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Conservation Methods

Feasibility of using high-resolution satellite imagery to assess vertebrate wildlife populations

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Abstract: *Although remote sensing has been used for >40 years to learn about Earth, use of very high-resolution satellite imagery (VHR) (<1-m resolution) has become more widespread over the past decade for studying wildlife. As image resolution increases, there is a need to understand the capabilities and limitations of this exciting new path in wildlife research. We reviewed studies that used VHR to examine remote populations of wildlife. We then determined characteristics of the landscape and the life history of species that made the studies amenable to use of satellite imagery and developed a list of criteria necessary for appropriate use of VHR in wildlife research. From 14 representative articles, we determined 3 primary criteria that must be met for a system and species to be appropriately studied with VHR: open landscape, target organism's color contrasts with the landscape, and target organism is of detectable size. Habitat association, temporal exclusivity, coloniality, landscape differentiation, and ground truthing increase the utility of VHR for wildlife research. There is an immediate need for VHR imagery in conservation research, particularly in remote areas of developing countries, where research can be difficult. For wildlife researchers interested in but unfamiliar with remote sensing resources and tools, understanding capabilities and current limitations of VHR imagery is critical to its use as a conservation and wildlife research tool.*

Keywords: conservation research, GIS, population monitoring, remote-sensing methods

Viabilidad de la Utilización de Imágenes Satelitales de Alta Resolución para Evaluar Poblaciones Silvestres de Vertebrados

Resumen: *Aunque la telemetría se ha utilizado por más de 40 años para aprender sobre la Tierra, el uso de imágenes satelitales de muy alta resolución (MAR) (<1-m de resolución) se ha vuelto más extendido en la última década como herramienta de estudio de la vida silvestre. Conforme incrementa la resolución de las imágenes, existe una necesidad de entender las capacidades y limitaciones de este nuevo y emocionante camino en la investigación de la vida silvestre. Revisamos estudios que utilizaron MAR para examinar poblaciones remotas de vida silvestre. Después determinamos las características del paisaje y de la historia de vida de las especies que hicieron a los estudios más dispuestos para el uso de imágenes satelitales y desarrollamos una lista de criterios necesarios para el uso correcto de MAR en la investigación de la vida silvestre. De 14 artículos representativos determinamos tres criterios primarios que deben cumplirse para que un sistema y las especies sean estudiadas correctamente con MAR: paisaje abierto, los contrastes de color del organismo estudiado con el paisaje y si el organismo estudiado es de un tamaño detectable. La asociación de hábitat, la exclusividad temporal, la colonización, la diferenciación del paisaje y el incremento en la verificación en el terreno incrementan la utilidad de MAR para la investigación de la vida silvestre. Existe una necesidad inmediata por las imágenes MAR en la investigación de la conservación, particularmente en áreas remotas de los países en desarrollo. Para los investigadores de la vida silvestre que están interesados pero que no están familiarizados con los recursos ni con las herramientas de telemetría, entender las capacidades y las limitaciones actuales de las imágenes MAR es crítico para su uso como una herramienta de conservación e investigación de la vida silvestre.*

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Palabras Clave: investigación de la conservación, métodos de telemetría, monitoreo poblacional, SIG

Introduction

The use of very high-resolution satellite imagery (VHR) (i.e., submeter resolution images) to assess wildlife populations has increased substantially over a relatively short time. Although Schwaller et al. (1984) first determined that 15-m resolution Landsat could be used to index Adélie Penguin (*Pygoscelis adeliae*) populations on Ross Island, Antarctica, Barber-Meyer et al. (2007) pioneered the use of VHR as a resource for research in polar ecology by using a supervised classification technique (i.e., training a computer to differentiate between image pixels) on panchromatic QuickBird-2 images to determine abundance of 7 populations of Emperor Penguins (*Aptenodytes forsteri*) in the Ross Sea. Since Barber-Meyer et al. (2007), >20 studies have been published in which VHR was used to assess populations of wildlife. Such work has also included estimates of animal abundance in the Arctic, African grasslands, and open ocean (Fretwell et al. 2014*a*; Stapleton et al. 2014*a*; Yang et al. 2014). The ability to remotely assess and monitor wildlife populations has the potential to revolutionize such monitoring in remote regions, particularly as technology advances and spatial and spectral resolution of satellite platforms improve.

The use of VHR will likely become more widespread in wildlife ecology and conservation, particularly as costs of the images decrease. To efficiently and effectively implement this resource, however, researchers must understand its capabilities and limitations. Our objective was to develop a feasibility guide for the use of VHR imagery in wildlife research. We conducted a comprehensive literature review of published articles in which VHR was used to assess wildlife populations. We qualitatively described the characteristics of the systems, including the landscape and the life history traits of the target species, and then identified those features that made VHR a suitable method for measuring occupancy and abundance of wildlife. Across 14 articles, we identified 3 primary criteria that must be met but do not guarantee success and 5 additional criteria that enhance the effectiveness of use of VHR in wildlife research.

Primary Criteria for Use of VHR

We identified an open landscape, organism color contrasts with the landscape, and sufficient organism size as the 3 main criteria that must be met for VHR to have utility for assessing wildlife (Table 1). The landscape over which the images would be taken must be open, such that the species of interest cannot be hidden. Polar vertebrates such as emperor penguins, Adélie penguins, Weddell seals (*Leptonychotes weddellii*), southern elephant seals (*Mirounga leonine*), polar bears (*Ursus maritmus*), and walruses (*Odobenus rosmarus*); large-bodied vertebrates on the African plains such as elephants (*Loxodonta africana*); and right whales (*Eubalaena australis*) at the surface of the water in calm conditions are examples of species living in areas where the landscape is accessible for detection via VHR (LaRue et al. 2011; Boltunov et al. 2012; Fretwell et al. 2012; Fretwell et al. 2014*a*; Lynch & LaRue 2014; Stapleton et al. 2014*a*; Yang et al. 2014). The open landscape is the primary reason that many of these studies have been conducted in polar regions, where vegetation cover that could preclude detection does not exist. Even in open landscapes, cloud cover and steep topography render detection difficult and sometimes impossible (Fretwell et al. 2012; Lynch & LaRue 2014).

An individual organism must be large enough for detection on images with resolutions of approximately 0.60 m (panchromatic images). Polar bears, for example, which are approximately 2 m long and 1 m wide, clearly appear on VHR as large white spots on a snow-free landscape (Stapleton et al. 2014*a*; LaRue et al. 2015). If organisms are too small to be individually identified on imagery, proxies may be used to infer presence. Such proxies are called positive indicators and are considered indirect remote sensing (LaRue & Knight 2014). Masked Boobies (*Sula dactylatra*) have a "nest signature"; the ground is cleared away leaving a conspicuous circle of dirt where nesting is occurring (Hughes et al. 2011). Adélie Penguins leave a unique guano stain, the size of which is positively correlated with the number of concurrent breeding pairs, which allows researchers to measure abundance (LaRue et al. 2014*b*).

The color of the target species (or of its positive indicator) must contrast with the surrounding landscape. For example, Weddell seals appear as black spots on white ice (Fig. 1) (LaRue et al. 2011; Ainley et al. 2015), and Masked Booby nests appear as bare ground among the surrounding green grass (Hughes et al. 2011). All 3 criteria are currently required for a vertebrate species to be detected via 0.5-m resolution VHR imagery. However, we suggest that these criteria are an absolute minimum and alone may not be sufficient to guarantee the effective use of imagery for wildlife research.

Secondary Criteria

Additional criteria increase the likelihood of detection and enhance the utility of using remote sensing as a monitoring and assessment tool. The ability to differentiate

Table 1. Criteria of imagery, landscape, and life history of vertebrate species necessary for using very high-resolution satellite imagery (VHR) in wildlife research.[a]

	Minimum necessary				*Enhances utility*				
Species (reference)	*open landscape*	*body size*	*positive indicator*	*contrast*	*habitat association*	*temporal exclusivity*	*coloniality*	*landscape differentiation*	*ground-truthing*
Emperor Penguins (Fretwell et al. 2012)	x	x	x	x	x	x	x	x	x
Weddell seals (LaRue et al. 2011)	x	x		x	x	x	x	x	x
Adélie Penguins (LaRue et al. 2014*b*; Lynch & LaRue 2014)	x		x	x	x	x	x	x	x
Chinstrap penguins (Naveen et al. 2012)	x		x	x	x	x	x	x	x
Southern right whales (Fretwell et al. 2014*a*)	x	x		x	x	x	x	x	
Walrus (Boltunov et al. 2012)	x	x		x	x	x	x	x	
Domestic cattle (Begall et al. 2008)	x	x		x	x	x	x	x	
Masked Boobies (Hughes et al. 2011)	x		x	x		x	x	x	
Gentoo Penguins (Lynch et al. 2012)	x		x	x			x	x	
Macaroni Penguins (Lynch et al. 2012)	x		x	x			x	x	
Southern elephant seals (McMahon et al. 2014)	x	x		x			x	x	
Polar bears (Stapleton et al. 2014*a*; LaRue et al. 2015)	x	x		x	x			x	x
African animals (Yang et al. 2014)	x	x		x			x	x	
Musk ox	x	x		x			x		x

[a]*An open landscape; large body size or a positive indication of species' presence; and organism's color contrasting with the landscape are the minimum necessary (but not sufficient) requirements for using VHR.*

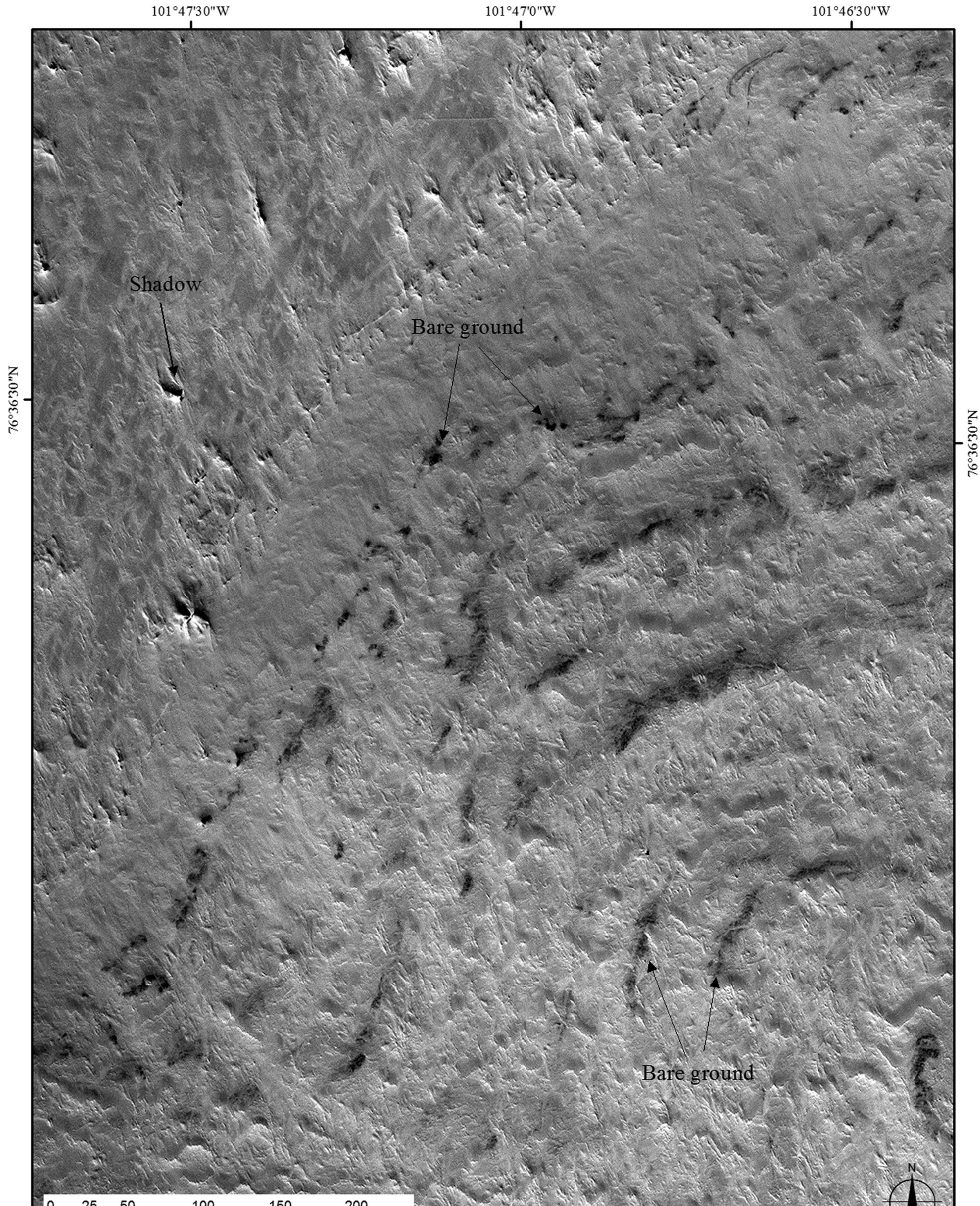

Figure 1. Snow-covered WorldView-1 image (0.6-m resolution, courtesy DigitalGlobe Foundation) of Bathurst Island, Canada, acquired 29 April 2013. Muskoxen were available for detection on Bathurst Island in April 2013 but because of the bare ground, shadows, and rock outcrops on images, we were unable to positively identify muskoxen on the imagery.

the target species from other objects on the landscape improves detection (Table 1). We contend that this is the most important secondary criterion. An individual may be a sufficient size for detection and may contrast with the landscape, but if it is not possible to differentiate the target species from other objects (e.g., rocks or pools of water), then one has less confidence in the accuracy of the estimate derived from the imagery. Polar bears on Rowley Island, Canada, provide a unique example in which combining knowledge of a species' life history with remote-sensing techniques can solve the problem of definitive differentiation (LaRue et al. 2015). In this case, image differencing—where one image is subtracted from another such that only the different pixels remain—allows researchers to differentiate rocks from bears.

Habitat associations of the target species (Table 1), referring to the organism's reliable presence at a specific location, improve detection of vertebrates via VHR. For example, the emperor penguin has a circumpolar distribution in the Antarctic and is typically associated only with land-fast sea ice (also called fast ice) (Kooyman et al. 2000; Fretwell et al. 2012). Detecting the guano signature on the ice is a sure indication of an emperor penguin colony and importantly nothing else because these birds are the only sea birds that breed on Antarctic fast ice (Le Maho 1977). Using VHR, Fretwell et al. (2014*b*) identified that some emperor penguin colonies use glacial or ice shelf in years of poor sea-ice conditions. This guano stain has facilitated the detection of >20 previously unknown colonies via remote sensing (Fretwell & Trathan 2009; Fretwell et al. 2012; LaRue et al. 2014*a*).

Temporal exclusivity—meaning only the target population occupies an area at specific time—is another criterion that improves the utility of VHR. Weddell seals have a circumpolar distribution and are associated with fast ice. Every austral spring, Weddell seals return to the same locations to give birth and raise pups (Stirling 1969; Siniff et al. 1977; Siniff 1981), but there is a specific window of time from which one can determine the size of a breeding population (Banner 2012). Although reproductive female seals are present on the fast ice from early spring through the molt (the following January), their activity is least variable during the first 2 weeks in November. By early November, females have given birth and are spending more time hauled out on the ice raising their pups (Stirling 1969; Cameron & Siniff 2004); nonreproductive females tend to be excluded from these core breeding locations (Stirling 1971). Thus, the likelihood of including nonbreeders in abundance estimates is minimal. Perhaps most importantly, because the pups are very young in early November, they are too small to be detected via satellite imagery (LaRue et al. 2011) and are not included in estimates of the breeding population size.

Detection improves if the target species is colonial or congregates in herds (Table 1). For example, Yang et al. (2014) used VHR and object-based image analysis to detect large-bodied animals on the African savannah. Begall et al. (2008) used Google Earth to demonstrate the magnetic orientation of domestic cattle in pastures across 6 continents. When animals congregate, detection is far easier than if individuals were solitary because detection probability generally increases with greater herd or colony size (Rivest et al. 1998). Conversely, polar bears live in open spaces in the Arctic, are large-bodied, and contrast with ice-free landscapes in some regions. Despite this, reliable detection can still be challenging because of their typically solitary behavior (Stapleton et al. 2014*b*; LaRue et al. 2015).

Finally, ground-truthing is an important secondary criterion that allows for increased confidence in both detection rates and abundance estimates. The first global estimates of both Antarctic penguin species were completed with ground validation built into models (Fretwell et al. 2012; Lynch & LaRue 2014), and confidence in detecting variability in the Weddell seal population in Erebus Bay was only possible because of comparison with concurrent ground counts (LaRue et al. 2011). In fact, it was only through ground validation that LaRue et al. (2011) determined differences in detection probability based on sea-ice conditions and that the increase in counts from images reflected a true increase in the population from 2004 to 2009. Conversely, Fretwell et al. (2014*a*) determined the presence of southern right whales (*E. australis*) off the coast of Argentina without direct ground-truthing because general knowledge of the species' life history was sufficient. Thus, ground validation benefits any pilot project, but detection of large vertebrates via VHR imagery is still possible without it.

Muskoxen

We evaluated our criteria while using VHR to search for muskoxen (*Ovibus moschatus*) on Bathurst Island, Canada. We searched approximately one-third of the 16,000-km^2 island. From an ecological perspective, muskoxen fulfill all primary criteria: their landscape is open and flat, adult muskoxen primarily live in herds and are large bodied, and they contrast with the surrounding landscape (Heard 1992). We hypothesized that they are readily apparent on snow-covered images and anticipated that generating an abundance estimate for comparison with aerial surveys (as in Stapleton et al. 2014*b*) would be straightforward.

Briefly, we obtained WV-01 and WV-02 VHR images of Bathurst Island, Canada (DigitalGlobe Foundation, Westminster, Colorado) acquired during April and May 2013. In an effort to identify muskoxen on VHR, we selected locations that overlapped in space and time with aerial surveys conducted by the Government of Nunavut. Although we knew that >1500 muskoxen were available for detection (Anderson 2014), we were unable to definitively identify them via manual detection on VHR images in ArcGIS 10.2 (for similar methods, see LaRue et al. [2011], Stapleton et al. [2014*b*], and LaRue et al. [2015]). We suspect the reason that we could not detect muskoxen was because of lack of habitat association and, in particular, insufficient differentiation from the landscape (Fig. 1). In other words, despite that muskoxen contrast spectrally with the landscape (black animals on white background), they were not different enough from other items on the landscape, such as rocks and outcrops, to be positively identified. Bathurst Island in April and May is mostly covered in snow, so large, dark muskoxen should appear easily on the images. The preference of muskoxen for well-vegetated lowlands is well known by Inuit and biologists (Thing et al. 1987; Ferguson 1991; Larter & Nagy 1997; Taylor 2005), but although they generally prefer productive lowlands, they are not restricted to these areas and use upland tundra and dwarf shrub habitats. Their habitat associations are not restrictive enough to allow us to rule out large areas of Bathurst Island. Furthermore, there are enough rock outcrops and boulders on the island and windswept ridges and deltas to make differentiating muskoxen from rocks impossible on 60-cm resolution images, even when toggling back and forth between 2 images taken at different times to visually inspect the images, as in Stapleton et al. (2014*a*).

Image differencing presents a possible solution to this problem. However, image differencing with VHR (especially in polar regions with topographic relief) may not have sufficient orthorectification necessary to line up both images exactly. Thus, even when one subtracts one image from another, there can still be a mismatch, such that rocks and outcrops appear to be different objects when they are not. In the case of polar bears on Rowley Island, LaRue et al. (2015) avoided this because the island is flat and relatively uniform across the landscape (little rubble and most rocks are large). Thus, our attempt to detect muskoxen on VHR provided an important lesson in the limitations of VHR for wildlife ecology. Our 3 primary criteria represent the bare minimum necessary for detection. These criteria alone, however, are not necessarily sufficient for accurate detection, and some combination of the secondary criteria may also need to be met.

Discussion

Satellite imagery is an important tool in ecological and conservation research (Turner et al. 2003; Leimgruber et al. 2005). Ecologists historically have been less inclined to use remotely sensed data and geographic information systems (GIS) programs due to lack of technical capacity (Leimgruber et al. 2005), but it appears that this capacity has increased recently along with an urgency in conservation research. Indeed, our review demonstrates the utility of VHR for vertebrates and is an encouraging step forward in better understanding populations of remote wildlife. However, what is most crucial at this point is gaining perspective on the current limitations and appropriate uses of this imagery. As scientists turn to VHR as a valuable monitoring tool, it is important to establish appropriate uses because misjudging the capacity of the method can cost valuable time, effort, and money without achieving desired outcomes. Traditionally, VHR imagery has been cost-prohibitive, and although licensing images can still be expensive, there are now multiple ways of piloting imagery, such as through the DigitalGlobe Foundation (where we obtained imagery used here) or through discounts for educational or nonprofit purposes.

There is an important and time-sensitive need for VHR imagery in ecological research, specifically for conservation efforts in remote areas of developing countries, where research efforts are depressed (Ripple et al. 2015). For example, developing countries contain 88% of populations of large herbivores that are amenable to research via VHR imagery, yet the number of peer-reviewed articles that include these threatened species in developing countries is substantially lower than those that include nonthreatened species in developed countries (Ripple et al. 2015). Presumably much of this disparity is due to funding, feasibility, and accessibility of remote regions in developing countries particularly in Africa and southeast Asia—some of which can be addressed through VHR imagery.

Given our criteria, it is obvious that research on these large herbivore species (e.g., African elephants [*Loxodonta africana*], white rhinoceros [*Ceratotherium simum*], and black rhinoceros [*Diceros bicornis*]) in Africa would benefit from the inclusion of VHR imagery in gathering some relatively basic data on population status, distribution, and trends. Not only do large African herbivores fit the criteria for successful VHR imagery use (open landscape, large-bodied herd animals distinct from the landscape, and specific habitat associations), but their populations are particularly threatened and declining (Ripple et al. 2015; Wasser et al. 2015; Kideghesho 2016). Poaching is one of the primary threats to elephants (Maisels et al. 2013); >100,000 elephants were poached in Africa from 2010 to 2012 (Wittemyer et al. 2014). Poaching of rhinoceros in South Africa increased from 13 in 2007 to >1000 in 2013 (Biggs et al. 2013; South African National Parks 2014). Most studies cited here (Table 1) were conducted in polar regions—which benefit from several of the criteria listed herein, such as open landscapes and contrast with the landscape—and on species that have been the subject of long-term research. Differentiating species (e.g., rhinos from elephants) will certainly take careful ground-truthing to determine differences in size, habitat associations, study areas, and times of year when animals are in identifiable locations. Only then can researchers be more confident in species identification and differentiation. The VHR imagery is increasing in spatial resolution (WV-03 has a spatial resolution of approximately 30 cm), and this will almost certainly help in species identification.

In addition to direct human persecution, conflict with livestock is another threat to African herbivores (Ripple et al. 2015), of which both populations should be detectable via VHR imagery. Pilot projects with VHR imagery used to determine distribution of elephant populations have occurred already (e.g., Satellite Sentinel Project), but we suggest that with our criteria, researchers will be able to more effectively plan for research on these and other species in similar habitats and subject to similarly large conservation threats. Lack of understanding of how to effectively use these resources may detract from important conservation efforts, so knowing the feasibility of use of VHR imagery is critical in the planning phases of research.

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