Remote Sensing in Ecology and Conservation
Open Access
ZSL LET'S WORK FOR WILDLIFE

ORIGINAL RESEARCH

Engaging 'the crowd' in remote sensing to learn about habitat affinity of the Weddell seal in Antarctica

Michelle A. LaRue[1,2], David G. Ainley[3], Jean Pennycook[3], Kostas Stamatiou[4], Leo Salas[5], Nadav Nur[5], Sharon Stammerjohn[6] & Luke Barrington[7]

[1]Department of Earth Sciences, University of Minnesota, 116 Church St SE, Minneapolis Minnesota, 55455
[2]Department of Geography, University of Canterbury, Private Bag, Christchurch New Zealand, 4800
[3]H. T. Harvey and Associates Ecological Consultants, 983 University Avenue, Building D, Los Gatos California, 95032
[4]Melissa Dozier and Jon Saints,DigitalGlobe, Inc., 1300 W 120th Avenue, Westminster Colorado, 80234
[5]Point Blue Conservation Sciences, 3820 Cypress Drive #11, Petaluma California, 94954
[6]Institute of Arctic and Alpine Research, 4001 Discovery Drive, University of Colorado-Boulder, Boulder, Colorado, 80303
[7]Google, 1600 Amphitheatre Parkway, Mountain View California, 94043

Keywords
Antarctica, citizen science, Southern Ocean, very high-resolution satellite imagery, VHR, Weddell seal

Correspondence
Michelle A. LaRue, Department of Earth Sciences, University of Minnesota, 116 Church St SE, Minneapolis, MN 55455.
Tel: +64 3 369 5953; Fax: +64 3 364 2197;
E-mail: larue010@umn.edu

Editor: Ned Horning
Associate Editor: Kylie Scales

Received: 9 May 2019; Revised: 2 July 2019;
Accepted: 12 July 2019

doi: 10.1002/rse2.124

Remote Sensing in Ecology and Conservation 2020;**6** (1):70–78

Abstract

Satellites Over Seals (SOS), a project initiated in late 2016, is a crowdsourced method to determine factors behind the presence/absence patterns and to ultimately determine the global population of the Weddell seal (*Leptonychotes weddellii*). An iconic species, the Weddell seal is proposed to be part of the Antarctic Research and Monitoring Program required in the newly designated Ross Sea Region Marine Protected Area. This species is easy to detect via satellite imagery, due to its large size (3–4 m long, 1 m wide) and its dark color contrasting with the Antarctic coastal fast ice, where it aggregates on during breeding season. Using very high-resolution satellite imagery (VHR; 0.31–0.60 m resolution) and the online platform Tomnod, we used VHR images from November 2010 and 2011 to cover the entirety of available fast ice around Antarctica. Before correcting for time of day or date, we searched for the presence/absence to identify a subset of where abundance estimates should be concentrated. More than 325 000 citizen scientists searched 790 VHR images, covering 268 611 km^2 of fast ice, to determine the locations of seals. Algorithms ranked searchers to the degree their votes corresponded with others, a measure of searcher relative quality that we used to filter out unreliable searchers. Seal presence was detected on only 0.55% of available maps (total n = 1 116 058) within fast ice, revealing a sparse, irregular distribution. The rate of false-negative detections was 1.7%, though false positives were high (67%), highlighting the importance of training for image interpretation to ensure differentiation between seals and landscape features (such as large rocks, ice chunks or depressions/holes in the ice). This approach not only allowed us to assess image resolution and quality, but also training, outreach and the effectiveness of this platform for introducing citizen scientists to the ecology of the Southern Ocean.

Introduction

The southernmost breeding population of mammals in the world is the Weddell seal (*Leptonychotes weddellii*) in McMurdo Sound, Ross Sea, a population involved in continuous mark-resight studies since the late 1960s (Stirling 1969; Siniff et al. 1977; Testa and Siniff 1987; Cameron and Siniff 2004; Garrott et al. 2012; Rotella et al. 2016). Weddell seals are probably the best studied of all pinnipeds, at least regarding its natural history and demography. Females haul out every austral spring to give birth and raise young (Stirling 1969; Siniff et al. 1971) and life history traits of Weddell seals are buffered against environmental extremes (Chambert et al. 2012; Rotella et al. 2012), and despite a high degree of philopatry (or, returning to the same locations to raise their pups every year; Cameron et al. 2007), these seals do emigrate, most often temporarily, and forego breeding in years of unsuitable fast ice (i.e. sea ice that is ‘fastened’ to the continent; Chambert et al. 2012, Rotella et al. 2012, Garrott et al. 2012).

Despite all that is known about Weddell seals, in McMurdo Sound and elsewhere, data on regional or continent-wide distributions and population variability have not existed to date. Antarctic research is largely conducted near national research stations or from ships, which generally avoid fast ice, precluding access other than from aircraft. Traditional methods for assessing populations of Weddell seals have included aerial surveys (Bester et al. 2002; Bengtson et al. 2011); ship-board surveys employing distance sampling (i.e. the Antarctic Pack-ice Seals [APIS] surveys as in Bengtson et al. 2011), other ship-board surveys (Ackley et al. 2003; Flores et al. 2008; Southwell et al. 2004) and ground- or ice-based surveys during the austral spring (Stirling 1969; Siniff et al. 1977; Testa and Siniff 1987; Cameron and Siniff 2004; Garrott et al. 2012; Rotella et al. 2016). Erickson et al. (1971), Seal et al. (1971) and then Erickson and Hanson (1990), provided a review of Antarctic seals, revealing that ~6100 km^2 of sea ice had been searched across six studies during 1958–1983; subsequent studies were added in 1996–2000 (Southwell et al. 2012). Certainly ships and aircraft allow for a large area to be searched, but notably the aforementioned surveys were mostly conducted within the dynamic pack ice (i.e. sea ice in the open ocean, in contrast to fast ice locations, mentioned above) during summer (see also Bester et al. 2002), where and when Weddell seal abundance is notoriously low (Smith 1965, Lugg 1966; Stirling 1969; Green et al. 1995 and references above), given Weddell seals are fast-ice seals.

In their review of seal surveys, Erickson and Hanson (1990) commented, ‘the striking difference in the density abundances of crabeater seals (*Lobodon carcinophaga*) for these two (aerial and ship-based) surveys would appear attributable to differences between the two types of census... As regards population trends for the remaining species of Antarctic pack-ice seals, the numbers of seals counted in the comparative surveys are too few and irregular to permit meaningful comparisons’. Siniff and Ainley (2008) recommended aerial surveys of Weddell seals on coastal fast ice during November as a mode of long-term monitoring in the Ross Sea region. However, due to their dark coloration, large size and predictable location on the fast ice, remote sensing has more recently provided a much-needed method for setting a baseline and for ultimately determining population trends (e.g. LaRue et al. 2011, 2019; Ainley et al. 2015).

Use of VHR (satellite imagery with 0.31–0.60 m spatial resolution) for detecting and enumerating colonial species, like Weddell seals, would allow for synoptic regional- to continental-scale assessments, posing a potential solution to the problem of consistent, spatial and temporal coverage (Devictor et al. 2010; Dickinson et al. 2010). Indeed, LaRue et al. (2016) reviewed the feasibility of VHR for wildlife research, suggesting that the landscape, size of the animal and image resolution will constrain the questions that can be addressed. Weddell seals are ideal for direct VHR investigation of their distribution and numbers, due to (1) their confinement to coastal fast ice during pupping, (2) large size (3–4 m long, 1 m wide), (3) dark color contrasting against the ice white background, (4) dispersed nature within haulouts (only loosely aggregated, maintaining ~1 m personal space; Stirling 1977) and 5) well-known seasonal and daily haulout patterns (Siniff et al. 1971; Thomas and DeMaster 1983). Their presence on fast ice is the key factor that allows researchers to quantify their population biology (Stirling 1969; Siniff et al. 1977; Testa and Siniff 1987; Garrott et al. 2012) and accurately detect the species on imagery (LaRue et al. 2011). Ainley et al. (2015) successfully combined historic Weddell seal counts with those using recent VHR images to assess regional trends of areas that historically had been frequented by seal researchers, but were then discontinued; thus, the recent VHR imagery allowed extension of the historical time series.

Though VHR is an effective way to assess remote populations, image cost and time intensity of conducting the searches in many cases preclude its use. For example, Stapleton et al. (2014) found that VHR counts of polar bears (*Ursus maritimus*) were more precise than counts from mark–recapture distance sampling (MRDS), but it took two observers >100 hrs to search 1100 km^2 of Rowley Island in Canada. So, while there is great potential in gaining access to inaccessible areas via VHR, the time it takes to not only manually search for individual animals, but also to train observers in this new method was a bottleneck for expanding the use of VHR imagery in wildlife ecology.

In an effort to address the issues of remote access and efficiency in assessing populations of remote wildlife, we describe a methodological innovation that combines VHR imagery, the power of citizen science (i.e. crowdsourcing) and wildlife ecology, to determine potential presence and true absence of the iconic Weddell seal across the entirety of fast ice around Antarctica. Named, “Satellites Over Seals” (SOS), our objectives were: 1) conduct a ‘search area reduction’ which makes the effort of enumerating seals even more efficient; 2) develop a novel citizen science method for efficient review of large swaths of Antarctic fast ice; 3) determine the accuracy of ‘the crowd to detect seal presence and absence; and) provide recommendations for adapting our method to other remote systems and wildlife populations.

Materials and Methods

Study area

Given Weddell seals have a circum-Antarctic distribution (Laws 1984), we focused our study area on the entirety of coastal Antarctica, including near-coast islands. To accomplish a full review of coastal fast ice, we conducted searches within several regions of interest: (1) Ross Sea (170E–150 W), (2) Amundsen and Bellingshausen seas (150–70 W), (3) Weddell Sea (60–20 W) and (4) East Antarctica divided into two parts (20 W–60 E and 60–160 (E). Partitioning our search campaigns into several sections was done to ensure that manageable chunks of coastline were being searched by the crowd. Though we acknowledge the presence of Weddell seals along the west coast of the Antarctic Peninsula, we excluded that area from our search, due to the low prevalence of fast ice and the difficulties in differentiating between other species (e.g. elephant seals *Mirounga leonina*). Over the last many decades, Weddell seals have dramatically decreased along the west coast of the Antarctic Peninsula as fast ice has nearly disappeared (Siniff et al. 2008). Interestingly, because of this change, seals are now occupying some land areas (Siniff et al. 2008), but because of the lack of contrast between seals and these dark snow-free areas they occupy, detection by satellite is no longer possible.

Citizen science and Tomnod

Citizen science and crowdsourcing have provided the opportunity to conduct research at temporal and spatial scales previously not possible. For example, eMammal engages citizen scientists across the world with the science behind camera trapping (McShea et al. 2016; Steenweg et al. 2017), and the Zooniverse platform has given rise to online, animal-searching and identifying projects such as Snapshot Serengeti (Swanson et al. 2015), Snapshot Wisconsin and Penguin Watch (Jones et al. 2018). With the advent of VHR, combining citizen science and remote sensing has blossomed as a possible solution to the problem of rapid and effective search over large swaths of Earth's surface (Barrington et al. 2011).

Tomnod is a web application that provides geospatial content for crowdsourcing and labeling, using DigitalGlobe's VHR (0.31 cm–0.6 m resolution). To effectively search the fast ice for seals, we had to complete three components: (1) identify suitable imagery and areas of interest (AOI); (2) recruit volunteers (i.e. 'the crowd') for image searching; and (3) develop tutorials to train volunteers in how to search and detect Weddell seals.

Identifying suitable imagery and GIS preparation

We first obtained the VHR 'footprint', which is a GIS shapefile containing the outlines of each image that intersected the Antarctic coastline. We extracted shapefiles that represented images with <20% cloud cover acquired during the pupping haulout periods of November 2010 and 2011, which were years of high image availability. Using the program QGIS, we sorted through all available images, removing those of poor quality (i.e. overexposed, striped, or difficult to interpret; as mentioned in LaRue et al. 2011, 2016) and manually delineated areas of fast ice only (i.e. no pack ice). This process, though onerous, allowed us to effectively 'clip' the area to be searched (i.e. we excluded land, glaciers and open water from our AOIs). Accomplishing this helped to forgo searcher fatigue from dealing with major sections of the coast where there was no chance of detecting any seals. Via Tomnod, we then requested the subset of useable images from DigitalGlobe and processed them using a digital elevation model (DEM) for viewing on the web platform.

Engaging 'the crowd' of citizen scientists

Using Tomnod's existing infrastructure (www.tomnod.com), we recruited volunteers via email, members of nonprofit conservation organizations (e.g. Sierra Club, World Wildlife Fund) and school groups contacted through various websites (e.g. SciStarter, Penguinscience). A crucial step in obtaining high-quality results was to provide: (1) high-resolution imagery that makes it easy and fun to feel like a true explorer venturing to remote areas; (2) accurate instructions (with example images) to help train 'the crowd' in accurate searches (especially to avoid false positives); (3) a game-like environment where users are informed in real time of the number of features they found, the number of images they have inspected, and how they are performing compared to other users; and (4) only those images that contained fast ice to prevent searcher fatigue (as noted above).

Providing tutorials

We created a detailed set of instructions, including multiple examples of 'maps' (i.e. ~500 m × 500 m tiles rendered from the AOI image) with seals and without seals (Fig. 1). We took care to label items on the landscape that might be of interest to volunteers, and to explain areas where there may be confusion (i.e. rocks, melt water pools, etc.). Then for each region we launched a search campaign, asking volunteers simply to vote 'seals' if they believed they saw seals on the image and 'no seals' if they

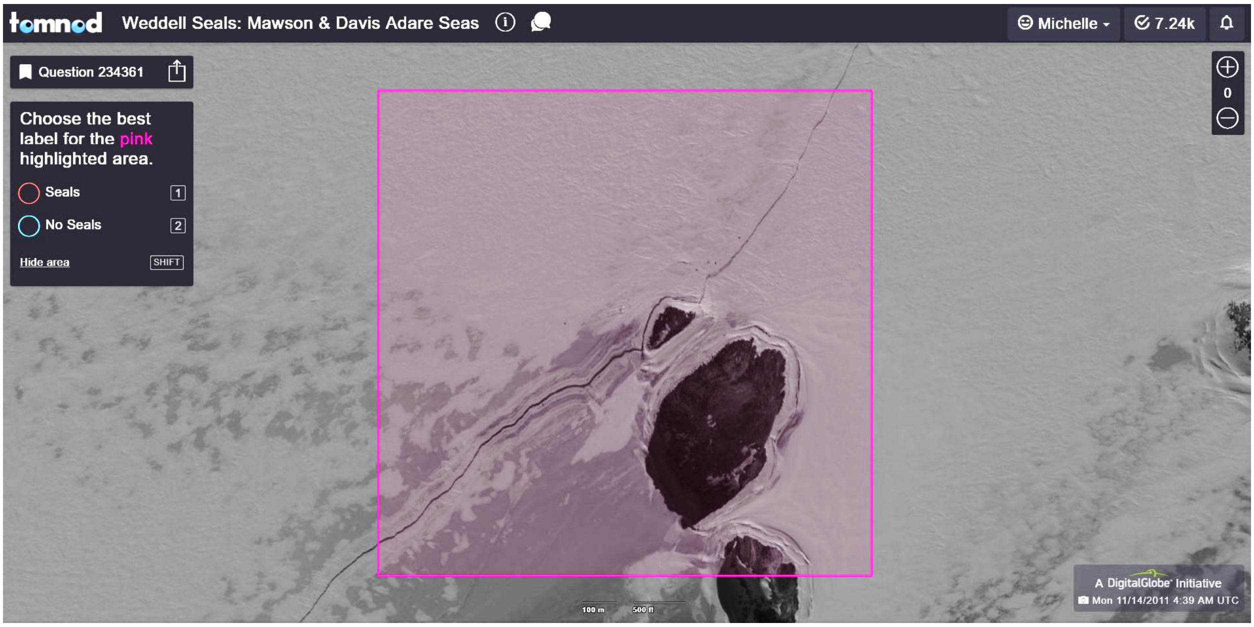

Figure 1. Example of a Tomnod search campaign of the Antarctic fast ice, asking citizen scientists to vote on whether or not they see seals within the pink box (which we call a 'map'). Image acquired on 14 November 2011, courtesy DigitalGlobe, Inc.

did not, the result being a record of seal presence/absence for each section of coast.

CrowdRank algorithm and validation

An important step in obtaining high-quality results was filtering the 'raw' crowd input. We assumed that 'the crowd' would consist of users having different levels of ability, perception, science literacy and knowledge. Tomnod employs a consensus-based algorithm, called 'CrowdRank', to compute a score for each user that reflects each person's ability and weighs its contribution in the dataset (hereafter 'the score'). In order to boost the accuracy of the scores computed via consensus, the score is computed based on: (1) the extent to which the user's input agrees with the independent input of other users on the same map; and (2) the injection of ground truth in the dataset, via validation of a small percentage of the user input (e.g. 5–10% of the raw data) by experts (Barrington et al. 2011). The result of the computed CrowdRank of all searchers of a map is a probability of seal presence in that map. Through validation with expert reviews of a subset of maps, we were able to set a threshold for the CrowdRank score to classify the maps into those with and without seal presence. We further conducted post-hoc validation of these 'seal' and 'no seal' maps to determine accuracy of 'the crowd' by visually inspecting a subset of these maps and determined a confusion matrix for seal presence. Finally, we calculated the total area searched, detection rates and time spent searching VHR.

Results

Over the course of several campaigns spanning six months in total, we enlisted >325 000 volunteers to conduct searches, viewing 1 116 058 unique maps that covered 268 611 km^2 of fast ice that were acquired during

Table 1. Confusion matrix for expert review of resulting map votes by 'the crowd' of Tomnod citizen scientists.

	No Seals – MAL	Seals - MAL	Total
No Seals – CS	21 082 (TN)	3 (FN)	21 085
Seals – CS	374 (FP)	183 (TP)	557
Total	21 456	186	21 642

'MAL' indicates lead author review of resulting maps to determine vote accuracy. 'CS' indicates votes from crowdsourcing; TN = true negative (i.e. 'the crowd' voted that seals were not present when seals were not present for detection); FN = false negative ('the crowd' voted that there were no seals present when there were seals present for detection); FP = false positive ('the crowd' voted that seals were present when no seals were present for detection); TP = true positive ('the crowd' voted that seals were present when there were seals present for detection). The confusion matrix excluded input from the Ross Sea, as seal presence there was informed by LaRue et al. (2019) and manual inspection by authors given our experience in the region (i.e. we knew where to expect seal presence/absence, which is in contrast to the rest of the continent).

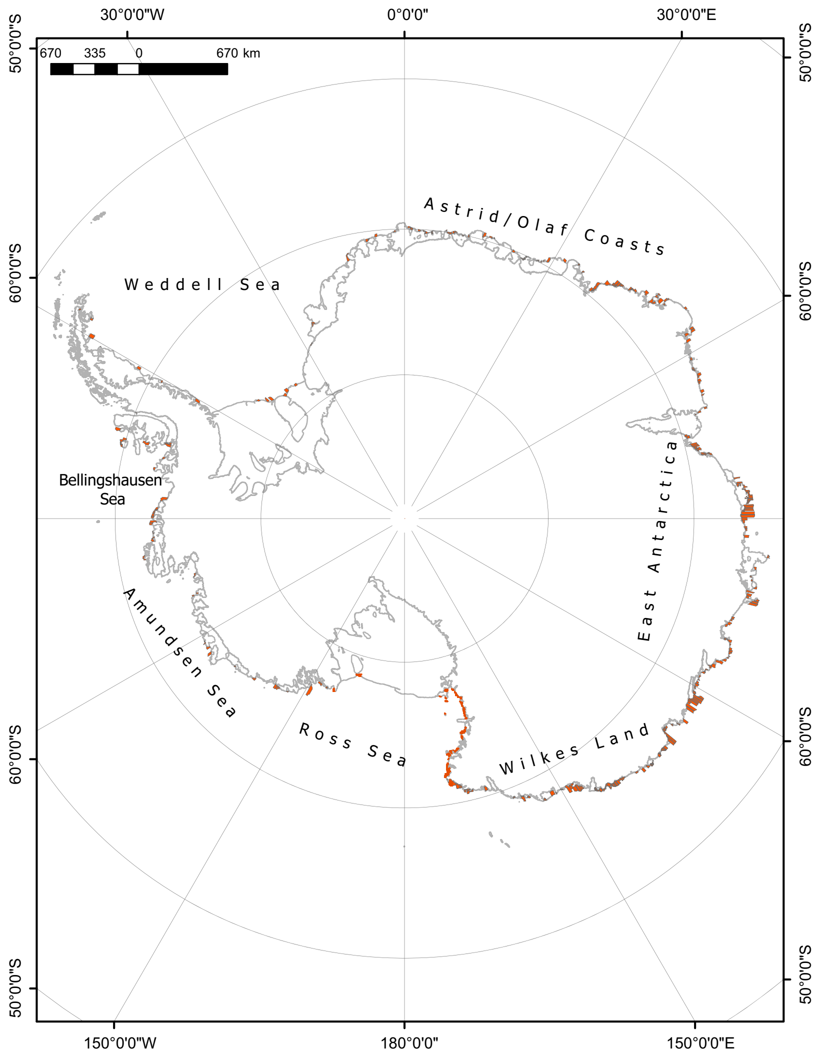

Figure 2. Distribution of Weddell seal search across seven campaigns along the fast ice around Antarctica during November 2010 and 2011. Orange areas indicate search effort on images of fast ice.

November 2010 and 2011. Each map was voted on at least once and some maps were voted on by >50 participants. We found <500 km of coastline that may have had suitable fast ice for searching but image searching was precluded by no images available, poor imagery (i.e. overexposed or striped) or clouds. For perspective, Antarctica has 17 968 km of coast (US CIA, 2011). Volunteers searched maps at a rate of 1493 km^2 per day. We found the overall accuracy of 'the crowd' in categorizing maps between 'seals' and 'no seals' was 98% (Table 1). False-positive rates were high (67%) but false-negative rates were low (1.7%). Thus we have high confidence in the determination of the absence of seals.

We found that seals were present on just ~0.55% or less of the total fast ice available for searching (in itself an unexpected finding) with the proportion of maps potentially containing seals varying by region (Table 2). East Antarctica had the most available fast ice (101 950 km^2) for searching, and the Ross Sea region had the highest proportion of maps where seal presence was identified (4.2% of maps).

Discussion

The first step in our SOS project describes an integrative method for efficiently ascertaining potential presence and almost certain absence of Weddell seals occupying fast ice areas around the entire coast of Antarctica, toward an ultimate goal of a first estimate of the global population of Weddell seals in Antarctica, while also providing a means (i.e. a baseline) for monitoring regional temporal trends. To our knowledge, our study is the first to

Table 2. Antarctic regions searched for seal presence on fast ice using the Tomnod crowdsourcing platform (see Fig. 2 for definitions of region locations), number of 500 m × 500 m maps searched, number of maps containing seals according to 'the crowd' of volunteers, and percentage of maps containing seals. Note that given authors' vast experience with the Ross Sea, seal presence on maps there was derived from LaRue et al. (2019), which meant that virtually the whole region was inspected by the lead author. Therefore, the percentage of maps containing seals in the Ross Sea is a more accurate reflection of reality given authors' knowledge of the region and verification of results. The remaining regions reported here still reflect a high proportion of false positives.

Antarctic region	Number of maps searched	Number of maps = seal	Percentage of maps = seal
Ross Sea	33 279	1393	4.19
Weddell Sea	36 767	603	1.64
Astrid/Olaf Coasts	107 203	1755	1.64
East Antarctica	407 801	1513	0.37
Bellingshausen Sea	165 491	439	0.27
Wilkes Land	97 939	209	0.21
Amundsen Sea	267 578	196	0.07
Total	1 116 058	6108	0.55

combine remote sensing, VHR and citizen science, to do ecological research on any vertebrate species. Above all else, we established an efficient and replicable method for understanding the potential presence and absence of Weddell seals in Antarctica. Further, we also provide lessons learned and recommendations for using this method on other large vertebrates in other remote areas.

Perhaps the most exciting result of our work here is the efficiency by which we obtained a presence/absence map of Weddell seals around the coast of Antarctica – within just six months we completely searched all available fast ice areas around the Antarctic continent: > 260 000 km^2 of fast ice. The only other program by which we can make such a comparison in spatial coverage is the Antarctic Pack Ice Seal (APIS) program, which was a coordinated, multinational effort to survey all four seal species around Antarctica (Southwell et al. 2012). APIS was conducted over the course of several years (mid-1990s into the early 2000s) and employed ship-board and aerial surveys, using distance sampling techniques (Buckland et al. 2004). These efforts resulted in several regional density estimates of seals found in pack-ice habitats, mostly crabeater seals (*Lobodon carcinophagus*). For example, as part of the United States' contribution, Bengtson et al. (2011) report on transects totaling 53 217 km^2 of searches (linear distance by transect width) conducted by ship and aerial surveys in the eastern Ross and western Amundsen seas during 3 months in the summer of 1999–2000, a rate of approximately 591 km^2 searched per day. Gurarie et al. (2016) reported results from surveys conducted in the Weddell Sea, a joint effort among German, Norwegian and South African researchers, an effort that resulted in 16 691 km^2 flown by aircraft during five austral summers. Comparatively, citizen scientists in our study searched >3 times this rate at nearly 1500 km^2 per day (and at a fraction of the cost, approximately $98 000 USD for all campaigns), with searches conducted exclusively and thus efficiently in only fast ice areas where Weddell seals are found. We are also convinced that our results are contaminant-free of other seal species, owing to the fact that Weddell seals are the only seal occupants of fast ice areas during November (Stirling 1969; Siniff et al. 2008). Providing that VHR resolution, acquisition rates and costs remain relatively constant or reduced over time, our work can be revisited to ascertain potential changes in seal presence.

Our study engaged thousands of volunteers in the scientific method and exposed people to Southern Ocean ecology and Weddell seal biology. Through Tomnod's proven online platform and web forum, we were able to communicate with thousands of volunteers, referred to as 'taggers' and to boost morale by offering incentives (such as postcards from the authors, at least during one of the campaigns) to help increase participation. This final point of engagement with volunteers is important to note, due to the fact that many people may be physically unable to conduct ecological field research, making our method more inclusive than field-based alternatives. Not only were we encouraged by the amount of participation, but we found our volunteers to be remarkably accurate in categorizing our maps (98% accurate). This is particularly notable given the novelty of our method and the fact that very few, if any, of our volunteers had ever seen a Weddell seal including on satellite images. The high overall accuracy is due to the fact that most maps had no seals in them and 'the crowd's' rate of false negatives is quite low (1.7%). Accounting for the few maps with potential seals due to a high rate of false positives (67%) only reduces the overall accuracy of our results by a small fraction.

Image- or remote camera-based efforts such as Snapshot Serengeti (Swanson et al. 2015) and Penguin Watch (Jones et al. 2018), among many others, point to the necessity of having solid training mechanisms so that people develop accurate search images of the features in question. Thus, we relied heavily on sets of instructions detailing the biology of Weddell seals, their habitat and examples of images with and without seals. The overall accuracy of our results is comparable to Swanson et al. (2015), who found citizen scientists' ability to accurately identify species within images was nearly indistinguishable from experts (~98%). However, our Boolean choice of maps, either having seals present or not, may have led to the high false-positive rate (67%), stemming from a combination of volunteers eager to see seals on images as well as ensuring that no seals were missed. In fact, of the images we reviewed as experts in this study (n = 21 374), we found only three maps categorized by the CrowdRank algorithm as having no seals when in fact seals were present. We are thus confident that our resulting distribution of potential seal presence at a continental scale is useful for honing the areas for further tagging to estimate population size. However, we note that estimates of seal presence as reported here will certainly decrease as we account for overidentification by citizen scientists.

We found that seals inhabit <1% of the fast ice available to them, at least during November 2010 and 2011. This was a surprise, especially given the fact that we also report that citizen scientists overidentify seal presence substantially but do not miss seals (Table 1), which means there is even less ice inhabited by seals than we report. The effort we describe here, where we asked volunteers to categorize maps for us, is considered a 'search area reduction' campaign and is a critical step in working with citizen scientists on VHR for a few reasons. Reaching our ultimate goal of determining the global population of Weddell seals will require volunteers via Tomnod to 'tag' seals on images by placing markers on each seal detected. However, in a place like Antarctica where the fast ice is vast (>260 000 km^2), it is critical to confine efforts of volunteers to only the areas where seals are present, rather than asking them to tag seals on every bit of fast ice they encounter. The criticality of reducing the search area is apparent in our results here – we found a 67% false-positive rate, indicating that if we had instructed volunteers to tag seals rather than categorize maps, we would have obtained a very large dataset full of 'seal features' that were not actually seals. Secondly, because breeding Weddell seals are known to be relatively philopatric (Cameron et al. 2007), we can now return to the locations where volunteers identified seals as being present – detected by volunteers' eager identification – substantially reducing the effort needed for the individual seal tagging campaign. In other words, by conducting this search area reduction first, we have eliminated 99.6% of the fast ice around Antarctica for a tagging campaign. This elimination will increase efficiency and accuracy for the next step that will yield actual counts.

Beyond uncovering a new method for determining the distribution of an important Southern Ocean upper trophic level predator, our work transcends both remote sensing and wildlife ecology, with lessons to be learned if applied to other systems or questions. We adhered to recommendations within LaRue et al. (2016), who for VHR image searches addressed suitable imagery, time of year and species considerations. To that end, we further recommend that applications of our method to other systems (e.g. Arctic, open plains, agriculture, open ocean) pay particularly close attention to the quality of images presented to citizen scientists. We found that slight overexposure of the sensor, striping and even minimal cloud cover led to confusion resulting in questions and comments on the Tomnod forum – thankfully we were able to be nimble in our responses and applied what we learned immediately to ensure that the best images were being searched and that our citizen scientist 'crowd' was as accurately prepared as possible. We also recommend adequate preparation time in providing solid instructions for what potential volunteers might expect. In our case, not only did we show to 'the crowd' examples of what seals looked like in a satellite image, but we also pointed out other features on the landscape (e.g. cracks in the ice) that might help to direct search efforts. Indeed, highlighting features on the fast ice allowed us to engage in the science communication and outreach that is a critical component of citizen science campaigns.

Our final recommendation is to promote research on social media or at least have access to organizations and groups who may be willing to co-promote research (Shiffman 2018). We noticed a substantial uptick in engagement when the lead author tweeted about the research, linked to the campaign and communicated about Weddell seal biology on social media. People who follow scientists on social media tend to be engaged and interested in the scientific method and are more likely to assist with a Tomnod-type citizen science campaign (Thaler et al. 2012), mostly because they have access to information about it.

Large-bodied animals are often convenient indicator species for the ecosystems which they inhabit (Odum 1971; Ward 1978; Landres et al. 1988; Siddig et al. 2015), thus understanding their distributions, habitats and factors that influence presence and absence are critical for gaining a full comprehension of ecosystem function. As VHR becomes more heavily used in ecology, we anticipate use in similar projects to assess in open habitat the distribution and status of large, endangered species, such as the African savannah (elephants *Elephantidae*, rhinos *Rhinocerotidae*), North American plains (bison *Bovinae*), open ocean (right whales *Eubalaena*) and the Arctic (polar bears *Ursus*, musk ox *Obvibos*). Given that climate is changing more rapidly in some regions of the world than others, we find it critical to expeditiously gain such an understanding so that effective monitoring and management plans can be implemented quickly in places like the Southern Ocean.

Acknowledgments

We are indebted to the thousands of volunteers who enthusiastically helped us search for seals on VHR images using Tomnod – we appreciate their indispensable labor. We received funding for this project from the National Science Foundation (collaborative proposals #1543311, #1543230, #1542791), Potterhead Running Club, the Antarctic and Southern Ocean Coalition; and the University of Minnesota, DigitalGlobe Foundation and SciStarter, further supported and promoted our work. Three anonymous reviewers provided helpful review to previous versions of this paper.

Funding Information

We received funding for this project from the National Science Foundation (collaborative proposals #1543311, #1543230, #1542791), Potterhead Running Club, via the Antarctic and Southern Ocean Coalition; and the University of Minnesota, DigitalGlobe Foundation and SciStarter, further supported and promoted our work.

Conflict of Interest

Authors have no conflict of interest to declare.

References

Ackley, S. F., J. L. Bengtson, P. Boveng, M. Castellini, K. L. Daly, S. Jacobs, et al. 2003. A top-down, multisdisciplinary study of the structure and function of the pack-ice ecosystem in the eastern Ross Sea, Antarctica. *Polar Rec.* **39**, 219–230.

Ainley, D. G., M. A. LaRue, I. Stirling, S. S. Stammerjohn, and D. B. Siniff. 2015. An apparent population decrease, or change in distribution, of Weddell seals along the Victoria Land coast. *Mar. Mamm. Sci.* **31**, 1338–1361.

Barrington, L., S. Ghosh, M. Greene, S. Har-Noy, J. Berger, S. Gill, et al. 2011. Crowdsourcing earthquake damage assessment using remote sensing imagery. *Ann. Geophys.* **6**, 68–687. https://doi.org/10.4401/ag-5324.

Bengtson, J. L., J. L. Laake, P. L. Boveng, M. F. Cameron, M. B. Hanson, and B. S. Stewart. 2011. Distribution, density, and abundance of pack-ice seals in the Amundsen and Ross Seas, Antarctica. *Deep Sea Res. Part II. Topical Stud. Oceanog.* **58**, 1261–1276. https://doi.org/10.1016/j.dsr2.2010.10.037.

Bester, M. N., J. W. H. Ferguson, and F. Jonker. 2002. Population densities of pack ice seals in the Lazarev Sea, Antarctica. *Ant. Sci.* **14**, 123–127.

Buckland, S. T., D. R. Anderson, K. P. Burnham, J. L. Laake, D. L. Borchers, and L. Thomas. 2004. *Advanced Distance Sampling*. Oxford University Press, New York.

Cameron, M. F., and D. B. Siniff. 2004. Age-specific survival, abundance, and immigration rates of a Weddell seal (*Leptonychotes weddellii*) population in McMurdo Sound, Antarctica. *Can. J. Zool.* **82**, 601–615.

Cameron, M. F., D. B. Siniff, K. M. Proffitt, and R. A. Garrott. 2007. Site fidelity of Weddell seals: the effects of sex and age. *Ant. Sci.* **19**, 149–155.

Chambert, T., J. J. Rotella, and R. A. Garrott. 2012. Environmental extremes versus ecological extremes: impact of a massive iceberg on the population dynamics of a high-level Antarctic marine predator. *Proc. Royal B.* **279**, 4532–4541.

Devictor, V., R. J. Whittaker, and C. Beltrame. 2010. Beyond scarcity: citizen science programmes as useful tools for conservation biogeography. *Div. Dist.* **16**, 354–362.

Dickinson, J. L., B. Zuckerberg, and D. N. Bonter. 2010. Citizen science as an ecological research tool: challenges and benefits. *Ann. Rev. Ecol. Syst.* **41**, 149–172.

Erickson, A. W., and M. B. Hanson. 1990. Continental estimates and population trends of Antarctic Ice Seals. *Antarctic Ecosys.* **1**, 253–264.

Erickson, A. W., D. B. Siniff, D. R. Cline, and R. J. Hofman. 1971. Distributional ecology of Antarctic seals. Pp. 55–76 in G. Deacon, ed. *Symposium on Antarctic Ice and Water Masses*. SCAR, Cambridge, UK.

Flores, H., C. Haas, J. A. van Franeker, and E. Meesters. 2008. Density of pack-ice seals and penguins in the western Weddell Sea in relation to ice thickness and ocean depth. *Deep Sea Research II* **55**, 1068–1074.

Garrott, R. A., J. J. Rotella, D. B. Siniff, C. L. Parkinson, and G. E. Stauffer. 2012. Environmental variation and cohort effects in an Antarctica predator. *Oikos* **121**, 1027–1040.

Green, K., H. R. Burton, V. Wong, R. A. McFarlane, A. A. Flaherty, B. C. Pahl, et al. 1995. Difficulties in assessing population status of ice seals. *Wild. Res.* **22**, 193–199.

Gurarie, E., J. L. Bengtson, M. N. Bester, A. S. Blix, M. Cameron, H. Bornemann, et al. 2016. Distribution, density and abundance of Antarctic ice seals off Queen Maud Land and the eastern Weddell Sea. *Pol. Biol.* **40**, 1149–1165.

Jones, F. M., C. Allen, C. Arteta, J. Arthur, C. Black, L. M. Emmerson, et al. 2018. Time-lapse imagery and volunteer classifications from the Zooniverse Penguin Watch poject. *Scientif. Data* **5**, 180124.

Landres, P. B., J. Verner, and J. W. Thomas. 1988. Ecological uses of vertebrate indicator species: a critique. *Conserv. Biol.* **2**, 316–328.

LaRue, M. A., J. J. Rotella, R. A. Garrott, D. B. Siniff, D. G. Ainley, G. E. Stauffer, et al. 2011. Satellite imagery can be used to detect variation in abundance of Weddell seals (*Leptonychotes weddellii*) in Erebus Bay, Antarctica. *Polar Biol.* **34**, 1727–1737.

LaRue, M. A., S. S. Stapleton, and M. Anderson. 2016. Feasibility of using high-resolution satellite imagery to assess vertebrate wildlife populations. *Cons. Biol.* **31**, 213–220.

LaRue, M. A., L. Salas, N. Nur, D. G. Ainley, S. Stammerjohn, L. Barrington, et al. 2019. Physical and ecological factors explain the distribution of Ross Sea Weddell seals during the breeding season. *Mar. Ecol. Prog. Ser.* **612**, 193–208. https://doi.org/10.3354/meps12877.

Laws, R. M. 1984. Seals. Pp. 621–715 in R. M. Laws, ed. *Antarctic Ecology* Vol. **2**. Academic Press, London.

Lugg, D. J. 1966. Annual cycle of the Weddell seal in the Vestfold Hills, Antarctica. *J. Mamm.* **47**, 317–322.

McShea, W. J., T. Forrester, R. Costello, Z. He, and R. Kays. 2016. Volunteer-run cameras as distributed sensors for macrosystem mammal research. *Land. Ecol.* **31**, 55–66.

Odum, E. P. 1971. *Fundamentals of Ecology*, 3rd ed. W.B. Saunders, Philadelphia, PA.

Rotella, J. J., J. T. Paterson, and R. A. Garrott. 2016. Birth dates vary with fixed and dynamic maternal features, offspring sex, and extreme climatic events in a high-latitude marine mammal. *Ecol. Evol.* **6**, 1930–1941.

Rotella, J. J., W. A. Link, T. Chambert, G. E. Stauffer, and R. A. Garrott.2012. Evaluating the demographic buffering hypothesis with vital rates estimated for Weddell seals from 30 years of mark–recapture data. *J Anim Ecol.* **81**, 162–173.

Seal, U. S., A. W. Erickson, D. B. Siniff, and R. J. Hofman. 1971. Biochemical, population genetic, phylogenetic and cytological studies of Antarctic seal specie. Pp. 77–95 in G. Deacon, ed. *Symposium on Antarctic Ice and Water Masses*. SCAR, Cambridge, UK.

Shiffman, D. 2018. Social media for fisheries science and management professionals: how to use it and why you should. *Fisheries* **43**, 123–129.

Siddig, A. H. A., A. M. Ellison, A. Ochs, C. Villar-Leeman, and M. K. Lau. 2015. How do ecologists select and use indicator species to monitor ecological change? Insights from 14 years of publication in Ecological Indicators. *Ecol. Ind.* **60**, 223–230.

Siniff, D. B., and D. G. Ainley. 2008. Aerial surveys of Weddell seals during 2007-08, with notes on the history of aerial censuses in the Ross Sea and recommendations for continued count effort. CCAMLRWG-EMM08-07. Hobart, Australia.

Siniff, D. B., J. R. Tester, and V. B. Kuechle. 1971. Some observations on the activity patterns of Weddell seals as recorded by telemetry. *Ant. Res. Ser.* **18**, 173–180.

Siniff, D. B., D. P. DeMaster, R. J. Hofman, and L. L. Eberhardt. 1977. An analysis of the dynamics of a Weddell seal population. *Ecol. Monogr.* **47**, 319–335.

Siniff, D. B., R. A. Garrott, J. J. Rotella, W. R. Fraser, and D. G. Ainley. 2008. Projecting the effects of environmental change on Antarctic seals. *Ant. Sci.* **20**, 425–435.

Smith, M. S. R. 1965. Seasonal movements of the weddell seal in McMurdo sound. *Antarctica. J wildlife manage.* **29**, 464–470.

Southwell, C. J., J. Bengtson, M. Bester, A. S. Blix, H. Bornemann, P. Boveng, et al. 2012. A review of data on abundance, trends in abundance, habitat use, and diet of ice-breeding seals in the Southern Ocean. *CCAMLR Sci.* **19**, 49–74.

Southwell, C., B. de la Mare, D. Borchers, and L. Burt.2004. Shipboard line-transect surveys of crabeater seal abundance in the pack-ice off East Antarctica: evaluation of assumptions. *Mar Mam Sci.* **20**, 602–620.

Stapleton, S., M. LaRue, N. Lecomte, S. Atkinson, D. Garshelis, C. Porter, et al. 2014. Polar bears from space: assessing satellite imagery as a tool to track arctic wildlife. *PLoS ONE* **9**, e101513. https://doi.org/10.1371/journal.pone.0101513.

Steenweg, R., M. Hebblewhite, R. Kays, J. Ahumada, J. T. Fisher, C. Burton, et al. 2017. Scaling-up camera traps: monitoring the planet's biodiversity with networks of remote sensors. *Front. Ecol Env.* **15**, 26–34.

Stirling, I. 1969. The ecology of the Weddell seal in McMurdo sound, Antarctica. *Ecology* **4**, 573–586.

Stirling, I. 1977. Adaptations of Weddell and ringed seals to exploit the polar fast ice habitat in the absence or presence of surface predators. Pp. 741-774 *in* G. A. Llano, ed. *Adaptations within antarctic ecosystems*. Smithsonian Institution, Washington, DC.

Swanson, A., M. Kosmala, C. Lintott, R. Simpson, A. Smith and C. Packer. 2015. Snapshot Serengeti, highfrequency annotated camera trap images of 40 mammalian species in an African savanna. *Scientific Data*. https://doi.org/10.1038/sdata.2015.26.

Testa, J. W., and D. B. Siniff. 1987. Population dynamics of Weddell seals (*Leptonychotes weddellii*) in McMurdo Sound, Antarctica. *Ecol. Monogr.* **57**, 149–165.

Thaler, A. D., K. A. Zelnio, A. Freitag, R. MacPherson, D. Shiffman, H. Bik, et al. 2012. Digital Environmentalism: Tools and strategies for the evolving online ecosystem. Pp. 364–373 *in* D. Gallagher, ed. *Environmental leadership: a reference handbook*. Sage, Thousand Oaks, CA. (Forthcoming).

Thomas, J. A., and D. P. DeMaster. 1983. Diel haul-out patterns of Weddell seal (*Leptonychotes weddellii)* females and their pups. *Can. J. Zool.* **61**, 2084–2086.

United States Central Intelligence Agency. 2011. *The World Factbook*. Government of the United States, Antarctica.

Ward, D. V. 1978. *Biological Environmental Impact Studies: Theory and Methods*. Academic Press, New York, NY.

