would likely impact identification of sections where lone or few walruses comprise only a small number of pixels, as well as accurate delineation of peripheries of amassed animals (which may not represent a limitation, however, considering the contributions of errors in the classification algorithm and walrus density estimates to the final abundance estimate). Previous studies comparing supervised classification with other methods have shown that the method typically underperforms relative to visual and fully automated detection methods (Fretwell et al., 2014). We also note that, because atmospheric conditions influence spectral results (Hollings et al. 2018), the algorithms developed from our training datasets would only be applicable for automated classification of pixels on the image with which it was trained; image processing software with atmosphere correction capabilities would be required to apply extracted spectral profiles for classification of images taken on other days.

Estimated walrus mean densities per zone in archived georeferenced aerial survey images were 1.10 ± 0.07, 0.77 ± 0.26, 0.94 ± 0.31, and 0.97 ± 0.21 ind.m^{-2} for zones 1 to 4, respectively (Table 3). Mean densities did not differ significantly among zones (ANOVA, df = 3, F value = 1.099, $p > 0.05$), so they were combined to give a single mean density of 0.94 ± 0.23 ind.m^{-2} representative of all areas where walruses were hauled out (Table 3). Applying this density to the total area of the island occupied by walruses as estimated by our three approaches (i.e., classification set 1, classification set 2, classification set 1 + manual editing) resulted in estimated walrus totals of 8654 ± 22, 2183 ± 11, and 4596 ± 16, respectively (Table 2). The estimate using the combination of automated detection with manual adjustments is comparable to raw walrus counts from aerial photos of Walrus Island in September 2017 (4500-7300; Mosnier et al. 2022). However, numbers of walruses hauled out at any given site vary greatly even over short time intervals (Mansfield and St Aubin 1991), and raw aerial survey counts at Walrus Island varied by over an order of magnitude between 2017 and 2014 (250-2600; Hammill et al. 2016). Validation of this area-based approach for estimating walrus abundance from satellite images thus requires comparison with independent counts during the same period the satellite image was taken.

4. SUMMARY AND FUTURE STEPS

Walruses could not be individually counted on the 30-cm resolution satellite image, the best spatial resolution currently available commercially, particularly where they were hauled out in clumped masses. However, we confirmed they could be detected visually, with more certainty in pansharpened images in which contrast between walrus and background elements was considerably greater than in panchromatic images. Supervised (semi-automated) classification of walrus using an algorithm trained to recognize the spectral profile of walrus based on user-defined pixels was variable and required manual adjustments. More advanced methods of feature identification provided by specialized image processing software (e.g., ENVI), incorporating texture and other spatial attributes, may improve object classification, and would standardize the process for later application on similar images (Hollings et al. 2018). Unsupervised classification methods, which use statistical algorithms to group image pixels based on spectral information without user input (Hollings et al. 2018), could potentially eliminate, or at least reduce, the varied results we obtained based on user-defined AOI, and should be explored further. Spectral profiles of walruses and other features of interest (in particular, rock) could be analysed from spectroradiometer measurements or hyperspectral camera images, which capture more of the electromagnetic spectrum (~1000 bands). Results could be downsampled to correspond to the spectrum obtained from 8-band satellite images, and thus allow for the use of other classification methods, including rule-based and thresholding.

Areas classified as walrus using a supervised classification approach nevertheless provided reasonable estimates of animals hauled out when multiplied by densities derived from previous aerial survey photographs. While we caution that additional research comparing concurrent satellite and aerial photographs needs to be conducted to properly validate this approach, our study shows that manual analysis of satellite images may be used, at least, for assessing walrus presence and absence, as well as areas of haulout occupancy. Applications could therefore include periodic assessment of presence/absence and relative abundance (by comparing area of occupancy) at a large number of haulout sites throughout the Canadian Arctic. This would allow for detection of largescale shifts in walrus distribution, such as re-occupancy of previously abandoned haulout sites, or abandonment of sites in response to shipping and other anthropogenic disturbances. Such empirical, population-specific data that might guide measures to avoid and/or mitigate disturbance of walruses and their habitat from shipping (e.g., buffer zones) has been lacking (DFO 2019).

Robust, quantitative estimation of walrus abundance from satellite images, however, requires improvement in resolution of commercially available images, rigorous validation of our area-based approach outlined above that uses a combination of manual and supervised detection, or yet-to-be developed automated methods potentially based on machine learning approaches. We stress, however, that weather conditions posed a major constraint on obtaining suitable images during the study period, and will likely be a limiting factor in applications of satellite images to walrus stock assessment (in the optical range, at least; see Fischbach and Douglas [2021], who showed that synthetic aperture radar [SAR] imagery was useful for identifying walrus in cloudy conditions). Spatial and temporal gaps in image coverage due to cloud obstruction are particularly relevant for applications requiring acquisition of images over a relatively large area, or with relatively high temporal resolution (e.g., daily) to quantify variation in walrus haulout behavior.

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7. FIGURES

Figure 1: Location of Walrus Island (red circle), the haulout site selected for satellite imaging in this pilot study.

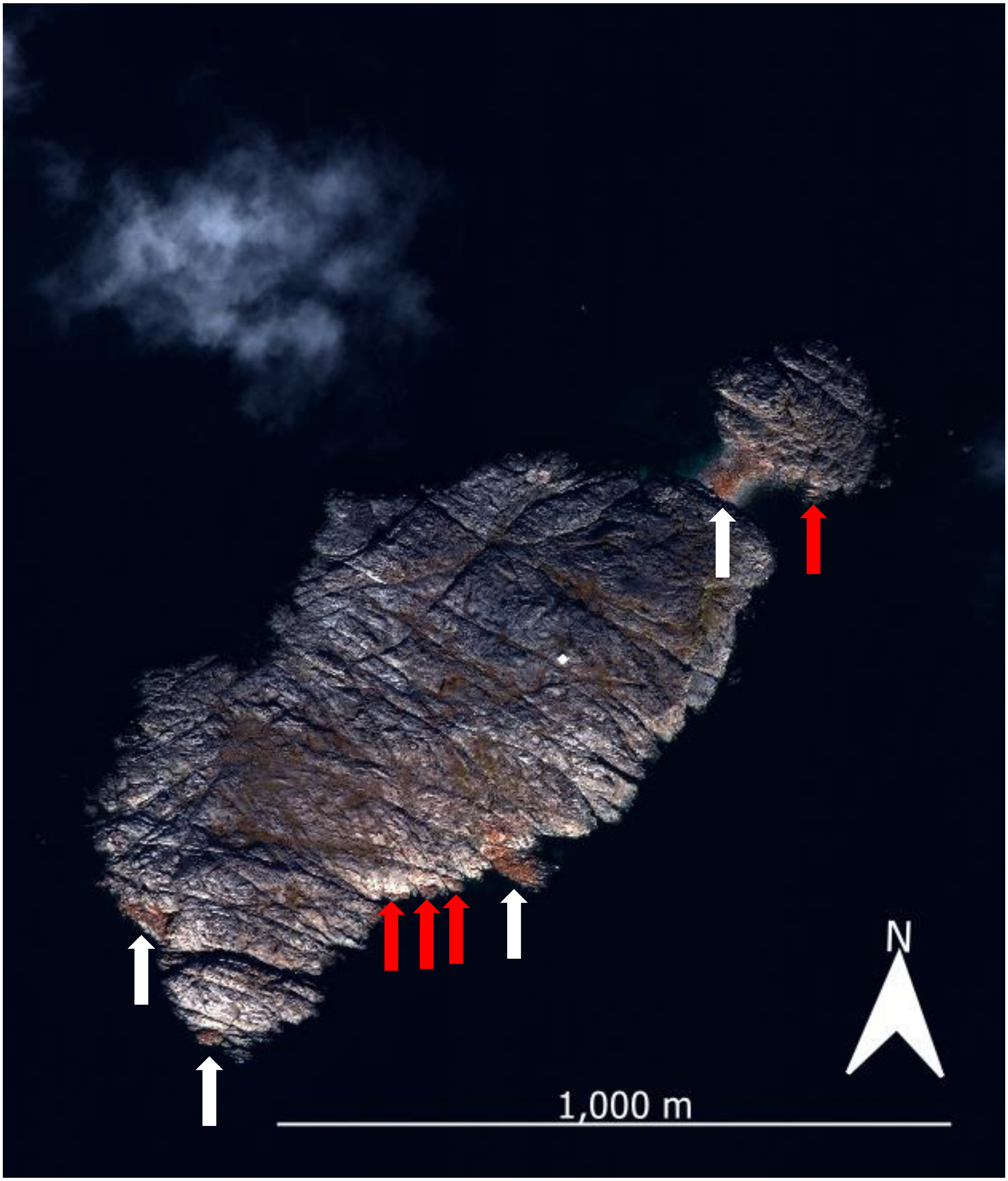

Figure 2: Pansharpened 30-cm resolution image of Walrus Island taken by the WorldView-3 satellite on September 25, 2020. Masses of hauled out walruses are visible as areas of reddish-brown (white arrows), as are smaller numbers of walrus more sparsely distributed along the coast (red arrows).

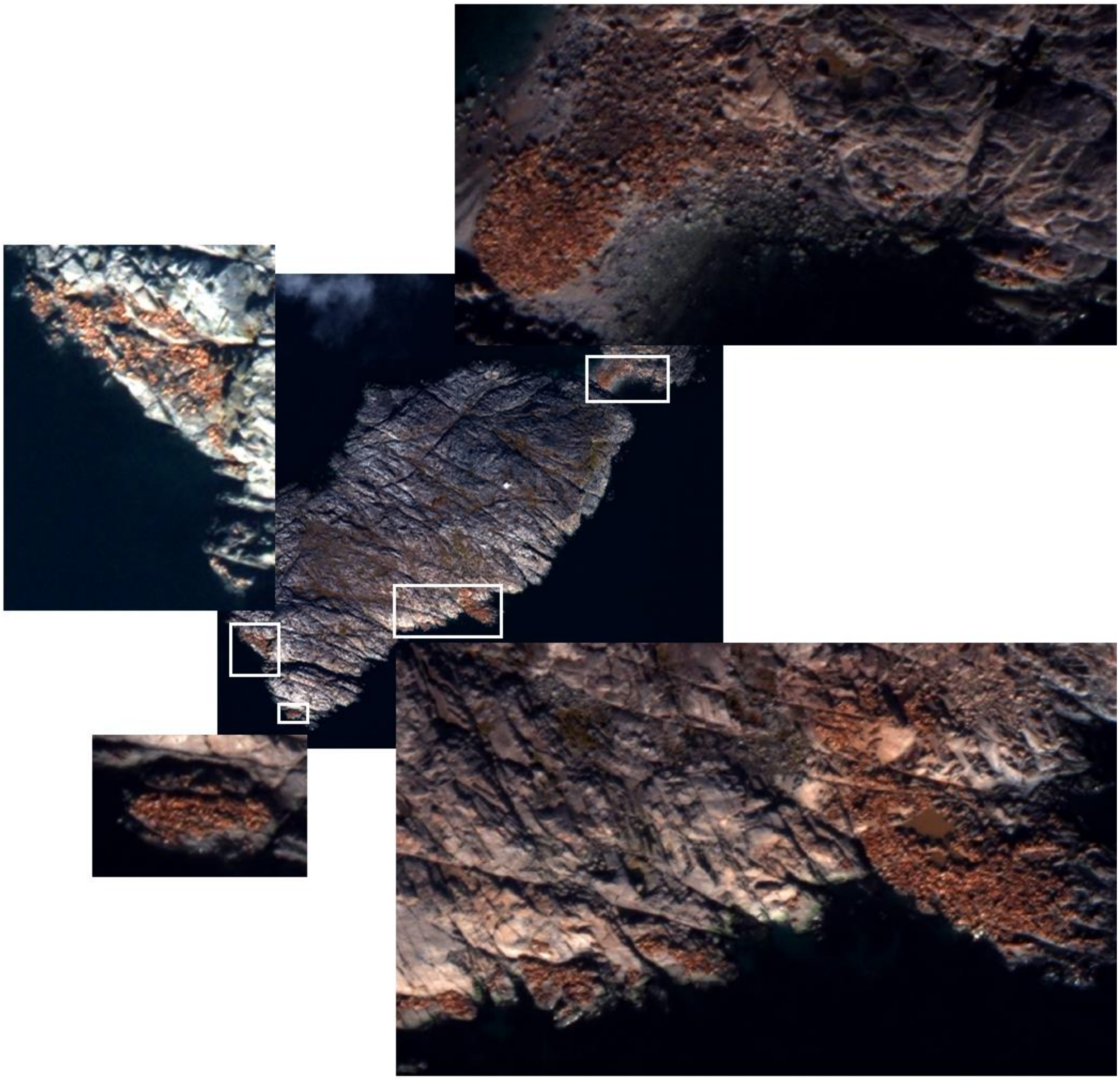

Figure 3: Zoomed-in sections of pansharpened image showing groups of hauled out walruses. Although visible in the image with distinct coloration from background (using four color bands – red, blue, green, and near-infrared – in the pansharpened image), the 30-cm resolution is insufficient to clearly identify and count individual walrus.

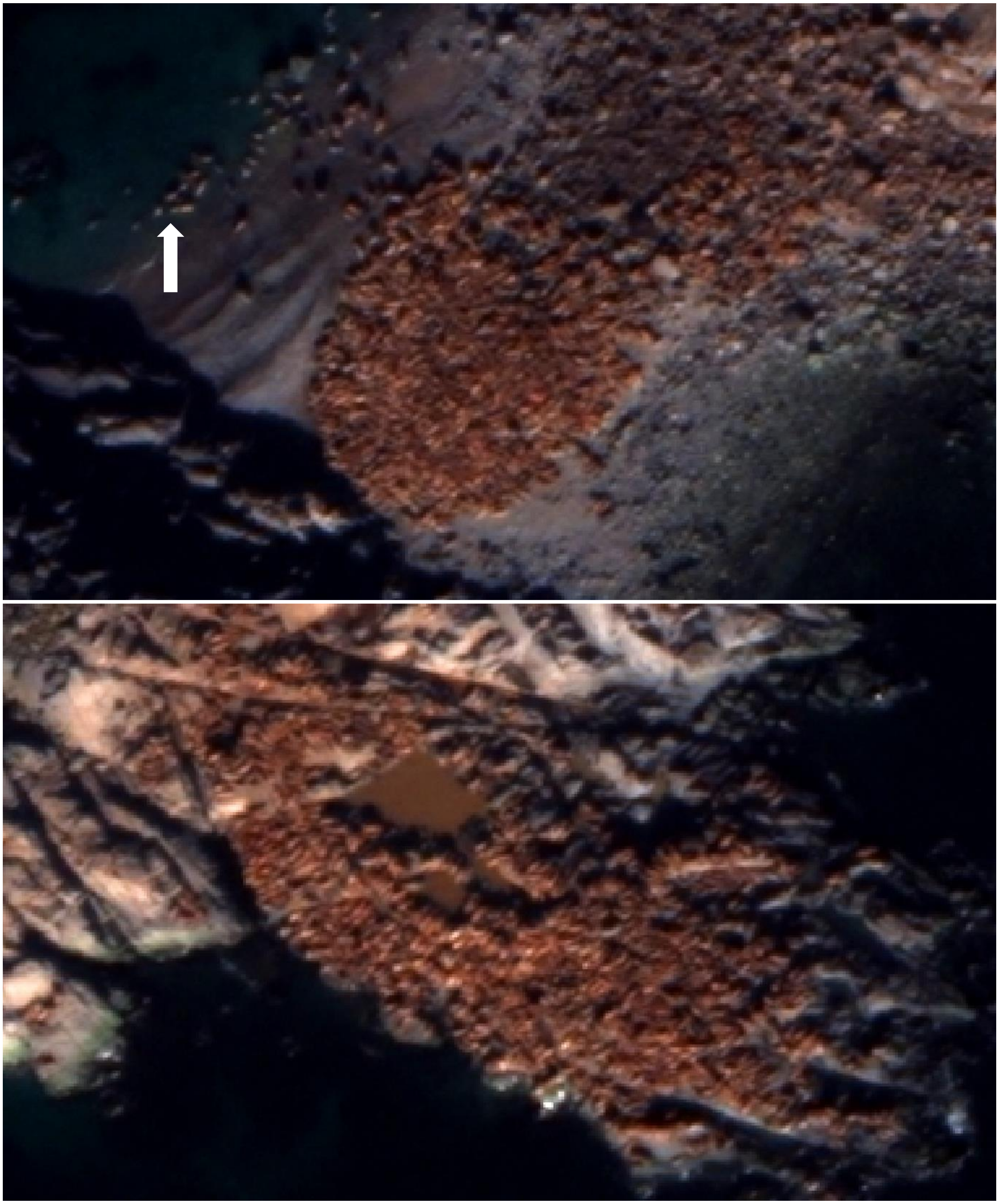

Figure 4: Two different sections of walrus photographed by the WorldView-3 satellite demonstrate the 30-cm resolution is insufficient to clearly identify and count individual walruses hauled out in masses on land. Note walruses in water, visible in the upper panel (white arrow), are a different color than those on land.

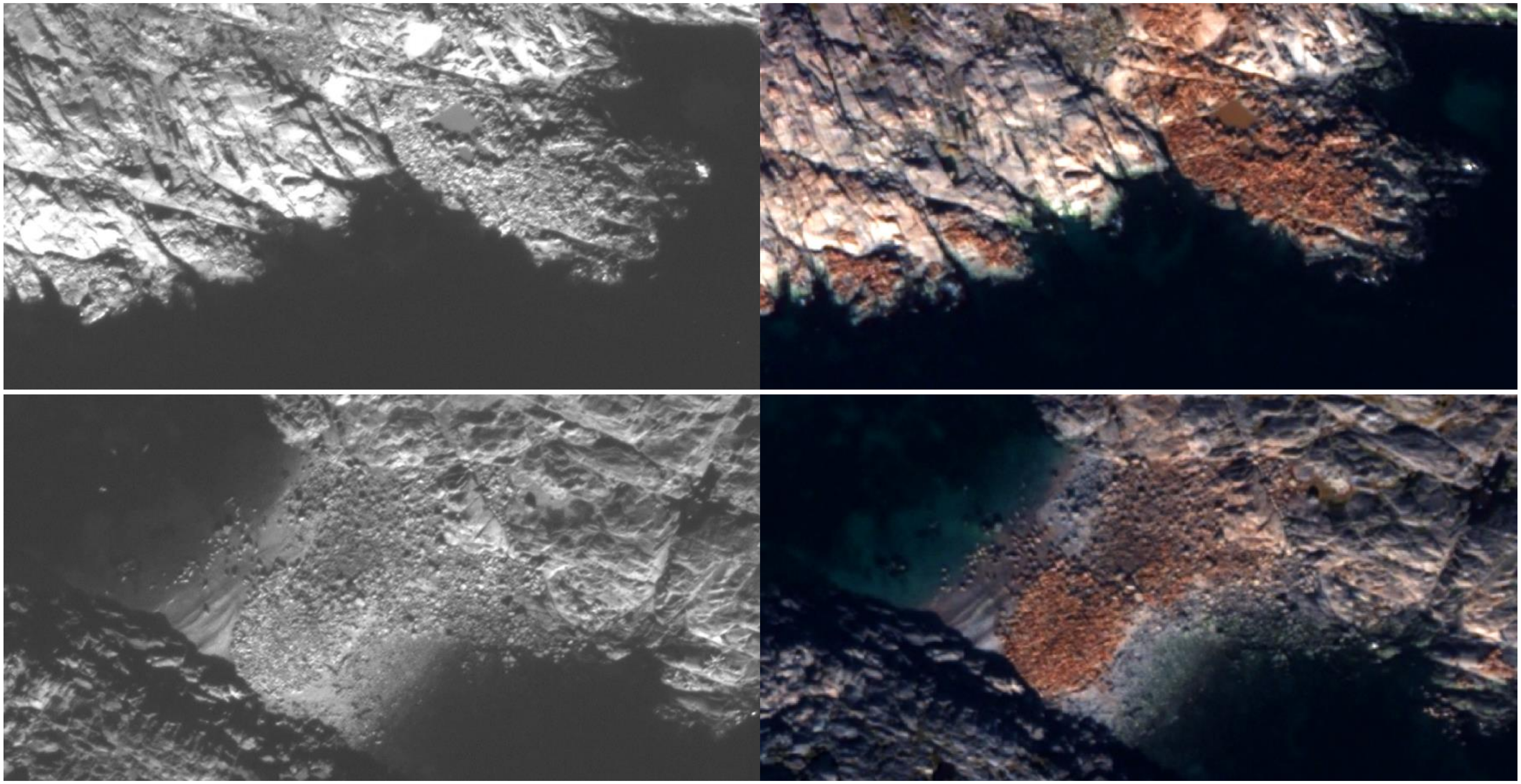

Figure 5: Side-by-side comparisons of two panchromatic (left) and pansharpened (right) WorldView-3 satellite images show walrus are more easily identified in the pansharpened images because the additional color bands provide greater contrast between walrus and their background.

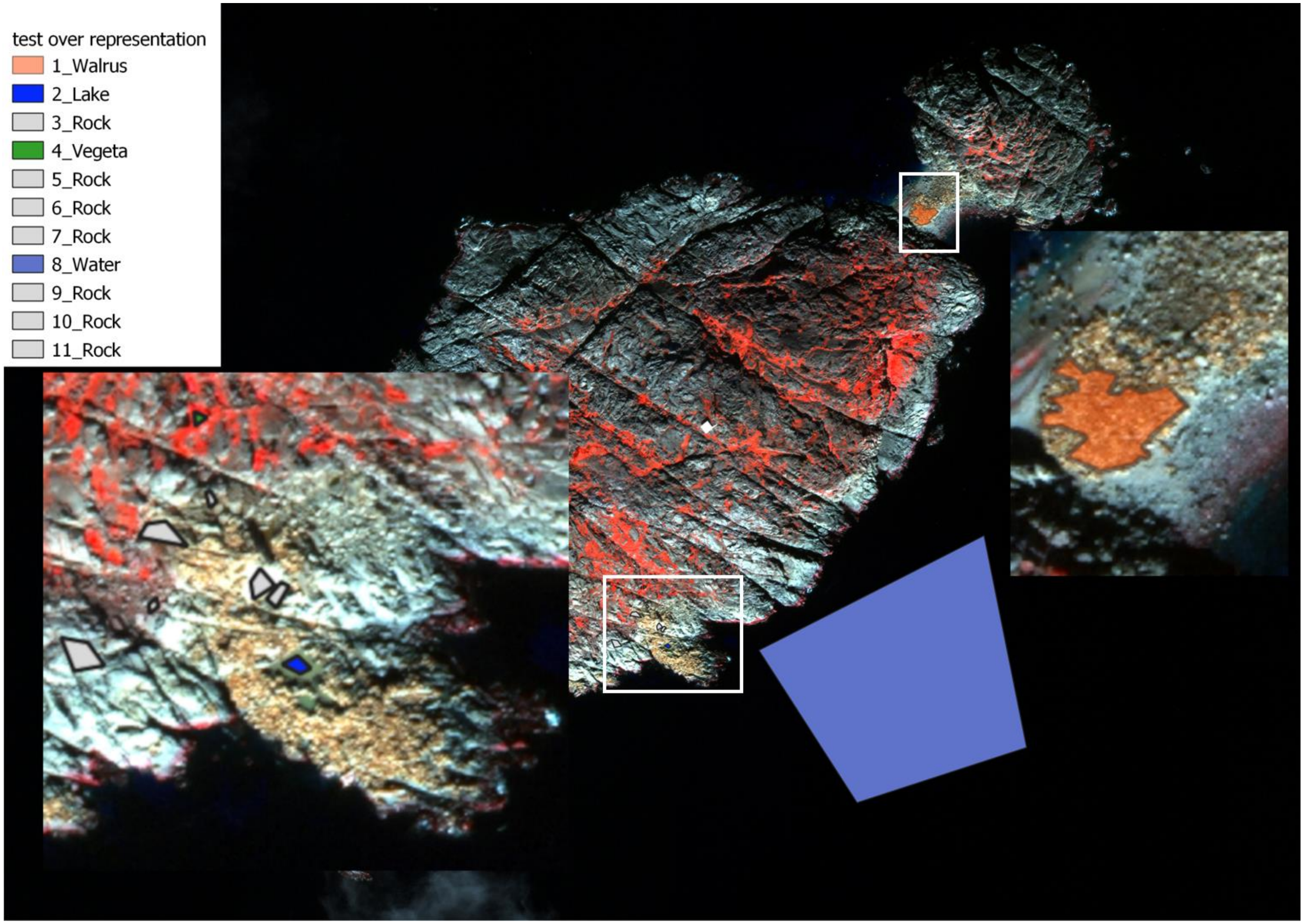

Figure 6: Selection of different areas of interest (AOI) for classification set 1, including walrus (orange), rock (grey), ocean water (purple), and lake water (blue), used to train the semi-automated detection algorithm on unique spectral profiles of each element. The walrus AOI was considerably larger, and located in a different area, than that used in classification set 2 (see Figure 7, Table 1).

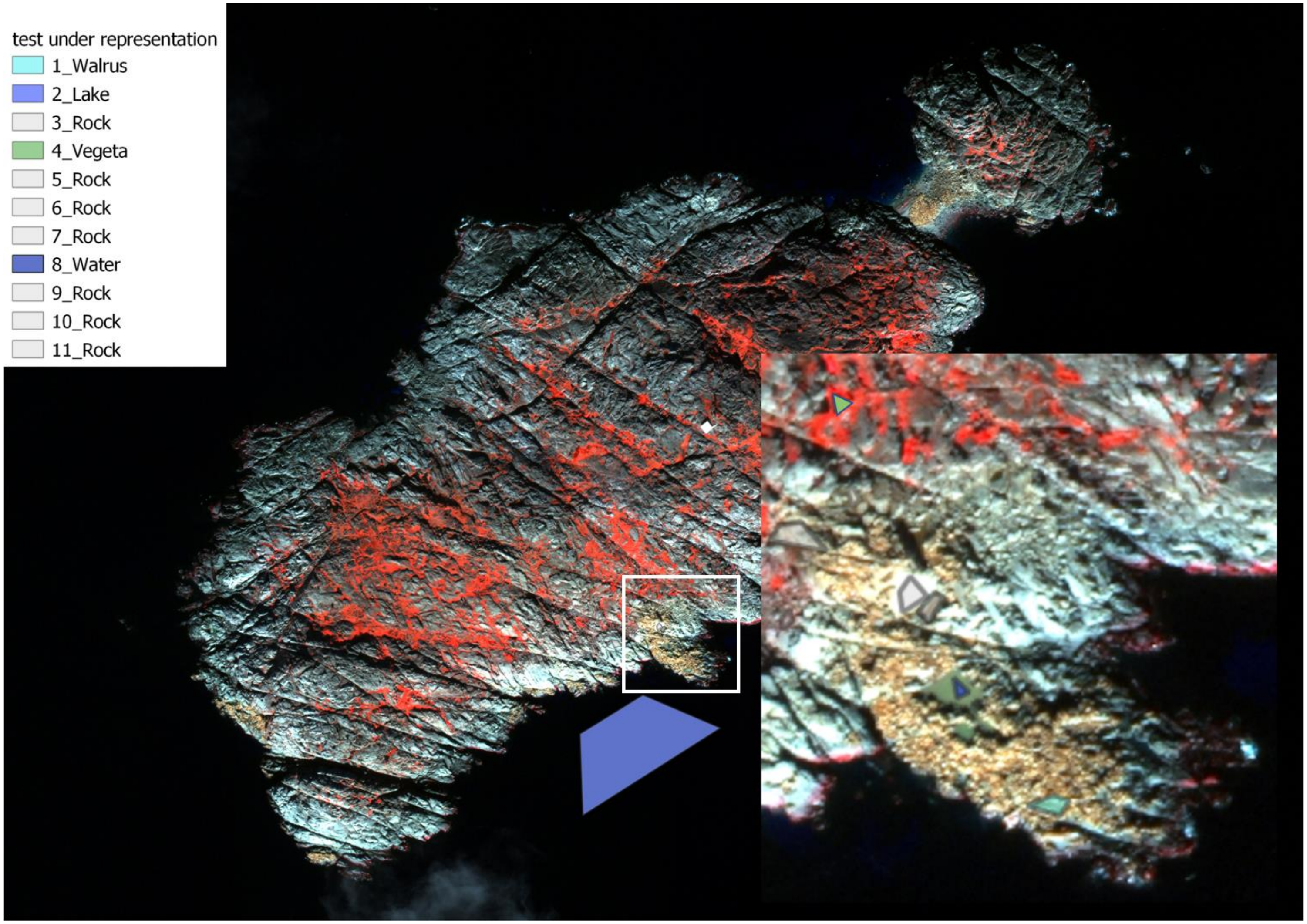

Figure 7: Selection of different areas of interest (AOI) for classification set 2, including walrus (turquoise), rock (grey), ocean water (purple), and lake water (blue), used to train the semi-automated detection algorithm on unique spectral profiles of each element. The walrus AOI was considerably smaller, and located in a different area, than that used in classification set 1 (see Figure 6, Table 1).

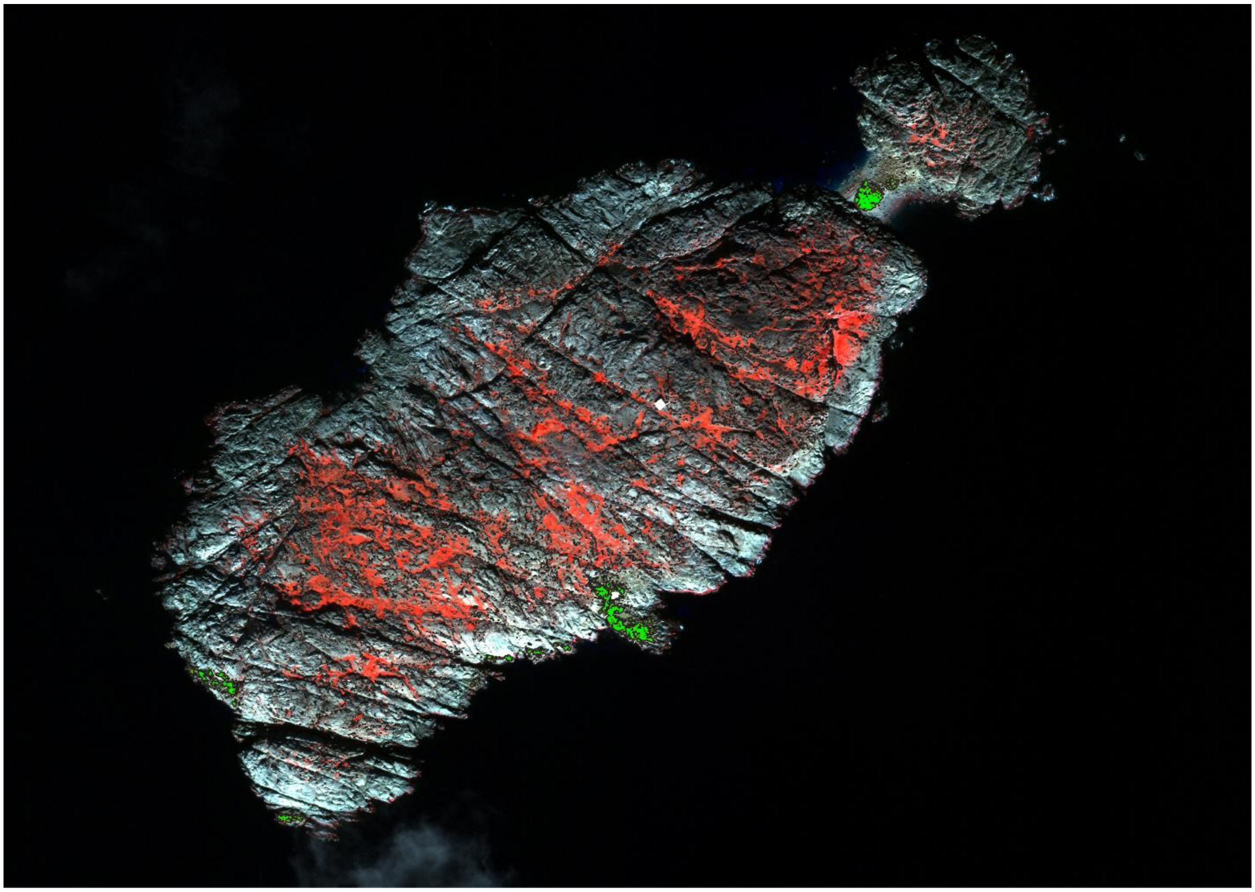

Figure 8: The first classification settings (classification set 1) applied to the pansharpened image overestimated the area covered by walrus (lime green) compared with visual assessment.

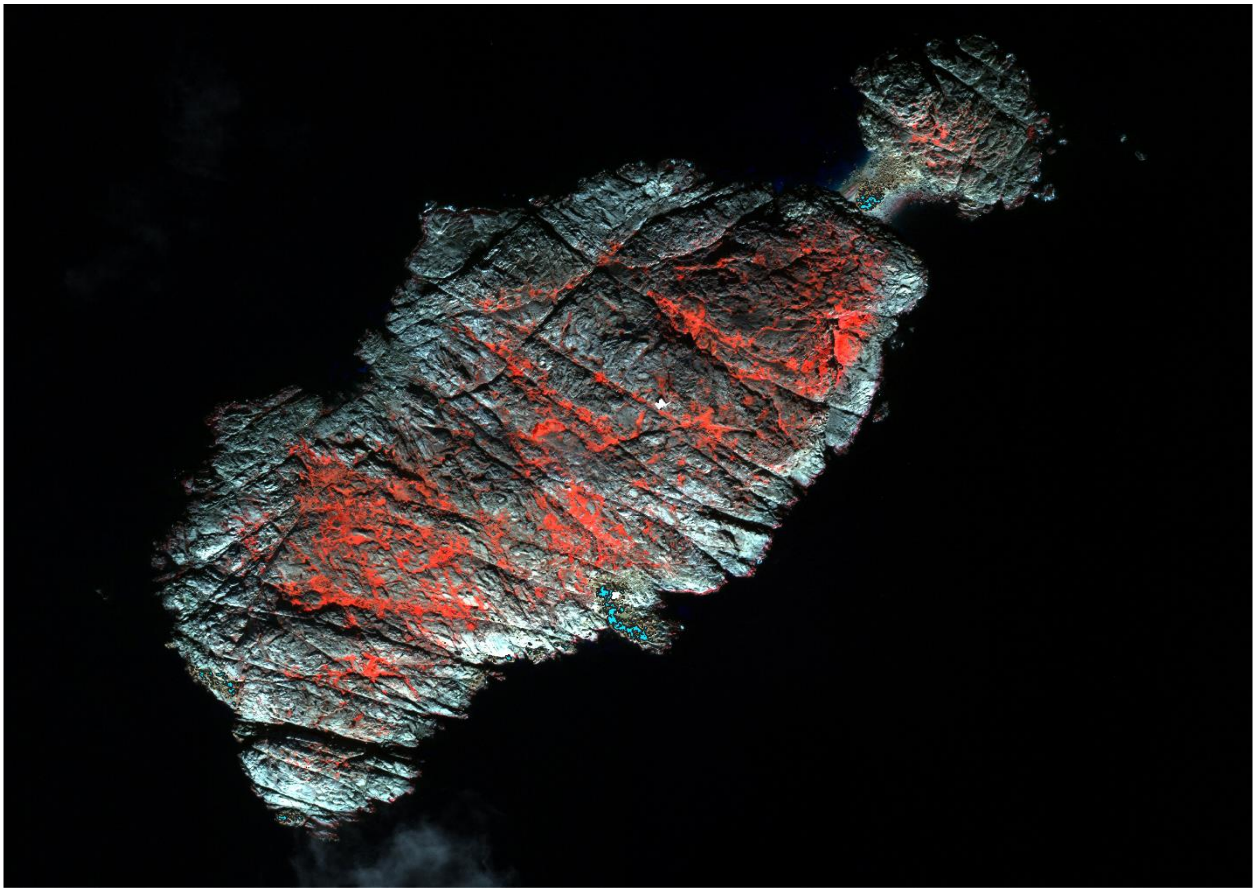

Figure 9: The second classification settings (classification set 2) applied to the pansharpened image underestimated the area covered by walrus (turquoise) compared with visual assessment (which clearly shows relatively large areas of walrus excluded by the turquoise polygons).

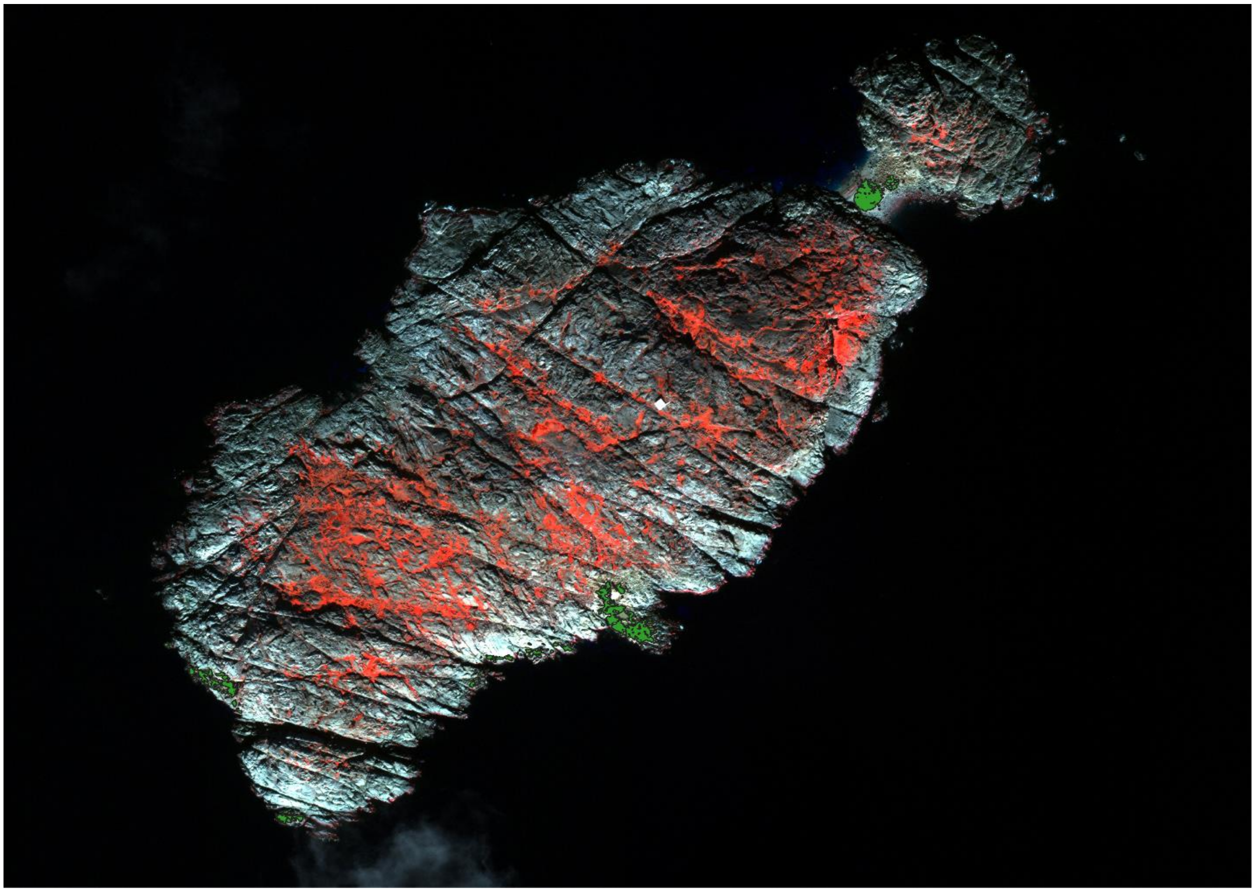

Figure 10: Manual editing of classification set 1 to remove misidentified areas from Zone 3 and include missed walrus from Zones 1, 2, and 4 (see Figure 11) resulted in an estimated area covered by walrus (green) that corresponded well with visual assessment of walrus coverage.

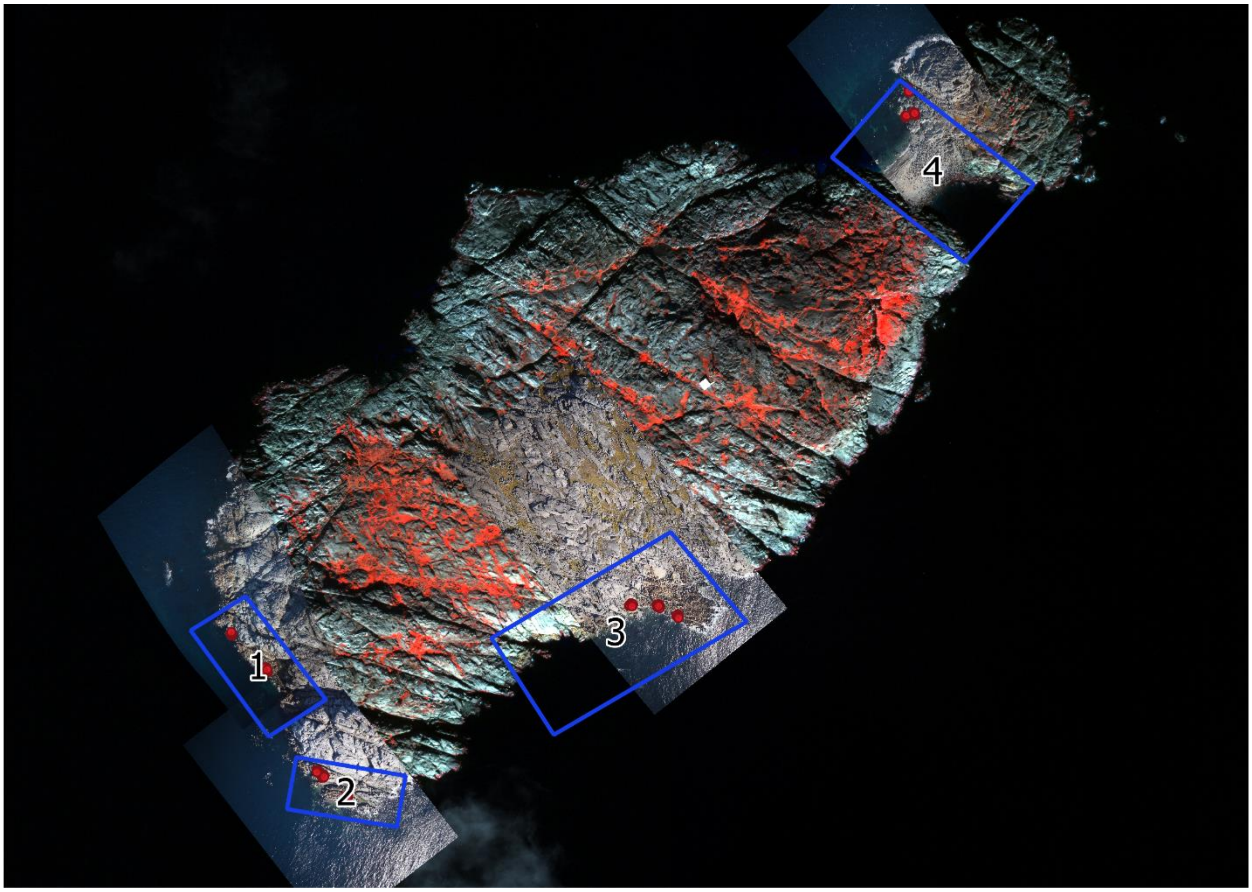

Figure 11: Walrus were located in Zones 1-4 in both the 2020 satellite images and 2017 aerial photographs (georeferenced aerial photographs overlaid on satellite image). Polygon locations in which walrus were counted to provide three density estimates per zone are shown as red circles.

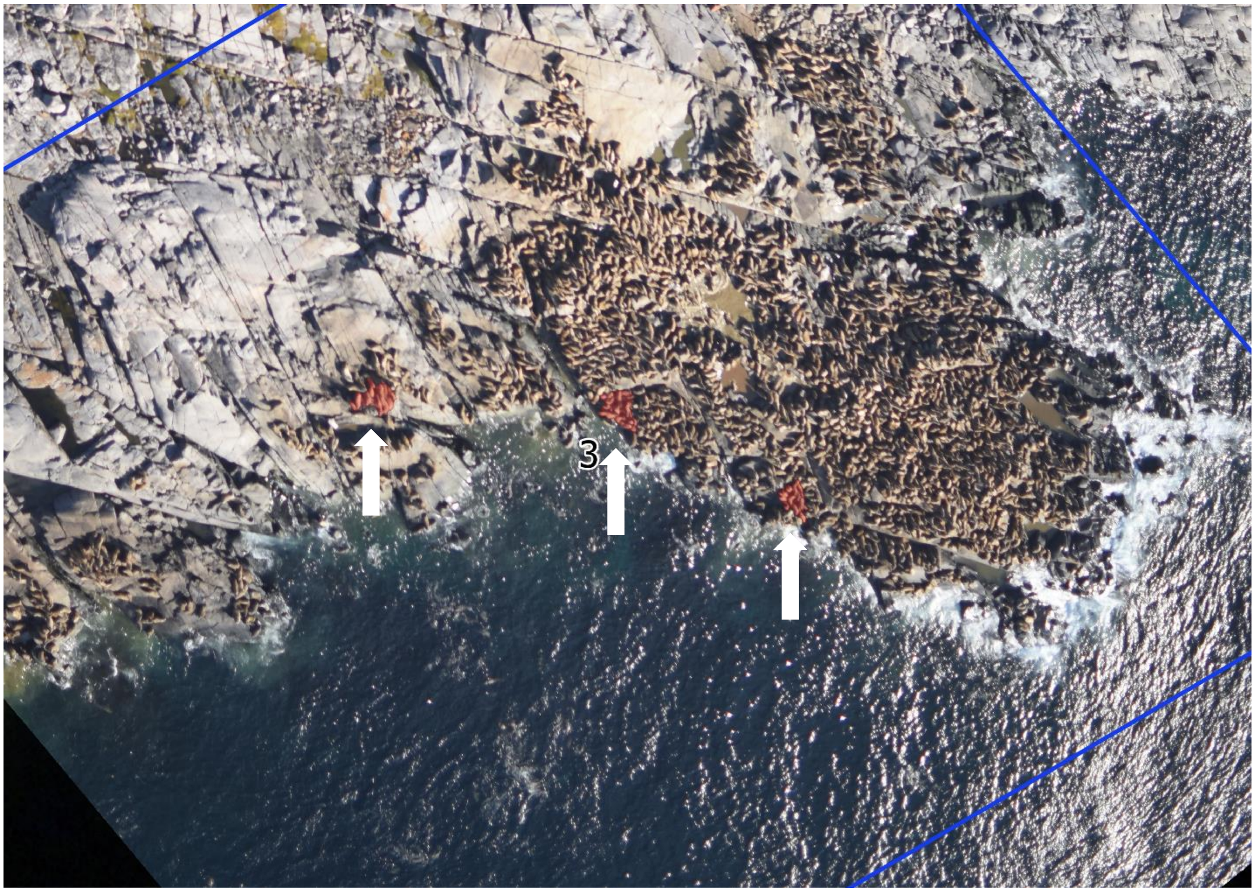

Figure 12: Close up of three polygons (transparent red; indicated by white arrows) encompassing different densities of walrus used to estimate average walrus densities in occupied areas of Zone 3.

8. TABLES

Table 1: Numbers of pixels used to define each area of interest (AOI) for two different classification sets (1 and 2) used to train a semi-automated (supervised) classification algorithm available in QGIS software. One area representative of each AOI was manually selected, with the exception of rock, which comprised seven separate areas (see also Figures 6 and 7).

Area of Interest (AOI)	Classification set 1	Classification set 2
walrus	6,043	364
rock	2,565	2,565
terrestrial vegetation	96	96
sea water	754,100	149,457
pooled surface water	259	106

Table 2: Area (A; m^2) of zones used by walrus identified by a semi-automated (supervised) classification algorithm available in QGIS software using two different sets of Areas of Interest (AOI; see Materials and Methods), plus a third approach in which areas identified by classification set 1 were manually adjusted to include/exclude walrus according to visual assessment. Numbers (N) and variance (Var N) of walrus were estimated by multiplying areas estimated by the classification algorithm by mean walrus densities (and associated variance) in aerial photographs of the same sites taken during a fixed-wing aircraft survey in 2017.

	AOI Classification set 1			**AOI Classification set 2**			**Manual Classification**		
	A (m^2)	**N**	**Var N**	**A (m^2)**	**N**	**Var N**	**A (m^2)**	**N**	**Var N**
Zone 1	641.30	707.25	2.74	299.45	330.24	1.28	782.75	863.26	3.35
Zone 2	217.70	166.74	14.38	118.93	91.09	7.86	286.53	219.46	18.93
Zone 3	2516.21	2369.29	234.61	1391.53	1310.28	129.75	2441.93	2299.34	227.69
Zone 4	1166.19	1128.96	53.37	481.67	466.30	22.04	1347.01	1304.01	61.65
Total (zones)	***4541.39***	***4289.87***	*230.59*	***2291.58***	***2164.67***	*116.35*	***4858.23***	***4589.16***	*246.67*
Total (island)	***9161.74***	***8654.33***	*465.18*	***2311.39***	***2183.38***	*117.36*	***4865.45***	***4595.98***	*247.04*

Table 3: Estimated walrus mean density per zone in archived georeferenced images from the 2017 aerial survey used to estimate walrus abundance from areas occupied by walrus (see Table 2). Numbers of walrus (N) in each of three smaller areas from each of four zones produced density estimates that did not differ among zones, and were therefore averaged to obtain an overall mean representative of all areas occupied by walrus.

Zone	**N**	**Area (m^2)**	**Density ($N\ m^{-2}$)**
1	10.00	9.24	1.08
1	12.00	10.20	1.18
1	10.00	9.52	1.05
		mean ± SD	**1.10 ± 0.07**
2	12.00	17.18	0.70
2	9.00	16.39	0.55
2	8.00	7.62	1.05
		mean ± SD	**0.77 ± 0.26**
3	19.00	21.57	0.88
3	13.00	19.37	0.67
3	17.00	13.36	1.27
		mean ± SD	**0.94 ± 0.31**
4	8.00	10.98	0.73
4	12.00	10.52	1.14
4	8.00	7.73	1.03
		mean ± SD	**0.97 ± 0.21**
Overall mean ± SD			**0.94 ± 0.23**