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Research Note

Applications of Very High-Resolution Imagery in the Study and Conservation of Large Predators in the Southern Ocean

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Abstract: *The Southern Ocean is one of the most rapidly changing ecosystems on the planet due to the effects of climate change and commercial fishing for ecologically important krill and fish. Because sea ice loss is expected to be accompanied by declines in krill and fish predators, decoupling the effects of climate and anthropogenic changes on these predator populations is crucial for ecosystem-based management of the Southern Ocean. We reviewed research published from 2007 to 2014 that incorporated very high-resolution satellite imagery to assess distribution, abundance, and effects of climate and other anthropogenic changes on populations of predators in polar regions. Very high-resolution imagery has been used to study 7 species of polar animals in 13 papers, many of which provide methods through which further research can be conducted. Use of very high-resolution imagery in the Southern Ocean can provide a broader understanding of climate and anthropogenic forces on populations and inform management and conservation recommendations. We recommend that conservation biologists continue to integrate high-resolution remote sensing into broad-scale biodiversity and population studies in remote areas, where it can provide much needed detail.*

Keywords: ecosystem management, polar regions, satellite imagery

Aplicaciones de Imágenes de Muy Alta Resolución en el Estudio y Conservación de Grandes Depredadores en el Océano Antártico

Resumen: *El Océano Antártico es uno de los ecosistemas con rápidos cambios en el planeta debido a los efectos del cambio climático y la pesca comercial de peces y kril ecológicamente importantes. Ya que se espera que la pérdida de hielo esté acompañada por declinaciones de depredadores de peces y kril, desacoplar los efectos de los cambios climáticos y antropogénicos de estas poblaciones de depredadores es crucial para el manejo basado en ecosistemas del Océano Antártico. Revisamos investigaciones publicadas desde 2007 hasta 2014, las cuales incorporaron imágenes satelitales de muy alta resolución para evaluar la distribución, abundancia y efectos del clima y otros cambios antropogénicos sobre las poblaciones de depredadores en las regiones polares. Las imágenes de muy alta resolución se han utilizado para estudiar siete especies de animales polares en 13 artículos, muchos de los cuales proporcionan métodos mediante los cuales se pueden llevar a cabo más investigaciones. El uso de imágenes de muy alta resolución en el Océano Antártico puede proporcionar un entendimiento más amplio de las fuerzas climáticas y antropogénicas que actúan sobre las poblaciones e informar a las recomendaciones de manejo y conservación. Recomendamos que los biólogos de la conservación integren sensores remotos de alta resolución en los estudios poblacionales y de biodiversidad a gran escala en áreas remotas, donde puede proporcionar detalles muy necesitados.*

Palabras Clave: imágenes satelitales, manejo de ecosistemas, regiones polares

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Introduction

The need to detect and predict change in the environment is greater than ever because human-induced climate and habitat changes have rapidly increased since the 1950s and have affected virtually all of Earth's biomes (Millennium Ecosystem Assessment 2005), including Antarctica, where ecosystems are changing faster than nearly anywhere else (Montes-Hugo et al. 2009; Smith et al. 2014). For example, as air temperatures have increased on the Antarctic peninsula, >70% of glaciers have retreated (Cook et al. 2005) and there has been substantial loss in extent and duration of sea ice (Stammerjohn et al. 2012) and correlated decreases in ice-obligate species such as the Weddell seal (*Leptonychotes weddellii*) and Adélie (*Pygoscelis adeliae*), Chinstrap (*Pygoscelis antarctica*), and Emperor Penguins (*Aptenodytes forsteri*) (Siniff et al. 2008; Montes-Hugo et al. 2009; Trathan et al. 2011).

Resources in the Southern Ocean are important economically, due to fishing for krill (*Euphasia* spp.), mackerel icefish (*Champsocephalus gunnari*), and toothfish (*Dissostichus* spp.; Agnew 1997; Croxall & Nicol 2004; Brooks 2013). The changing environment coupled with extraction of key prey and competitors from the Southern Ocean creates a substantial need for informed conservation and resource management. However, gathering necessary data to make such management decisions remains difficult because little is known about the life cycle of toothfish (Blight et al. 2010) and data on krill abundance and distribution is expensive to gather and prone to error (Croxall & Nicol 2004; Demer 2004). Thus, using krill and toothfish predators (e.g., Adélie Penguin, Weddell seal) as a proxy for abundance and distribution of their prey remains the most viable option for building accurate resource use models (Agnew 1997). To best gain information at regional to global scales, remote sensing of predator populations in the Southern Ocean is likely to be the most efficient and cost-effective complement to Antarctic field work.

Very high-resolution (VHR) satellite imagery here refers to images with spatial resolutions of 0.5–2.4 m (DigitalGlobe and GeoEye platforms), and until recently it had not been used to assess populations of animals in polar regions. We considered peer reviewed and grey literature from 2007 to 2014 on the use of VHR imagery to study polar animal populations and examined the implications of VHR images and geospatial methods for conservation of ecosystems and sustainable resource use in the Southern Ocean.

Direct Remote Sensing of Ice-Obligate Vertebrates

Direct assessment here refers to visually identifying individual animals on satellite images; only larger animals can be identified directly in 0.6 m imagery. LaRue et al. (2011) used Quickbird-2 imagery to directly count Weddell seals in Erebus Bay, Antarctica, and found a strong correlation between ground and satellite counts ($r^2 = 0.98$). Their image counts captured a population rebound from an all-time low of adults in 2004 to an all-time high in 2009. This result suggested that imagery counts could detect variation in abundance and thus provide a viable alternative to ground or aerial counts in population assessments where little is known about Weddell seals. Recently, McMahon et al. (2014) tested the utility of VHR images to assess abundance of elephant seals (*Mirounga leonina*) hauled out at beaches on Macquarie Island. They found that ground and image counts were correlated, a finding that suggests that VHR imagery can be used to assess even cryptically colored species.

Detection of large-bodied animals from VHR imagery has also been conducted in the Russian Arctic, where Boltunov et al. (2012) used EROS B images with different off-nadir angles and cloud cover to determine the best conditions for identifying walrus (*Odobenus rosmarus*) from high-resolution imagery. Stapleton et al. (2014) used a unique combination of VHR imagery in a mark-recapture framework to assess a population of polar bears (*Ursus maritimus*) on Rowley Island, Canada. Using an image from September 2012 and a reference image from September 2010, 2 observers compared images for differences in presence of polar bears and assessed results in a double-observer method (Nichols et al. 2000). Results of this procedure indicated that assessing high-resolution imagery was comparable to and more precise than aerial survey methods. High-resolution image assessment could fill in gaps in knowledge of distribution and abundance of predators in polar regions.

Indirect Assessment of Populations

Although direct assessments of populations with satellite imagery are isolated to large-bodied mammals, indirect assessments can also be used to determine population status. Shortly after the first VHR satellites launched (Quickbird-2 and Worldview-1), researchers used VHR images and a supervised classification technique to develop a method for estimating abundance of Emperor Penguins (Barber-Meyer et al. 2007) and found that absolute deviation from the ground counts varied substantially (0.2–128%). However, this work led to the idea that pan-sharpened multispectral images (images with enhanced spatial resolution derived by sharpening the multispectral images to match the higher resolution of their panchromatic pair) would provide greater power to differentiate items on the landscape. Building on this work, Fretwell et al. (2012) used a similar technique to assess the global estimate of emperor penguins by incorporating pan-sharpened images, which allowed for enhanced differentiation of the spectral classes (i.e., guano, ice, and penguin pixels). They found approximately 595,000 Emperor Penguins in Antarctica in 2009 at 46 colonies—nearly double previous estimates—and an additional 7 colonies previously unknown to science. This was the first study to examine the global population of an important indicator species in the Southern Ocean.

Much research has focused on Antarctic penguins because they are indicators of the condition of the Southern Ocean and the relative availability of its resources (i.e., krill and fish) (Ainley 2002*a*; Le Bohec et al. 2013). LaRue et al. (2014) were the first to specify a method for estimating abundance of Adélie Penguins. They used a supervised classification combined with maximum likelihood estimators to determine the size of guano stains, which is a strong predictor of population size. That method was subsequently used to estimate, for the first time, the global abundance of Adélie Penguins (Lynch & LaRue 2014). VHR images have also been used to find longitudinal changes at colonies as well. Naveen et al. (2012) combined VHR imagery with reports in the literature and found a drastic decrease (>50%) in the Chinstrap Penguin population over 25 years at Baily Head on Deception Island by manually delineating the guano stain in each image. Similarly, LaRue et al. (2013) combined VHR images with historic aerial photos and found that glacial retreat over >50 years resulted in habitat release at Beaufort Island and affected emigration rates among Adélie Penguin colonies in the southern Ross Sea metapopulation. These studies demonstrate the power of data fusion and represent important applications of remote sensing to improve understanding of population change of Southern Ocean predators.

Researchers have used VHR imagery to understand other aspects of Antarctic predators. For example, Lynch et al. (2012) used VHR images to differentiate penguin species on the Antarctic peninsula from differences in guano stains. Fretwell et al. (2014) found that Emperor Penguins breed on ice shelves in years of unfavorable sea ice. D. G. Ainley et al. (unpublished) found a decrease in Weddell seals in the Ross Sea over >50 years, and a recent analysis suggests that Emperor Penguins may emigrate frequently (LaRue et al. 2014). VHR imagery is becoming an invaluable resource for basic research and has provided insight into the behavioral ecology of some of Antarctica's most iconic and ecologically important species.

Biodiversity Conservation in Polar Regions

The Southern Ocean represents just 10% of the world's ocean area, yet it contains approximately 280 of known, endemic species of fishes (Eastman 2005), endemic penguins (Adélie and Emperor), and the most pristine body of water on Earth (the Ross Sea [Halpern et al. 2008]). Our southernmost ocean is also economically important. For example, in 2012 alone fisheries took ~160,000 tons of krill and 1,000 tons of ice fishes, with a market value of US ~$162 million (Brooks 2013). Fishing in the Southern Ocean is managed by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), an organization committed to an ecosystem-based approach to resource management (Agnew 1997; Brooks 2013). One important way CCAMLR manages the Southern Ocean ecosystem is to monitor the distribution and abundance of krill predators, which includes penguins and seals (Agnew 1997). In the case of the Adélie penguin, very few of their approximately 250 colonies in Antarctica are regularly monitored; thus, current resource use models may be underestimated and catch limits for krill may be set too high (Lynch & LaRue 2014). Rational use of Southern Ocean resources, in this case, may be in jeopardy.

Another economically viable resource that may be exploited in the Southern Ocean is the Antarctic toothfish (*Dissostichus mawsoni*) in the Ross Sea. The Ross Sea is home to 25% of the world population of Emperor Penguins (Fretwell et al. 2012; Smith et al. 2014), approximately 33% of Adélie Penguins (Lynch & LaRue 2014; Smith et al. 2014), thousands of Weddell seals and killer whales (*Orcinus orca*), and the Antarctic toothfish. The Antarctic toothfish is an important piscine predator in the Ross Sea because it is prey for Weddell seals and killer whales (Ainley & Siniff 2009) and competes with Adélie and Emperor Penguins for Antarctic silverfish (*Pleuragramma antarctica*). The current issue for the Ross Sea is its protection from commercial toothfish fishing, which may already be affecting ecosystem function (Ainley 2002*b*; Ainley & Siniff 2009; Ainley et al. 2013). After >15 years of commercial fishing in the region, studies show a decrease in occurrence of type C killer whales (Ainley et al. 2010) and Weddell seals (D.G. Ainley et al., unpublished) and in scientific catch of toothfish (Ainley et al. 2013). However, Adélie penguin populations have increased (LaRue et al. 2013; Lyver et al. 2014), that could be indicating a trophic cascade from increased take of toothfish from the system. Because very little is known about the toothfish life cycle (e.g., fecundity, survival [Blight et al. 2010]) that would inform fishery catch models, CCAMLR decision makers could use population abundance data, provided through censuses from VHR imagery, for toothfish predators and competitors. As evidenced by the Antarctic Pack Ice Seals Program research cruises, the Antarctic coastline is a logistically challenging and cruises are an expensive mode of gathering data needed for management decisions (Bengston et al. 2011). Analysis of VHR imagery is currently the only feasible method for estimating annual abundance of these important predators in the Ross Sea and the rest of the inaccessible Southern Ocean.

Ecologists and conservation biologists have slowly adopted geospatial technologies and remote sensing into their research (Turner et al. 2003). However, remote sensing, and VHR imagery in particular, is needed to gain understanding of some of the most basic population parameters and to increase knowledge about environmental drivers of species distributions and changes. Given the vast challenges facing biodiversity globally, it is imperative that ecologists and conservation biologists gain exposure to available remote sensing and geospatial tools and collaborate with experts in remote sensing to address challenges in some of the world's most remote areas.

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