

PERSPECTIVE

Growth and opportunities for drone surveillance in pinniped research

Gregory D. LARSEN*  *Duke University Marine Lab, Beaufort, NC 28516, USA and Wake Forest University, Winston-Salem, NC 27109, USA. Email: larseng@wfu.edu*

David W. JOHNSTON  *Duke University Marine Lab, Beaufort, NC 28516, USA. Email: david.johnston@duke.edu*

Keywords

drone, photogrammetry, pinniped, remote sensing, wildlife technology

*Correspondence

Received: 14 March 2023

Accepted: 27 June 2023

Editor: DR

doi: 10.1111/mam.12325

ABSTRACT

Pinniped species undergo uniquely amphibious life histories that make them valuable subjects for many domains of research. Pinniped research has often progressed hand-in-hand with technological frontiers of wildlife biology, and drones represent a leap forward for methods of aerial remote sensing, enabling data collection, and integration at new scales of biological importance. Drone methods and data types provide four key opportunities for wildlife surveillance that are already advancing pinniped research and management: 1) repeat and on-demand surveillance, 2) high-resolution coverage at large extents, 3) morphometric photogrammetry, and 4) computer vision and deep learning applications. Drone methods for pinniped research represent early stages of technological adoption and can reshape the field as they scale towards the full potential of their techniques.

INTRODUCTION

Pinnipeds embody a variety of qualities that make many species interesting and suitable subjects for scientific research. As amphibious marine predators, all pinniped species haul out of the water, on land or ice, to breed or moult (Berta 2018). This characteristic makes pinnipeds relatively accessible and observable among marine predators. During these major life history events, many species exhibit philopatry (returning to their place of birth), gregariousness (gathering in large groups), and general site fidelity (revisiting sites that have been visited before) to various degrees; these qualities enable scientists to reliably access predictable populations and even individuals within single seasons and across years and generations (McKnight & Boyd 2018). Many species occupy terrestrial habitats that are accessible to humans and topographically open to on-the-ground or aerial surveillance. Finally, select species can be trained and safely housed in human care, so under appropriate ethical circumstances some pinnipeds can accommodate uniquely managed behavioural and physiological studies and assessments. Owing to these distinctive qualities, pinnipeds are often studied as sentinel species of their marine ecosystems (Bossart 2011, Fossi & Panti 2017), as models of marine adaptations in mammals

(Hochachka 2000), and for a variety of other scientific motivations. The equipment and methods that are used to study pinnipeds often represent the technological frontiers of wildlife science, incorporating the ongoing miniaturisation of computers and sensors, faster processing speeds, and growing quantities of 'big data' (Corlett 2017, Lahoz-Monfort & Magrath 2021). In this vein, the use of small unoccupied aircraft systems (sUAS), or drones, represents a major frontier of wildlife technology (Linchant et al. 2015, Wirsing et al. 2022) that is poised also to unlock new methods in the study of pinnipeds.

The term 'drone' most commonly refers to a variety of small robotic autonomous aircraft that are used increasingly across a variety of disciplines in environmental sciences (Floreano & Wood 2015, Jiménez López & Mulero-Pázmány 2019, Johnston 2019, Wirsing et al. 2022). Drones can achieve a variety of in situ environmental techniques by virtue of their mobility and precise aerial positioning, including sampling of aerosols (Pirotta et al. 2017), water, soil, and invertebrates (Robinson et al. 2022), but most applications for environmental research, and wildlife in particular, use drones as versatile remote sensing platforms (Chabot & Bird 2015, Johnston 2019, Mo & Bonatakis 2022, Robinson et al. 2022). With increasingly lightweight sensors and onboard processing

computers, drones can collect diverse types of sensing data at a high-throughput (Jiménez López & Mulero-Pázmány 2019), expanding both data collection and post-processing techniques for analyses that require big data.

Drones have several advantages over occupied aircraft, including simpler logistical requirements, greater safety, and lower costs (Jones et al. 2006, Linchant et al. 2015). Drones can, thereby, conduct operations with on-demand or repeat schedules and in sites far removed from supporting infrastructure. At the same time, low-altitude flights can collect imagery at low ground sample distances (GSDs) with precise navigation and spatially referenced metadata from global navigation satellite systems (GNSS) to achieve exhaustive spatial coverage in ultra-high (sub-decimetre) resolutions (Koh & Wich 2012, Raoult et al. 2020). For pinnipeds, these specific advantages directly allow researchers to safely study pinnipeds in habitats that are otherwise inaccessible to alternative methods (Christie et al. 2016, Krause & Hinke 2021). However, beyond site access, the advantages of drone surveillance also unlock new possibilities for study design and data analysis, potentially transforming downstream research and management capabilities. We discuss four key opportunities of drone methods that are already being deployed and developed for the study of pinnipeds, as well as future potential and limitations of the technology, demonstrating applications with original examples created from an open dataset of drone imagery over pinniped haul-out sites (Larsen et al. 2022a).

REPEAT AND ON-DEMAND DEPLOYMENT

Pinnipeds experience an annual cycle of physiological changes and life-history events that determines their terrestrial availability to research. The annual cycles of polar species are often especially coupled to seasonally available resources, such as habitat or prey (Bowen 2018). The mechanism of such phenology may be triggered or influenced by relatively predictable environmental attributes, like photoperiod (Temte & Temte 1993, Temte 1994, Trites & Antonelis 1994), dynamic environmental cues, like climate or sea ice (Hind & Gurney 1998), and intrinsic factors, like maternal age (Trites 1991, Lunn & Boyd 1993). Depending on the species, pinniped phenology unfolds with different degrees of interannual consistency (Bowen 2018), so single scheduled population surveys might not align with their target event, like maximum on-land abundance, and additional context is often necessary to estimate where a survey occurs within the annual cycle. This concern is especially relevant for optical imagery collected by satellites, whose orbital revisit period is further limited by cloud cover (LaRue et al. 2011, 2017), and imagery collected by occupied aircraft, whose flight schedules require advanced planning and are limited to longer

windows of safe weather (Sweeney et al. 2016). Drones are less limited by such logistical factors: lower infrastructure requirements allow operators to deploy drones on a more flexible and ad hoc schedule; rapid on-demand deployment and recovery can exploit very short weather windows; low-altitude flights can collect imagery under cloud cover; and repeat surveillance can obtain data series at frequencies and temporal ranges not practical or achievable by occupied aircraft or orbiting satellite platforms (Linchant et al. 2015, Christie et al. 2016).

On-demand deployment over pinnipeds can target expected phenological events, such as breeding and moulting, or respond to contextual triggers, such as peak counts from a local index site. Repeat surveys can establish a context for temporally dynamic processes, describing trends before and after a target survey, and can functionally expand the period of sampling to increase the likelihood that targeted events are captured within the period (Fig. 1). High-frequency monitoring may also capture short-term temporal factors, like within-day effects of tide, weather and diel cycle, and multi-day occupancy patterns, like conspecific recruitment to haul-out sites, time-partitioned occupancy by different age–sex classes (Le Boeuf & Laws 1994), and the balance of foraging and fasting activities among territorial males and lactating females on the rookery (Champagne et al. 2012). These advantages of repeat and on-demand drone surveys apply most obviously to research questions concerning demography, which often require temporal and phenological context to interpret counts and surveys, but high-frequency observations can also reveal the balance and budget of energetically costly behaviours across aggregated groups of pinnipeds, especially during reproductive periods (Costa 1991). The spatial context of repeat drone imagery may still further describe spatiotemporal processes of on-land behaviour, such as territoriality, sociality, and early behavioural ontogeny as they unfold across land or ice habitats. Drones can record these processes with spatial detail and at aggregate scales not typically achieved by conventional methods at ground level.

SPATIAL COVERAGE AND RESOLUTION

Drone imagery expands on the legacy of aerial photography – a long-established tool of wildlife biology (Leedy 1948, Jolly 1969). Occupied aircraft have been used to survey and estimate pinniped populations since the era of industrial sealing (Bartlett 1929), exploiting aerial perspectives to scout large regions of land or ice habitat at a time. Today, high-resolution satellites provide even greater spatial coverage of pinniped habitats (LaRue et al. 2011, Rodolfi et al. 2022), with advantages that include automated and relatively passive data collection, once sensors are placed

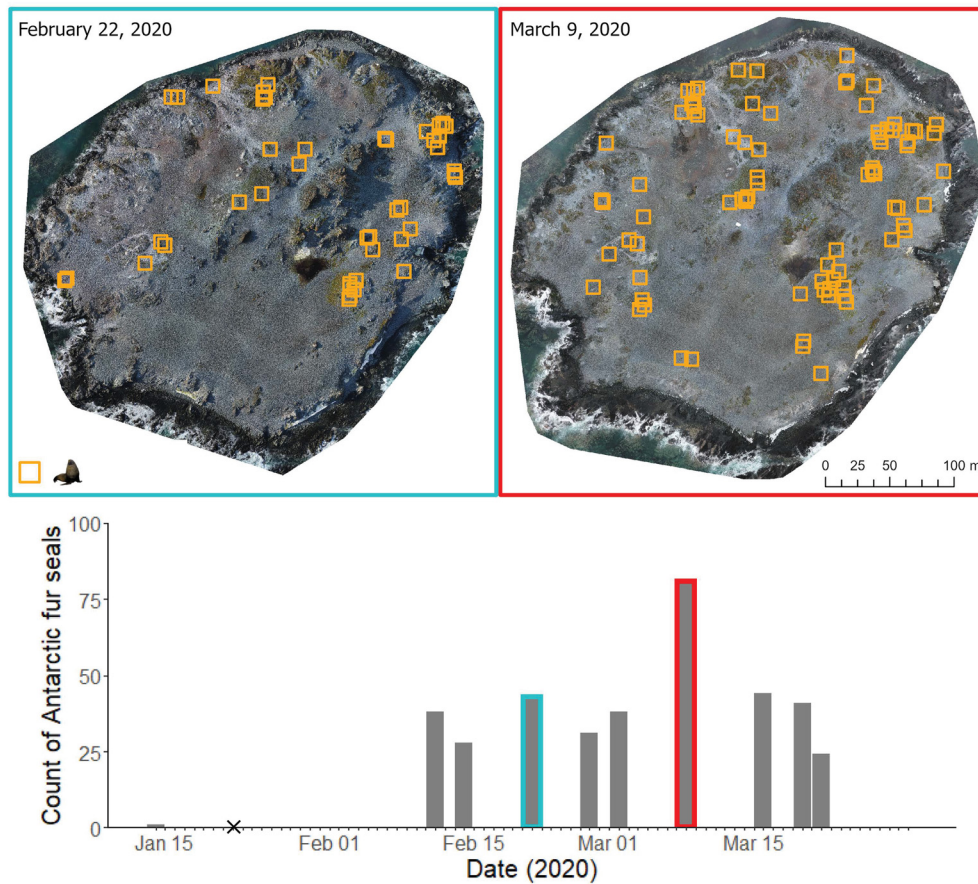


Fig. 1. Example drone orthomosaics (top) describe changes in abundance and occupancy of Antarctic fur seals (*Arctocephalus gazella*, orange squares) on Torgersen Island, Antarctica (64°44'49" S, 64°4'24" W) in summer 2020. Orthomosaics show imagery from February 22 and March 9 with total counts (bottom) from 11 drone surveys during January–March 2020. Repeat drone surveys, here, provide temporal context that informs estimates of both the timing and abundance of seals at this site.

in orbit, and regular coverage that depends on the satellite's orbit and revisit period, though this is reduced by coincident cloud cover. Imagery from occupied aircraft regularly achieves GSDs and quality necessary to distinguish seals in their ice or land habitats (Johnston et al. 2017) and, under select circumstances, very high-resolution satellite imagery can enable the same (LaRue et al. 2017).

In this context, the spatial data that drones collect are distinguished chiefly by their resolution, coverage and topographic accuracy compared with alternative imagery. Densely structured flight plans, enabled by GNSS and the absence of a human occupant, can rapidly achieve exhaustive overhead coverage at nadir or near-nadir camera angles over an entire habitat, reconstructing complex terrain (Kyriou et al. 2021) and reducing animal occlusion behind terrain relief. Additionally, custom flight plans or manual operations can achieve oblique camera angles to locate animals inside caves, crevices or overhangs. Such robust coverage is often impossible from an orbital perspective (LaRue et al. 2017), and uncommon from occupied

aircraft, which are limited by their higher operating altitudes and lower manoeuvrability. High-resolution sensors at low altitudes (<400 m) document habitat, flora and fauna at GSDs sufficient for visual and automated interpretation (Fig. 2), and overlap between images within a survey enables structure-from-motion methods that can be used to model high-resolution 3D surface models of habitats and to orthorectify imagery to more accurately represent locations and spatial relationships among features of interest (Fig. 3; Nex & Remondino 2014).

The spatial qualities of drone data provide clear benefits for demographic and abundance surveys by obviating the potential bias of undercounting in complex terrain, where animals may be partially or completely hidden from non-nadir perspectives. Additionally, high-resolution mapping products and orthorectified positional data can reveal precise, fine-scale relationships between pinnipeds and landcover or physical topography that might not resolve in comparable stereoscopic products from high-altitude aerial photography or satellite imagery (Larsen et al. 2022b).

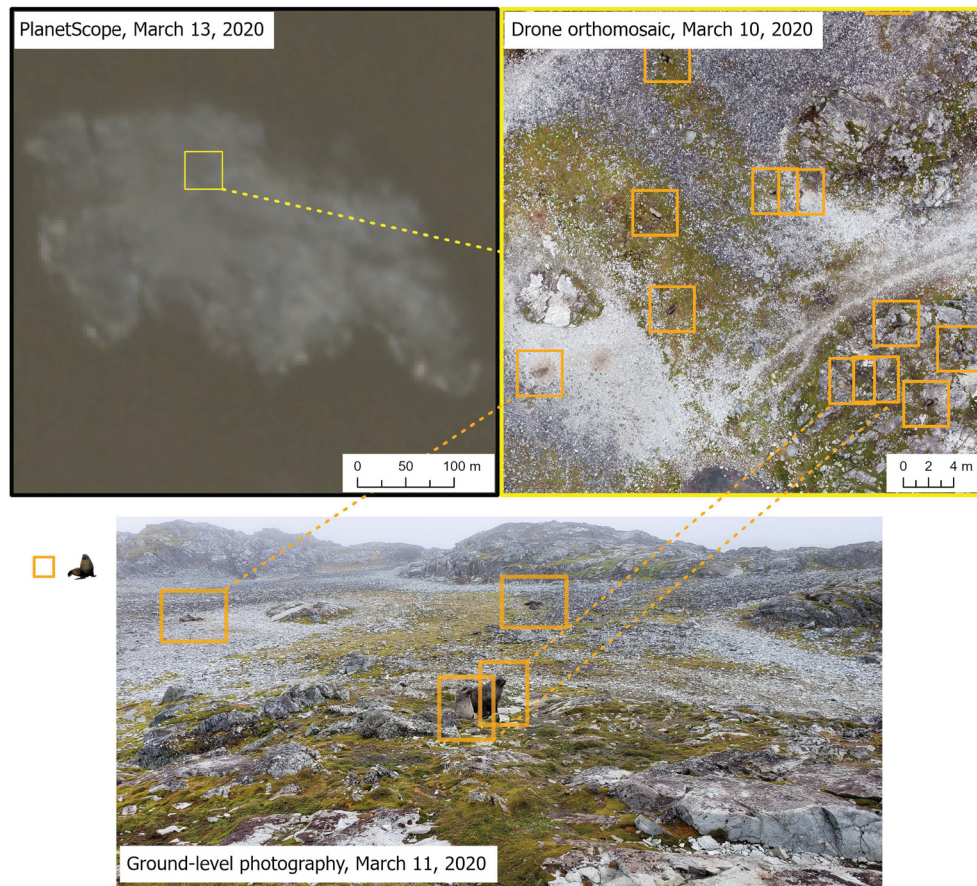


Fig. 2. Near-contemporaneous satellite, drone and ground photography demonstrate differences in resolution and spatial context between imaging modes. A PlanetScope image (top left) describes Humble Island ($64^{\circ}44'20''$ S, $64^{\circ}5'9''$ W) in 3.125 m GSD, here subset from a 25-km swath-width that can provide regional context. A drone orthomosaic (top right) describes landforms, flora and Antarctic fur seals (orange boxes) in 1.3 cm GSD, here subset from a survey of the entire island. A ground-level photograph, captured on a Samsung Galaxy S9+ smartphone camera, shows Antarctic fur seals within the landscape at varying distances. Individual seals can be identified with high confidence in both drone imagery and ground imagery (orange dashed lines) based on their pelage and locations. PlanetScope image ID: 3226192_2009012_2020-03-13_1054.

Such species–habitat relationships can reveal preferences and limitations of pinniped habitat selection that might be driven by terrestrial locomotive ability (Beentjes 1990, Garrett & Fish 2015, Fish 2018) or thermoregulatory behaviours (White & Odell 1971, Liwanag et al. 2014, Montero-Serra et al. 2014, Chaise et al. 2018), linking individual energetic costs to emergent patterns of terrestrial occupancy. The higher GSDs of drone imagery additionally facilitate the location of camouflaged species, morphs, and age-classes, and discrimination between species and age-classes that can appear similar at coarser resolutions (Johnston et al. 2017, Rexer-Huber & Parker 2020). At highest image quality, drone imagery can even be used to locate and quantify marine debris entanglements and interactions with fishing gear (McIntosh et al. 2018), and depending on animal postures, may enable identification of individuals based on brands (Sweeney et al. 2016), scarring, flipper tags (Hodgson et al. 2020), and pelage

characteristics (Fig. 2), or the classification of pups by moult stage (Johnston et al. 2017, den Heyer et al. 2021).

MORPHOMETRIC PHOTOGRAMMETRY

Photogrammetry – measuring objects from a photograph – is a technique that predates drones and even digital photography, but has become more common, accessible and advanced in their wake (Linder 2009). Simple 2D measurements can be estimated from a photograph, if the camera's focal length and distance-from-object are known, and drones enable this process from aerial perspectives. Distance-from-object can be informed by the drone's positional data from GNSS, triangulation among images with shared features, barometric altimetry, a time-linked laser range-finder, or some combination of these measurements – all of which provide different degrees of confidence that can be encoded with imagery and spatial data products

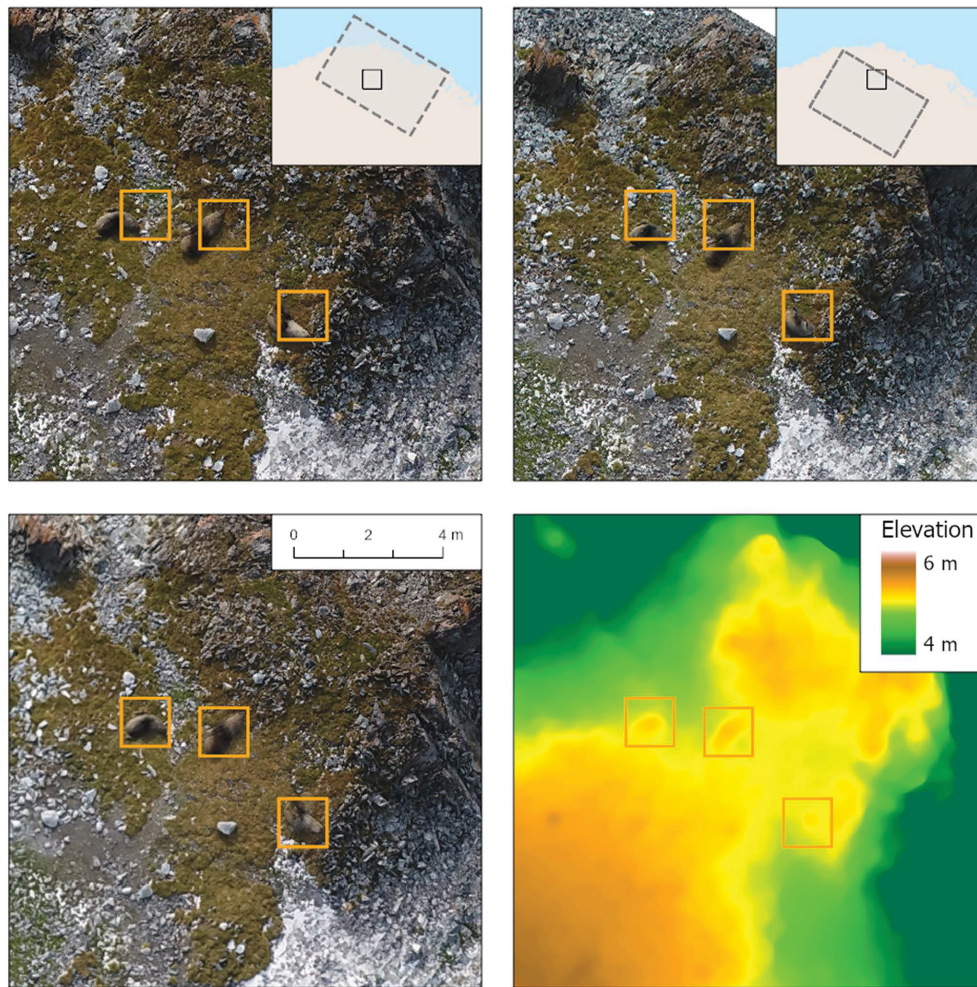


Fig. 3. Unprocessed drone imagery and corrected photogrammetric products illustrate orthorectification at ultra-fine scales. Uncorrected photographs (top) show visible displacement of seals from their true locations (orange boxes) resulting from the parallax between different camera perspectives. Insets show the subset location (black square) within the footprint of its source photograph (grey-dashed rectangle). Orthorectified imagery (bottom left) shows the true relationships among features in Euclidean space. A derived DEM (bottom right) describes the topography of those features. Imagery is subsetting from a survey of Torgersen Island (64°44'49" S, 64°4'24" W), captured on March 23, 2020.

(Bierlich et al. 2021). When serial imagery is captured across multiple locations, drones enable yet more complex photogrammetric analyses from derived products: many 2D measurements can be estimated from orthomosaics rectified to a known GSD, and 3D volumetry can be estimated using structure-from-motion models with a stationary individual (Postma et al. 2015).

Photogrammetry has been applied to pinnipeds at ground level under a variety of scenarios for both 2D and 3D measurements (reviewed in Hodgson et al. 2020), but drone-specific applications remain few and experimental. First attempts have demonstrated success with 2D measurements from single photographs (Krause et al. 2017, Alvarado et al. 2020), 2D measurements from orthomosaics (Fig. 4; Allan et al. 2019, Hodgson et al. 2020, Infantes et al. 2022), and 3D measurements from

structure-from-motion models (Hodgson et al. 2020, Shero et al. 2021). Such studies generally require validation against conventional ground-truth measurements with captured animals to confirm the veracity of photogrammetric methods (Krause et al. 2017, Alvarado et al. 2020) – though, at sufficient sample sizes, UAS-derived measurements have been validated against archival ground-truth measurements of a comparable sample (Allan et al. 2019). Critically, most measurements are sensitive to animal posture and, depending on the technique and number of photographs needed, animal activity (Shero et al. 2021), and care is required when relating 2D indices or 3D volumetry to mass, body condition, and physiological attributes (Hodgson et al. 2020, Shero et al. 2021). Within these provisions, however, drone imagery encodes an abundance of morphometric information about imaged animals, and

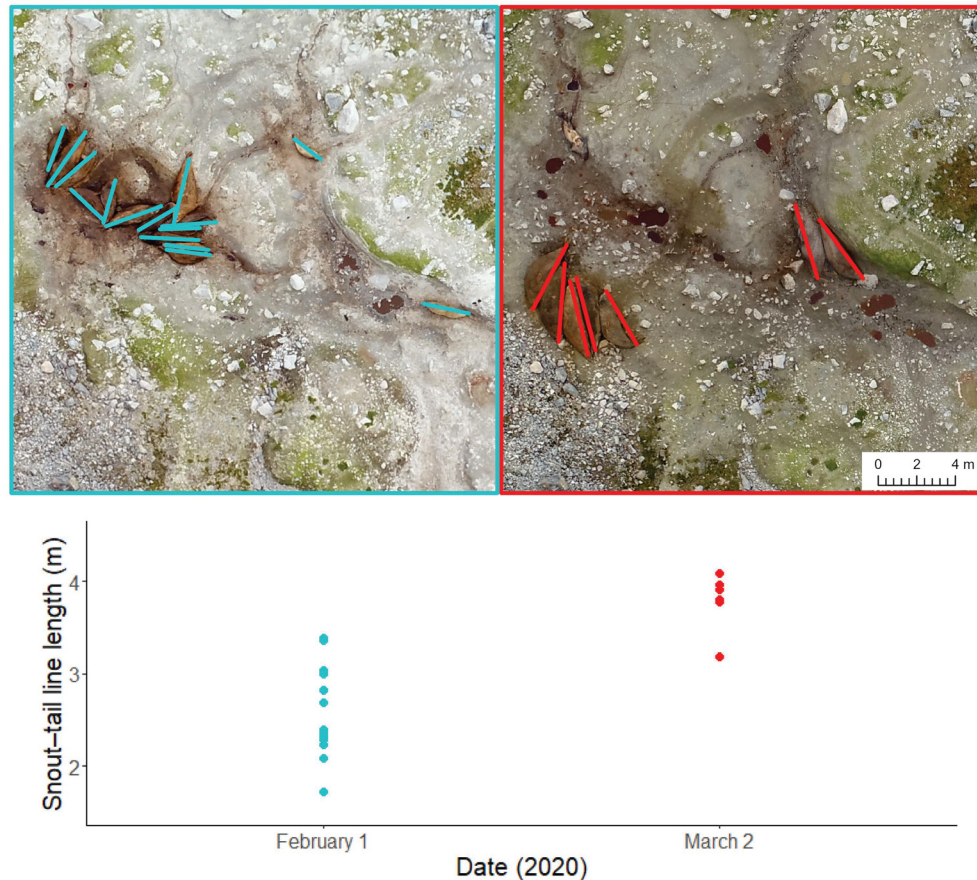


Fig. 4. Example orthomosaic imagery (top) describes the presence and approximate lengths of southern elephant seals (*Mirounga leonina*) across multiple drone surveys of Amsler Island, Antarctica ($64^{\circ}44'16''$ S, $64^{\circ}3'55''$ W) in summer 2020. Orthomosaics allow measurements of seals, here a coarse snout-tail straight line, based on the known GSD of the imagery. Repeat measurements at the same site reveal potential differences in occupancy with respect to abundance and age-classes as the region shifted from the peak moulting period of cows and juveniles (late December to early February) towards the peak moulting period of bulls (early March to late April), as has been described previously for more northerly rookeries.

with increased image quality, refined photogrammetric modelling algorithms, calibrated relationships among morphometric indices, and dynamic physiological models, drone photogrammetry may become an increasingly valuable method of non-invasively canvassing pinniped populations for both focal and aggregate distributions of size and condition.

COMPUTER VISION AND DEEP LEARNING

Drone surveys of wildlife produce abundant, high-resolution image-type data that are conventionally interpreted visually by humans, but computer vision techniques can ease the burden of image interpretation (Weinstein 2018), especially where deep learning methods can capitalise on growing archival collections for training data. Early computer-aided wildlife surveys exploited high contrast between select species and their backgrounds to locate and count animals using a simple thresholding

technique (Bajzak & Piatt 1990). Today, similar thresholding methods can be used with thermal (Beaver et al. 2020) and multispectral sensors (Colefax et al. 2021) to overcome the potential lack of contrast in the visible-light spectrum. This is facilitated by the capacity of drone platforms to support modular or customisable payloads. In the absence of suitably high contrast, however, convolutional neural networks (CNNs) can be trained to detect focal objects in remotely sensed data with high success (Zhu et al. 2017), leveraging spatial context and multiscale feature representation to extract and discriminate targets from background and alternative classes. There are many bespoke examples of CNNs achieving satisfactory or higher success in tasks of wildlife detection (reviewed in Kellenberger et al. 2018, Corcoran et al. 2021), and generalisable workflows are beginning to emerge for diverse wildlife research scenarios (Kellenberger et al. 2020, Koger et al. 2023). However, implementation is often still hindered by a high threshold

of requisite technological ability and mismatches of scale between demonstration scenarios and practical applications (Lyons et al. 2019).

Some current drone applications with pinnipeds leverage thermal or multispectral imagery to facilitate detection by high contrast in drone imagery (Seymour et al. 2017, Sweeney et al. 2019, Larsen et al. 2022b), but many more studies rely exclusively on visible-light photography to detect pinnipeds. With visible-light aerial imagery, deep learning techniques have already been applied to estimate aggregate pinniped counts (Hoekendijk et al. 2021), detect individual pinnipeds (Dujon et al. 2021), and classify pinnipeds by age class (Salberg 2015, Infantes et al. 2022), though success and generalisability vary widely between examples. Upcoming applications also include deep learning for photogrammetry, as has already been demonstrated with drone-based photography of cetaceans (Gray et al. 2019) and more recently with harbour seals (Infantes et al. 2022), and deep learning for individual identification, as has been demonstrated with ground-based photography of harbour seals (Nepovinnikh et al. 2018, 2022, Birenbaum et al. 2022). In this early stage of its technological deployment, deep learning for computer vision remains an experimental technique in pinniped research, and still few examples characterise its error and generalisability across large-scale applications. As implementations coalesce around useful software and prioritised research objectives, researchers will need to establish best practices to guide data acquisition and curation for model training, tuning model performance, and accurately estimating model error. In the absence of such guidance, deep learning can still enhance accuracy and efficiency by complementing, rather than replacing, human interpretation.

FUTURE POTENTIAL

New drone methodologies for pinniped research will undoubtedly emerge from these strengths and others yet to be recognised. Considering this ongoing evolution of the technology and its applications, a particular strength of drone methods is that they record a wealth of information, often far exceeding a mission's precise objective. Spatially referenced images with metadata and flight logs encode rich contextual information in digital formats that are often ready for archival or distribution before processing. If preserved, raw data products can be reprocessed and reanalysed as downstream methods continue to improve. Best practices and standards are still emerging for collection, storage and distribution of drone data, but even within local repositories, growing collections of drone imagery and products can facilitate new analyses across

spatial and temporal dimensions, satisfying methods that require large datasets for model training or rigorous statistical tests.

LIMITATIONS

Amid their promising potential, drones are not appropriate for all scenarios, and, notably, drone applications often complement rather than replace conventional and alternative methodologies. Remote sensing methods, by definition, collect data at a distance through the spectra and media that they monitor (Campbell & Wynne 2011), and cannot replace many in situ methods. Drone methods have recently accomplished scientific interactions with large animals at short distances, such as tag deployment (Zak et al. 2022) and blow sampling from whales (Pirotta et al. 2017); but similar techniques have not been demonstrated for pinnipeds and would likely incur significant disturbance to target and nearby animals from a drone's acoustic and visual profile at close proximity in open air (Duporge et al. 2021).

The risk of wildlife disturbance represents a major concern in drone applications (Mulero-Pázmány et al. 2017); however, multiple studies have demonstrated drone surveillance over pinnipeds while noting little or no disturbance (Arona et al. 2018, McIntosh et al. 2018). Experimental exposures suggest that flights above 30m are unlikely to cause significant disturbance to many species (Pomeroy et al. 2015, Mustafa et al. 2018, Krause et al. 2021, Laborie et al. 2021), and increasingly quiet drones may further reduce disturbance at closer distances (Duporge et al. 2021). Ultimately, advisable altitudes depend on the choice of drone and the choice of species, accounting for the potential sensory and behavioural sensitivity of an individual in its environment and life history stage (Duporge et al. 2021). In all scenarios, the risk of disturbance from drones should be weighed against the risk from alternative possible methodologies (Moreland et al. 2015, McIntosh et al. 2018, Krause et al. 2021, Laborie et al. 2021), and aspects of study design can further reduce the risk of disturbance from drones (Mo & Bonatakis 2021).

Beyond potential disturbance, many other factors can disqualify drones from a study's design. Battery life limits the range and duration of drone flights, such that most cannot achieve the larger range and extent that is commonly collected from occupied aircraft (Colefax et al. 2021). Drones often must be transported to survey sites or adjacent launch sites by boat or aircraft, potentially incurring costs and disturbance beyond that of the drone. Where drones are scientifically appropriate, local regulations may restrict the airspace, pilot qualification, or choice of aircraft for a study (Floreano & Wood 2015,

Linchant et al. 2015, Crutsinger et al. 2016, Newman 2017). Like any complex technology, drones also require training and expertise for safe operation and maintenance. The selection of a drone-based methodology should follow careful consideration of research objectives, available expertise and resources, regulatory context, and potential risks to researchers, animals – both focal and non-target individuals – and the environment.

CONCLUSIONS

Drones constitute a new frontier in wildlife biology that, like other recent technological advancements, heralds transformative, transdisciplinary opportunities for both methods and theory in the study of pinnipeds. Though increasingly common, many drone applications remain at the scale of ‘proofs of concept’ or direct substitution for conventional research methods, like annual population counts. As practitioners refine and scale drone techniques towards their logistical and technological limits, pinniped researchers can begin to fully utilise the advantages of drone systems: their unique combination of large spatial coverage, ultra-fine resolution, simple and rapid deployment, and ease of customisation. Downstream opportunities of drone imagery include structure-from-motion and orthorectified spatial products, precise 2D and 3D photogrammetry, computer vision, and yet-to-be imagined applications for data with such rich abundance, detail, metadata, and archival potential. These advancements will complement other research themes by integrating previously independent data streams from complementary measurement and monitoring techniques, pioneering new syntheses and transforming the field towards further integrated, multiscale themes of research and management. Such integration is already taking place in the adjacent field of cetacean research, where drone measurements have been calibrated and integrated alongside biologging and biomechanical models to reveal new evolutionary and ecological insights (Goldbogen et al. 2019, Savoca et al. 2021, Cade et al. 2023). As new methods and standards emerge for the use of drones in research, scientists must advance applications towards the scales of management objectives and statistical rigour by validating potential methods, highlighting current limitations, and testing new applications beyond the current frontiers of pinniped research.

ACKNOWLEDGEMENTS

We thank Andrew J. Read, Ari S. Friedlaender, and Jennifer J. Swenson for their input on the conceptualisation of this manuscript, and Duke University and Wake Forest University for their institutional support during the writing of this manuscript. We also thank the journal editors

and anonymous reviewers whose feedback improved this manuscript before publication.

REFERENCES

- Allan BM, Ierodiaconou D, Hoskins AJ, Arnould JPY (2019) A rapid UAV method for assessing body condition in fur seals. *Drones* 3: 24. <https://doi.org/10.3390/drones3010024>
- Alvarado DC, Robinson PW, Frasson NC, Costa DP, Beltran RS (2020) Calibration of aerial photogrammetry to estimate elephant seal mass. *Marine Mammal Science* 36: 1347–1355. <https://doi.org/10.1111/mms.12714>
- Arona L, Dale J, Heaslip SG, Hammill MO, Johnston DW (2018) Assessing the disturbance potential of small unoccupied aircraft systems (UAS) on gray seals (*Halichoerus grypus*) at breeding colonies in Nova Scotia, Canada. *PeerJ* 6: e4467. <https://doi.org/10.7717/peerj.4467>
- Bajzak D, Piatt JF (1990) Computer-aided procedure for counting waterfowl on aerial photographs. *Wildlife Society Bulletin* (1973–2006) 18: 125–129.
- Bartlett RA (1929) The sealing saga of Newfoundland. *National Geographic* 56: 91–130.
- Beaver JT, Baldwin RW, Messinger M, Newbolt CH, Ditchkoff SS, Silman MR (2020) Evaluating the use of drones equipped with thermal sensors as an effective method for estimating wildlife. *Wildlife Society Bulletin* 44: 434–443. <https://doi.org/10.1002/wsb.1090>
- Beentjes MP (1990) Comparative terrestrial locomotion of the Hooker's sea lion (*Phocartos hookeri*) and the New Zealand fur seal (*Arctocephalus forsteri*): evolutionary and ecological implications. *Zoological Journal of the Linnean Society* 98: 307–325. <https://doi.org/10.1111/j.1096-3642.1990.tb01204.x>
- Berta A (2018) Pinnipeds. In: Würsig B, Thewissen JGM, Kovacs KM (eds) *Encyclopedia of Marine Mammals*, 733–740. 3rd ed. Academic Press, London, UK.
- Bierlich KC, Schick RS, Hewitt J, Dale J, Goldbogen JA, Friedlaender AS, Johnston DW (2021) Bayesian approach for predicting photogrammetric uncertainty in morphometric measurements derived from drones. *Marine Ecology Progress Series* 673: 193–210. <https://doi.org/10.3354/meps13814>
- Birenbaum Z, Do H, Horstmyer L, Orff H, Ingram K, Ay A (2022) SEALNET: facial recognition software for ecological studies of harbor seals. *Ecology and Evolution* 12: e8851. <https://doi.org/10.1002/ece3.8851>
- Bossart GD (2011) Marine mammals as sentinel species for oceans and human health. *Veterinary Pathology* 48: 676–690. <https://doi.org/10.1177/0300985810388525>
- Bowen WD (2018) Pinniped ecology. In: Würsig B, Thewissen JGM, Kovacs KM (eds) *Encyclopedia of Marine Mammals*, 705–712. 3rd ed. Academic Press, London, UK.
- Cade DE, Kahane-Rapport SR, Gough WT, Bierlich KC, Linsky JMJ, Calambokidis J, Johnston DW, Goldbogen JA, Friedlaender AS (2023) Minke whale feeding rate

- limitations suggest constraints on the minimum body size for engulfment filtration feeding. *Nature Ecology & Evolution* 7: 535–546. <https://doi.org/10.1038/s41559-023-01993-2>
- Campbell JB, Wynne RH (2011) *Introduction to Remote Sensing*. 5th ed. Guilford Press, New York City, New York, USA.
- Chabot D, Bird DM (2015) Wildlife research and management methods in the 21st century: where do unmanned aircraft fit in? *Journal of Unmanned Vehicle Systems* 3: 137–155. <https://doi.org/10.1139/juvs-2015-0021>
- Chaise LL, Prinot I, Toscani C, Gallon SL, Paterson W, McCafferty DJ, Théry M, Ancel A, Gilbert C (2018) Local weather and body condition influence habitat use and movements on land of molting female southern elephant seals (*Mirounga leonina*). *Ecology and Evolution* 8: 6081–6090. <https://doi.org/10.1002/ece3.4049>
- Champagne CD, Crocker DE, Fowler MA, Houser DS (2012) Fasting physiology of the pinnipeds: the challenges of fasting while maintaining high energy expenditure and nutrient delivery for lactation. In: McCue MD (ed) *Comparative Physiology of Fasting, Starvation, and Food Limitation*, 309–336. Springer, Berlin, Germany.
- Christie KS, Gilbert SL, Brown CL, Hatfield M, Hanson L (2016) Unmanned aircraft systems in wildlife research: current and future applications of a transformative technology. *Frontiers in Ecology and the Environment* 14: 241–251. <https://doi.org/10.1002/fee.1281>
- Colefax AP, Kelaher BP, Walsh AJ, Purcell CR, Pagendam DE, Cagnazzi D, Butcher PA (2021) Identifying optimal wavelengths to maximise the detection rates of marine fauna from aerial surveys. *Biological Conservation* 257: 109102. <https://doi.org/10.1016/j.biocon.2021.109102>
- Corcoran E, Winsen M, Sudholz A, Hamilton G (2021) Automated detection of wildlife using drones: synthesis, opportunities and constraints. *Methods in Ecology and Evolution* 12: 1103–1114. <https://doi.org/10.1111/2041-210X.13581>
- Corlett RT (2017) A bigger toolbox: biotechnology in biodiversity conservation. *Trends in Biotechnology* 35: 55–65. <https://doi.org/10.1016/j.tibtech.2016.06.009>
- Costa DP (1991) Reproductive and foraging energetics of pinnipeds: implications for life history patterns. In: Renouf D (ed) *The Behaviour of Pinnipeds*, 300–344. Springer, Dordrecht, the Netherlands.
- Crutsinger GM, Short J, Sollenberger R (2016) The future of UAVs in ecology: an insider perspective from the Silicon Valley drone industry. *Journal of Unmanned Vehicle Systems* 4: 161–168. <https://doi.org/10.1139/juvs-2016-0008>
- Dujon AM, Ierodiaconou D, Geeson JJ, Arnould JPY, Allan BM, Katselidis KA, Schofield G (2021) Machine learning to detect marine animals in UAV imagery: effect of morphology, spacing, behaviour and habitat. *Remote Sensing in Ecology and Conservation* 7: 341–354. <https://doi.org/10.1002/rse2.205>
- Duporge I, Spiegel MP, Thomson ER, Chapman T, Lamberth C, Pond C, Macdonald DW, Wang T, Klinck H (2021) Determination of optimal flight altitude to minimise acoustic drone disturbance to wildlife using species audiograms. *Methods in Ecology and Evolution* 12: 2196–2207. <https://doi.org/10.1111/2041-210X.13691>
- Fish FE (2018) Locomotion, terrestrial. In: Würsig B, Thewissen JGM, Kovacs KM (eds) *Encyclopedia of Marine Mammals*, 552–554. 3rd ed. Academic Press, London, UK.
- Floreano D, Wood RJ (2015) Science, technology and the future of small autonomous drones. *Nature* 521: 460–466. <https://doi.org/10.1038/nature14542>
- Fossi MC, Panti C (2017) *Sentinel Species of Marine Ecosystems*. Oxford Research Encyclopedia of Environmental Science, Oxford, UK.
- Garrett JN, Fish FE (2015) Kinematics of terrestrial locomotion in harbor seals and gray seals: importance of spinal flexion by amphibious phocids. *Marine Mammal Science* 31: 459–478. <https://doi.org/10.1111/mms.12170>
- Goldbogen JA, Cade DE, Wisniewska DM, Potvin J, Segre PS, Savoca MS et al. (2019) Why whales are big but not bigger: physiological drivers and ecological limits in the age of ocean giants. *Science* 366: 1367–1372. <https://doi.org/10.1126/science.aax9044>
- Gray PC, Bierlich KC, Mantell SA, Friedlaender AS, Goldbogen JA, Johnston DW (2019) Drones and convolutional neural networks facilitate automated and accurate cetacean species identification and photogrammetry. *Methods in Ecology and Evolution* 10: 1490–1500. <https://doi.org/10.1111/2041-210X.13246>
- den Heyer CE, Bowen WD, Dale J, Gosselin J-F, Hammill MO, Johnston DW, Lang SLC, Murray KT, Stenson GB, Wood SA (2021) Contrasting trends in gray seal (*Halichoerus grypus*) pup production throughout the increasing northwest Atlantic metapopulation. *Marine Mammal Science* 37: 611–630. <https://doi.org/10.1111/mms.12773>
- Hind AT, Gurney W (1998) Are there thermoregulatory constraints on the timing of pupping for harbour seals? *Canadian Journal of Zoology* 76: 2245–2254. <https://doi.org/10.1139/z98-181>
- Hochachka PW (2000) Pinniped diving response mechanism and evolution: a window on the paradigm of comparative biochemistry and physiology. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology* 126: 435–458. [https://doi.org/10.1016/S1095-6433\(00\)00231-2](https://doi.org/10.1016/S1095-6433(00)00231-2)
- Hodgson JC, Holman D, Terauds A, Koh LP, Goldsworthy SD (2020) Rapid condition monitoring of an endangered marine vertebrate using precise, non-invasive morphometrics. *Biological Conservation* 242: 108402. <https://doi.org/10.1016/j.biocon.2019.108402>

- Hoekendijk JPA, Kellenberger B, Aarts G, Brasseur S, Poiesz SSH, Tuia D (2021) Counting using deep learning regression gives value to ecological surveys. *Scientific Reports* 11: 23209. <https://doi.org/10.1038/s41598-021-02387-9>
- Infantes E, Carroll D, Silva WTAF, Härkönen T, Edwards SV, Harding KC (2022) An automated work-flow for pinniped surveys: a new tool for monitoring population dynamics. *Frontiers in Ecology and Evolution* 10: 905309. <https://doi.org/10.3389/fevo.2022.905309>
- Jiménez López J, Mulero-Pázmány M (2019) Drones for conservation in protected areas: present and future. *Drones* 3: 10. <https://doi.org/10.3390/drones3010010>
- Johnston DW (2019) Unoccupied aircraft systems in marine science and conservation. *Annual Review of Marine Science* 11: 439–463. <https://doi.org/10.1146/annurev-marine-010318-095323>
- Johnston DW, Dale J, Murray KT, Josephson E, Newton E, Wood S (2017) Comparing occupied and unoccupied aircraft surveys of wildlife populations: assessing the gray seal (*Halichoerus grypus*) breeding colony on Muskeget Island, USA. *Journal of Unmanned Vehicle Systems* 5: 178–191. <https://doi.org/10.1139/juvs-2017-0012>
- Jolly GM (1969) Sampling methods for aerial censuses of wildlife populations. *East African Agricultural and Forestry Journal* 34(Suppl 1): 46–49. <https://doi.org/10.1080/00128325.1969.11662347>
- Jones GP, Pearlstone LG, Percival HF (2006) An assessment of small unmanned aerial vehicles for wildlife research. *Wildlife Society Bulletin (1973–2006)* 34: 750–758.
- Kellenberger B, Marcos D, Tuia D (2018) Detecting mammals in UAV images: best practices to address a substantially imbalanced dataset with deep learning. *Remote Sensing of Environment* 216: 139–153. <https://doi.org/10.1016/j.rse.2018.06.028>
- Kellenberger B, Tuia D, Morris D (2020) AIDE: accelerating image-based ecological surveys with interactive machine learning. *Methods in Ecology and Evolution* 11: 1716–1727. <https://doi.org/10.1111/2041-210X.13489>
- Koger B, Deshpande A, Kerby JT, Graving JM, Costelloe BR, Couzin ID (2023) Quantifying the movement, behaviour and environmental context of group-living animals using drones and computer vision. *Journal of Animal Ecology* 92: 1357–1371. <https://doi.org/10.1111/1365-2656.13904>
- Koh LP, Wich SA (2012) Dawn of drone ecology: low-cost autonomous aerial vehicles for conservation. *Tropical Conservation Science* 5: 121–132. <https://doi.org/10.1177/194008291200500202>
- Krause DJ, Hinke JT (2021) Finally within reach: a drone census of an important, but practically inaccessible, Antarctic fur seal colony. *Aquatic Mammals* 47: 349–354. <https://doi.org/10.1578/AM.47.4.2021.349>
- Krause DJ, Hinke JT, Perryman WL, Goebel ME, LeRoi DJ (2017) An accurate and adaptable photogrammetric approach for estimating the mass and body condition of pinnipeds using an unmanned aerial system. *PLoS ONE* 12: e0187465. <https://doi.org/10.1371/journal.pone.0187465>
- Krause DJ, Hinke JT, Goebel ME, Perryman WL (2021) Drones minimize Antarctic predator responses relative to ground survey methods: an appeal for context in policy advice. *Frontiers in Marine Science* 8: 648772. <https://doi.org/10.3389/fmars.2021.648772>
- Kyriou A, Nikolakopoulos K, Koukouvelas I (2021) How image acquisition geometry of UAV campaigns affects the derived products and their accuracy in areas with complex geomorphology. *ISPRS International Journal of Geo-Information* 10: 408. <https://doi.org/10.3390/ijgi10060408>
- Laborie J, Christiansen F, Beedholm K, Madsen PT, Heerah K (2021) Behavioural impact assessment of unmanned aerial vehicles on Weddell seals (*Leptonychotes weddellii*). *Journal of Experimental Marine Biology and Ecology* 536: 151509. <https://doi.org/10.1016/j.jembe.2020.151509>
- Lahoz-Monfort JJ, Magrath MJL (2021) A comprehensive overview of technologies for species and habitat monitoring and conservation. *Bioscience* 71: 1038–1062. <https://doi.org/10.1093/biosci/biab073>
- Larsen GD, Falvo C, Tuohy C, Goerke M, Friedlaender AS, Nichols RC, et al. (2022a) Aerial data from drone surveys of coastal habitats on the West Antarctic Peninsula during austral summer (January–March 2020 and February–March 2019). [Data set]. *Duke Research Data Repository*. <https://doi.org/10.7924/R4SF2XS2W>
- Larsen GD, Seymour AC, Richmond EL, Divine LM, Moreland EE, Newton E, London JM, Johnston DW (2022b) Drones reveal spatial patterning of sympatric Alaskan pinniped species and drivers of their local distributions. *Drone Systems and Applications* 10: 235–255. <https://doi.org/10.1139/dsa-2021-0050>
- LaRue MA, Rotella JJ, Garrott RA, Siniff DB, Ainley DG, Stauffer GE, Porter CC, Morin PJ (2011) Satellite imagery can be used to detect variation in abundance of Weddell seals (*Leptonychotes weddellii*) in Erebus Bay, Antarctica. *Polar Biology* 34: 1727–1737. <https://doi.org/10.1007/s00300-011-1023-0>
- LaRue MA, Stapleton S, Anderson M (2017) Feasibility of using high-resolution satellite imagery to assess vertebrate wildlife populations. *Conservation Biology* 31: 213–220. <https://doi.org/10.1111/cobi.12809>
- Le Boeuf BJ, Laws RM (eds) (1994) Elephant seals: an introduction to the genus. In: *Elephant Seals*, 1–26. University of California Press, Berkeley, California, USA. <https://doi.org/10.1525/9780520328150-003>
- Leedy DL (1948) Aerial photographs, their interpretation and suggested uses in wildlife management. *Journal of Wildlife Management* 12: 191–210. <https://doi.org/10.2307/3796415>

- Linchant J, Lisein J, Semeki J, Lejeune P, Vermeulen C (2015) Are unmanned aircraft systems (UASs) the future of wildlife monitoring? A review of accomplishments and challenges. *Mammal Review* 45: 239–252. <https://doi.org/10.1111/mam.12046>
- Linder W (2009) *Digital Photogrammetry*, Vol. 1. Springer, Berlin, Germany.
- Liwanag HEM, Orazé J, Costa DP, Williams TM (2014) Thermal benefits of aggregation in a large marine endotherm: huddling in California sea lions. *Journal of Zoology* 293: 152–159. <https://doi.org/10.1111/jzo.12130>
- Lunn NJ, Boyd IL (1993) Effects of maternal age and condition on parturition and the perinatal period of Antarctic fur seals. *Journal of Zoology* 229: 55–67. <https://doi.org/10.1111/j.1469-7998.1993.tb02620.x>
- Lyons MB, Brandis KJ, Murray NJ, Wilshire JH, McCann JA, Kingsford RT, Callaghan CT (2019) Monitoring large and complex wildlife aggregations with drones. *Methods in Ecology and Evolution* 10: 1024–1035. <https://doi.org/10.1111/2041-210X.13194>
- McIntosh RR, Holmberg R, Dann P (2018) Looking without landing—using remote piloted aircraft to monitor fur seal populations without disturbance. *Frontiers in Marine Science* 5: 202. <https://doi.org/10.3389/fmars.2018.00202>
- McKnight JC, Boyd IL (2018) Pinniped life history. In: Würsig B, Thewissen JGM, Kovacs KM (eds) *Encyclopedia of Marine Mammals*, 722–726. 3rd ed. Academic Press, London, UK.
- Mo M, Bonatakis K (2021) Approaching wildlife with drones: using scientific literature to identify factors to consider for minimising disturbance. *Australian Zoologist* 42: 1–29. <https://doi.org/10.7882/AZ.2021.015>
- Mo M, Bonatakis K (2022) An examination of trends in the growing scientific literature on approaching wildlife with drones. *Drone Systems and Applications* 10: 111–139. <https://doi.org/10.1139/dsa-2021-0003>
- Montero-Serra I, Páez-Rosas D, Murillo JC, Vegas-Vilarrúbia T, Fietz K, Denking J (2014) Environment-driven changes in terrestrial habitat use and distribution of the Galapagos sea lion. *Endangered Species Research* 24: 9–19. <https://doi.org/10.3354/esr00573>
- Moreland EE, Cameron MF, Angliss RP, Boveng PL (2015) Evaluation of a ship-based unoccupied aircraft system (UAS) for surveys of spotted and ribbon seals in the Bering Sea pack ice. *Journal of Unmanned Vehicle Systems* 3: 114–122. <https://doi.org/10.1139/juvs-2015-0012>
- Mulero-Pázmány M, Jenni-Eiermann S, Strebel N, Sattler T, Negro JJ, Tablado Z (2017) Unmanned aircraft systems as a new source of disturbance for wildlife: a systematic review. *PLoS ONE* 12: e0178448. <https://doi.org/10.1371/journal.pone.0178448>
- Mustafa O, Barbosa A, Krause DJ, Peter H-U, Vieira G, Rümmler M-C (2018) State of knowledge: Antarctic wildlife response to unmanned aerial systems. *Polar Biology* 41: 2387–2398. <https://doi.org/10.1007/s00300-018-2363-9>
- Nepovinnikh E, Eerola T, Kälviäinen H, Radchenko G (2018) Identification of Saimaa ringed seal individuals using transfer learning. In: Blanc-Talon J, Helbert D, Philips W, Popescu D, Scheunders P (eds) *Advanced Concepts for Intelligent Vision Systems*, 211–222. Springer International Publishing, Cham, Switzerland.
- Nepovinnikh E, Chelak I, Lushpanov A, Eerola T, Kälviäinen H, Chirkova O (2022) Matching individual Ladoga ringed seals across short-term image sequences. *Mammalian Biology* 102: 957–972. <https://doi.org/10.1007/s42991-022-00229-3>
- Newman LH (2017) The army grounds its DJI drones over security concerns. *Wired*. <https://www.wired.com/story/army-dji-drone-ban/>
- Nex F, Remondino F (2014) UAV for 3D mapping applications: a review. *Applied Geomatics* 6: 1–15. <https://doi.org/10.1007/s12518-013-0120-x>
- Pirotta V, Smith A, Ostrowski M, Russell D, Jonsen ID, Grech A, Harcourt R (2017) An economical custom-built drone for assessing whale health. *Frontiers in Marine Science* 4: 425. <https://doi.org/10.3389/fmars.2017.00425>
- Pomeroy P, O'Connor L, Davies P (2015) Assessing use of and reaction to unmanned aerial systems in gray and harbor seals during breeding and molt in the UK. *Journal of Unmanned Vehicle Systems* 3: 102–113. <https://doi.org/10.1139/juvs-2015-0013>
- Postma M, Tordiffe ASW, Hofmeyr MS, Reisinger RR, Bester LC, Buss PE, de Bruyn PJN (2015) Terrestrial mammal three-dimensional photogrammetry: multispecies mass estimation. *Ecosphere* 6: 1–16. <https://doi.org/10.1890/ES15-00368.1>
- Raoult V, Colefax AP, Allan BM, Cagnazzi D, Castelblanco-Martínez N, Ierodiaconou D et al. (2020) Operational protocols for the use of drones in marine animal research. *Drones* 4: 64. <https://doi.org/10.3390/drones4040064>
- Rexer-Huber K, Parker G (2020) *Bounty Islands Drone Trials: Feasibility for Population Assessment of NZ Fur Seal*. Final Report. Conservation Services Programme, Department of Conservation, Parker Conservation.
- Robinson JM, Harrison PA, Mavoa S, Breed MF (2022) Existing and emerging uses of drones in restoration ecology. *Methods in Ecology and Evolution* 13: 1899–1911. <https://doi.org/10.1111/2041-210X.13912>
- Rodofili EN, Lecours V, LaRue M (2022) Remote sensing techniques for automated marine mammals detection: a review of methods and current challenges. *PeerJ* 10: e13540. <https://doi.org/10.7717/peerj.13540>
- Salberg A-B (2015) Detection of seals in remote sensing images using features extracted from deep convolutional neural networks. 2015 IEEE International Geoscience and

- Remote Sensing Symposium (IGARSS), 1893–1896. <https://doi.org/10.1109/IGARSS.2015.7326163>
- Savoca MS, Czapanskiy MF, Kahane-Rapport SR, Gough WT, Fahlbusch JA, Bierlich KC et al. (2021) Baleen whale prey consumption based on high-resolution foraging measurements. *Nature* 599: 85–90. <https://doi.org/10.1038/s41586-021-03991-5>
- Seymour AC, Dale J, Hammill M, Halpin PN, Johnston DW (2017) Automated detection and enumeration of marine wildlife using unmanned aircraft systems (UAS) and thermal imagery. *Scientific Reports* 7: 45127. <https://doi.org/10.1038/srep45127>
- Shero MR, Dale J, Seymour A, Hammill M, Mosnier A, Mongrain S, Johnston D (2021) Tracking wildlife energy dynamics with unoccupied aircraft systems and three-dimensional photogrammetry. *Methods in Ecology and Evolution* 12: 2458–2472. <https://doi.org/10.1111/2041-210X.13719>
- Sweeney KL, Helker VT, Perryman WL, LeRoi DJ, Fritz LW, Gelatt TS, Angliss RP (2016) Flying beneath the clouds at the edge of the world: using a hexacopter to supplement abundance surveys of Steller sea lions (*Eumetopias jubatus*) in Alaska. *Journal of Unmanned Vehicle Systems Virtual Issue* 1: 70–81. <https://doi.org/10.1139/juvs-2015-0010@juvs-vi.2016.01.issue-1>
- Sweeney KL, Padula F, Cook M, Sterling J, Towell R, Ream R, Gelatt T (2019) *Seeing the Northern Fur Seals from the Boulders: Developing an UAS Approach for Abundance Assessments* [Poster]. World Marine Mammal Conference, Barcelona, Spain.
- Temte JL (1994) Photoperiod control of birth timing in the harbour seal (*Phoca vitulina*). *Journal of Zoology* 233: 369–384. <https://doi.org/10.1111/j.1469-7998.1994.tb05271.x>
- Temte JL, Temte J (1993) Photoperiod defines the phenology of birth in captive California sea lions. *Marine Mammal Science* 9: 301–308. <https://doi.org/10.1111/j.1748-7692.1993.tb00457.x>
- Trites AW (1991) Fetal growth of northern fur seals: life-history strategy and sources of variation. *Canadian Journal of Zoology* 69: 2608–2617. <https://doi.org/10.1139/z91-367>
- Trites AW, Antonelis GA (1994) The influence of climatic seasonality on the life cycle of the Pribilof northern fur seal. *Marine Mammal Science* 10: 311–324. <https://doi.org/10.1111/j.1748-7692.1994.tb00485.x>
- Weinstein BG (2018) A computer vision for animal ecology. *Journal of Animal Ecology* 87: 533–545. <https://doi.org/10.1111/1365-2656.12780>
- White FN, Odell DK (1971) Thermoregulatory behavior of the northern elephant seal, *Mirounga angustirostris*. *Journal of Mammalogy* 52: 758–774. <https://doi.org/10.2307/1378924>
- Wirsing AJ, Johnston AN, Kiszka JJ, Wirsing AJ, Johnston AN, Kiszka JJ (2022) Foreword to the special issue on ‘the rapidly expanding role of drones as a tool for wildlife research’. *Wildlife Research* 49: i–v. <https://doi.org/10.1071/WR22006>
- Zak J, Lipari M, Lasinski N, Han S, Hausch L (2022) UAV attachment of biologging tags. *Deep Blue Documents*. <https://doi.org/10.7302/3795>
- Zhu XX, Tuia D, Mou L, Xia G-S, Zhang L, Xu F, Fraundorfer F (2017) Deep learning in remote sensing: a comprehensive review and list of resources. *IEEE Geoscience and Remote Sensing Magazine* 5: 8–36. <https://doi.org/10.1109/MGRS.2017.2762307>