Contemporary Remote Sensing Tools for Integrated Assessment and Conservation Planning of Ice-free Antarctica

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This is a non-peer reviewed pre-print submitted to EarthArXiv. This paper has been submitted to the Global Change Biology journal for review.

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Abstract: Monitoring and understanding Antarctica is critical for conservation of its values. Remote sensing has been increasingly employed to observe large areas at higher frequency than traditional monitoring methods, enabling systematic assessments at low cost. However, currently there are limitations in the ability of the available remote sensing tools to answer the most pressing scientific, ecological, and biological questions associated with anthropogenic impacts, including climate change, in Antarctica. Here we summarise the latest findings on remote sensing tools and techniques, identifying the gaps and highlighting priority areas for future development. Major ongoing challenges concern the intensive cloud coverage and ephemeral snow cover that prevent ongoing observations of ice-free areas and the fine spatial scales required to undertake assessments of terrestrial ecosystems, their biota, and the human footprint. Opportunities arise in the realms of advanced statistical techniques to harness the potential of increasingly available data from orbital satellites and Unmanned Aerial Systems also commonly known as drones, at multiple scales and resolutions. We conclude that harnessing emerging technological advances in remote sensing will enable new understanding and ultimately protection of Antarctic ecosystems.

1. Introduction

Antarctica is relatively pristine and collaboratively protected (The Antarctic Treaty System, 1961), yet its ecosystems are subject to persistent ongoing threats and rapid changes (Robinson et al., 2020). Climatic shifts (Clem et al., 2020; Meredith et al., 2019; Turner et al., 2014), research infrastructure development, invasive species (Hughes et al., 2020; McCarthy et al., 2019), pollution, and the rapidly expanding tourism industry (IAATO, 2021) threaten Antarctic terrestrial ecosystems. Ecological impacts of climate change linked with warming in parts of Antarctica are easily detectable (Bokhorst et al., 2022; Moreau et al., 2015; Royles & Griffiths, 2015; Turner et al., 2014; Wege et al., 2021b). Feedbacks prompted by the expansion of ice-free areas (Lee et al., 2017) are a catalyst to increasing temperatures as these surfaces reduce the local albedo, with further consequences to climate and biodiversity (Amesbury et al., 2017). While major disturbances have been documented in the Antarctic Peninsula, recent studies demonstrate that the rapid effects of climatic shifts are reaching the entire Antarctic continent including areas previously thought undisturbed (Kingslake et al., 2017; Robinson et al., 2018). Therefore, now more than ever, continental scale assessments of Antarctica's ecosystems are crucial to inform the prioritization of conservation actions. Establishing continuous, systematic, long-term, and spatially adequate monitoring of this remote and harsh setting is very challenging (Sanderson, 2010). Directly monitoring Antarctica has been likened to surveying and monitoring extra-terrestrial planetary conditions (Barthels, 2020; Cassaro et al., 2021; Page, 2019; Salvatore & Levy, 2021; Sassenroth et al., 2021). Although polar environments are home to unique ecosystems, have high conservation value, and are vital for regulating global climate (British Antarctic Survey, 2017; Meredith et al., 2019; National Aeronautics and Space Administration, 2021; Norwegian Polar Institute, 2021), only a fraction has been invested in Antarctic research compared to the amount of money invested in past Mars missions (McCarthy, 2021).

Polar environments are changing rapidly (Cannone et al., 2021; Robinson et al., 2018), often outpacing our ability to determine baselines or monitor ecosystems through traditional means. Remote sensing products are relatively cheap, geographically comprehensive, and have measurable uncertainties. Satellite observations play a significant role in providing instantaneous, large-scale, and continuous products for informed decision making and for the assessment of impacts due to climate change in a broad range of ecosystems (Yang et al., 2013). Critically for Antarctica, satellite sensors provide observations in remote and difficult to reach areas, reducing field workload and associated risks to researchers. Satellites provide information at a scale unable to be determined through on ground research.

Orbital satellites and drone sensors offer sufficient capability to detect seals (LaRue et al., 2020; McMahon et al., 2014; Wege et al., 2021a), penguins (Bird et al., 2020; Cimino et al., 2013; Fretwell & Trathan, 2021; LaRue et al., 2019; Pfeifer et al., 2021), and other seabirds (Dunn et al., 2021; Southwell & Emmerson, 2015) in Antarctica and the Sub-Antarctic Islands. More recent advances reveal the potential of remote sensing observations for identifying and monitoring Antarctic photosynthetic organisms, such as grasses (Calviño-Cancela & Martín-Herrero, 2016), lichens, moss (Malenovský et al., 2017; Sotille et al., 2020; Turner et al., 2018) and even highly ephemeral snow algae blooms (Gray et al., 2020, 2021; Huovinen et al., 2018; Levy et al., 2020; Salvatore, 2015; Salvatore et al., 2020). Another emerging field of research is detecting the human footprint on ice-free areas of Antarctica (Bollard et al., 2015; Brooks et al., 2019a) with fine-scale satellite and high-resolution drone imagery.

Challenges remain in current data scales, processing methods, and analysis techniques. Spatial resolution is one critical issue for biological data, particularly in Antarctica. While Antarctic vegetation are distributed in small (< 1 m) patches, most freely available satellite imagery has spatial resolution beyond 10 meters. Although commercial satellite observations may offer sufficient spatial (< 1 m) and spectral resolve, acquisition costs largely constrain long-term assessments of rapidly changing ecological processes. Clouds pose a further challenge, resulting in critical data loss in optical satellite observations while seasonal snow cover hampers the accurate identification of ice-free areas. Drone mounted hyperspectral, multispectral, thermal and RGB sensors allow near-real time observations to be acquired at ultra-high spatial resolutions (1 cm) over regional areas but can be expensive to deploy and mostly must be accompanied by a drone operator.

Addressing these challenges will be essential for protecting Antarctica's ecosystems, which requires processing and synthesising considerable amounts of data (Nowogrodzki, 2020). Decisions about protected area management (LaRue et al., 2022), biosecurity (Bergstrom et al., 2021; Hughes et al., 2020; Smith et al., 2022), and species status (Jenouvrier et al., 2020) are all underpinned by data and data-informed models. Harnessing advanced remote sensing products is likely to lessen the cost of research and the impacts associated with field work in Antarctica, while addressing major data gaps in biodiversity and ecosystem monitoring (Leihy et al., 2020).

Here we identify current challenges to monitoring terrestrial ecosystems in Antarctica with remote sensing techniques, focused on ice-free areas. We focus on how remote sensing can assist in answering the scientific priorities for terrestrial Antarctica identified by the Antarctica and Southern Ocean Horizon Scan (Kennicutt et al., 2014): the understanding of ice sheet mass loss (melt), the expansion of ice-free areas and impacts to local biodiversity and finally, identifying large-scale direct human impacts. Then, we explore solutions currently available for these challenges. Where gaps persist, we highlight priority areas for future work in remote sensing and Antarctic research.

2. Opportunities and Challenges for Remote Sensing Antarctica

In the next subsections, we review the state of the art and challenges of monitoring and detecting changes in vegetation, water tracks, ice-free areas, and human impacts in ice-free areas of Antarctica. The temporal and spatial scales required for adequately monitoring terrestrial ecosystems in Antarctica are summarised in Figure 1. For instance, photosynthetic organisms may present diurnal to decadal changes and at sub-centimetre to meter spatial scales. These several ranges of scales may be collectively covered with ground-based observations, drones, nano, and large orbital satellites. Nano satellites bridge the gap between large satellites and drones.

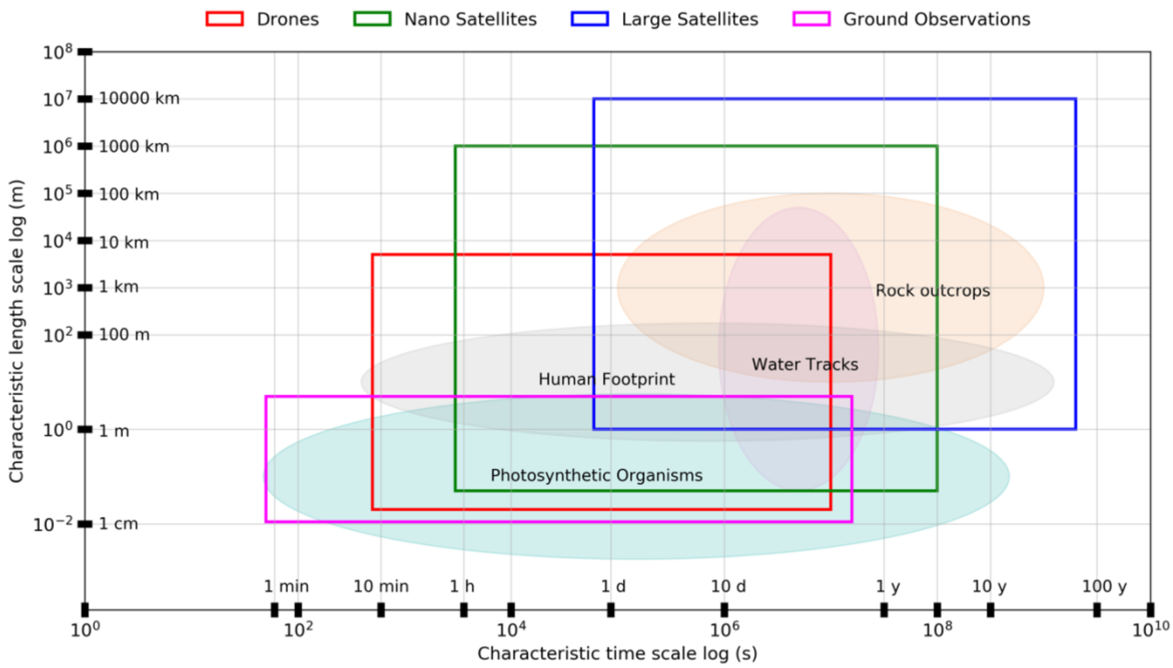


Figure 1: Characteristic spatial and temporal scales required for remote sensing and ground monitoring of terrestrial photosynthetic organisms, human footprint, water tracks and rock outcrops in ice-free areas of Antarctica.

2.1. Characterising Terrestrial Photosynthetic Organisms

Long term ground monitoring of vegetation cover, type and health have increased our understanding of decadal patterns and drivers of change in localised areas of Antarctica (King et al., 2020). In-situ assessments, while accurate, are weather dependent, constrained by logistics, intrusive and spatially inadequate to comprehensively map and monitor the distribution and health of Antarctic vegetation on large or continental scale. Moss turfs and lichen patches are small (cm to m) and spatially fragmented, therefore discriminating from other land surfaces is challenging even with fine-scale satellite observations (Malenovský et al., 2017). The rapid changes in Antarctic vegetation due to pressures like climate change occur at sub-meter scales (Amesbury et al., 2017; Cannone et al., 2021; Robinson et al., 2018), while techniques for remotely sensing vegetation in Antarctica and elsewhere are mostly at coarser resolutions (>10 m) (Gray et al., 2020; Sotille et al., 2020). Without baseline data at adequate scales, predicted or observed ecological response to future climatic events will remain uncertain (Royles et al., 2013; Royles & Griffiths, 2015).

Some solutions to fine-scaled vegetation mapping have arisen. Sub-meter scale satellite observations have provided insights into snow algae blooms and primary productivity on seasonal scales (Gray et al., 2021). Alternatively, multispectral and hyperspectral sensors onboard drones have provided insights into the physiological state of moss beds, species distribution and subtle changes at ultra-high spatial resolutions (~5 cm) and over regional ice-free areas of Antarctica (Bollard et al., 2022; Levy et al., 2020; Malenovský et al., 2017; Miranda et al., 2020; Sotille et al., 2020; Turner et al., 2018). Recent studies have investigated the role snow algae play in reducing albedo and accelerating melt rates (Cook et al., 2020), and as an important terrestrial carbon sink in polar areas (Gray et al., 2020). Cook et al. (2020) employed centimetre-scale multispectral drone imagery and meter-scale satellite observations to upscale the drone data. However, retrieving ephemeral snow algae blooms with remote sensing requires hyperspectral information for accurate discrimination against other light absorbing impurities (Huovinen et al., 2018).

The contemporary challenges in identifying and mapping Antarctic vegetation with remote sensing concern the classic trade-off between spatial, spectral, and temporal resolutions. Currently utilized multispectral sensors, such as Sentinel-2 (20 m) and Landsat-8 (30 m), provide a limited number of visible spectral channels (~4), insufficient for determining plant species, health, and physiological status (Turner et al., 2019). In addition, the ability to detect individual targets deteriorates with decreasing spatial resolution, and therefore, sub-meter scale imagery is critical for accurate determination of fragmented moss beds among rocks, regardless of the number of channels. Using drone-mounted sensors for harnessing long-term and large-scale continuous observations is challenging and costly due to their limited spatial and temporal coverage. Finally, cloud/snow coverage is an intermittent feature over Antarctica, resulting in major data gaps, needing weekly or monthly composites for systematic and continuous long-term assessments.

The main opportunities for future remote sensing of Antarctic vegetation include: First, exploring centimetre-scale observations from drones and upscaling to those acquired by the constellation of nanosatellites instruments such as Pleiades and SkySat, for reliable and continuous identification of moss beds and other types of fragmented vegetation. In addition, the strategic deployment of hyperspectral sensors on drones across Antarctica offers opportunities for local, centimetre-scale and high-quality observations for validating products from orbital satellites (Calviño-Cancela & Martín-Herrero, 2016). Second, Light Detection and Ranging (LiDAR) observations are helpful to structurally discriminate bryophytes, lichens, and other cryptic plants at meter-scale resolution Moeslund et al. (2019). This is an opportunity not yet explored in Antarctic ecosystems and may help validation of more-frequent satellite data for identifying vegetation types. Third, Synthetic Aperture Radar (SAR) observations such as those provided by COSMO SkyMed (0.8 m), and TerraSAR-X (0.6 m) instruments may be employed to overcome data gaps due to clouds and low solar elevation (Schmid et al., 2017). Fourth, advanced statistical processing techniques for automated image classification such as support vector regressions (Malenovský et al., 2017), random forest modelling (Turner et al., 2018) and machine learning (Esposito et al., 2019) are being actively developed as computational and statistical methods arise from non-Antarctic applications.

2.2. Mapping Water Tracks

Water tracks are pathways of liquid water or high soil moisture down streaming in ice-free polar areas (Levy et al., 2011). Monitoring water tracks in Antarctica is critical for understanding the evolution, ecology, and biodiversity of sensitive terrestrial ecosystems at the threshold of change

(George et al., 2021). Snow and ice melting has accelerated at unprecedented rates in the past century (Abram et al., 2013), leading to the expansion of water tracks and hydrological systems in polar environments. The seasonal development of water tracks and shallow groundwater systems are a major source of liquid water to the arid and barren ice-free areas of Antarctica (Barrett et al., 2006), as shown in Figure 2. Increased liquid water availability associated with recent climatic shifts suggest significant effects on ecosystem functioning of ice-free areas (Amesbury et al., 2017; Ball et al., 2021; Cannone et al., 2021; Royles et al., 2013). Water tracks drive biodiversity in Antarctica as pathways of solutes and nutrients to cold, desert soil ecosystems (Levy et al., 2011). Water tracks provide favourable conditions for the development and maintenance of cyanobacteria, invertebrates, and photosynthetic communities (Ball et al., 2021; Buelow et al., 2016; Eifert et al., 2020). The microbial ecosystems enabled by water tracks can impact biogeochemical fluxes and stocks of carbon within Antarctic cold desert soils (Ball & Levy, 2015; Power et al., 2020).

Figure 2: Ice free area in Stevenson's Cove, ASPA 136, Windmill Islands, including rock outcrops, moss beds and liquid water. Photo by Sharon Robinson.

Although water tracks have been broadly investigated with in situ measurements (George et al., 2021; Gooseff et al., 2013; Levy, 2021; Levy et al., 2011) and remotely elsewhere (Evans et al., 2020; Jorgenson et al., 2018; May et al., 2018; Trochim et al., 2016), their distribution and evolution remain scarcely described Antarctica wide. Optical satellite observations acquired at sub-meter scale (~0.5 m) have been useful to locally detect and monitor water tracks during the annual thaw season (Langford et al., 2015). Likewise, optical satellites have aided the identification of microbial mats adjacent to glacial meltwater streams and lakes, and key biological properties, such as carbon stock, were estimated within an Antarctic Specially Protected Area (ASPA) (Power et al., 2020). However, a composite of several images is often required to overcome data availability issues due to cloud cover and shadows (Kingslake et al., 2017). Alternatively, these hydrological features are highly detectable with active and passive microwave sensors and with Synthetic Aperture Radar (SAR) instruments (Lavender et al., 2016; Leduc-Leballeur et al., 2020; Picard & Fily, 2006; Torinesi et al., 2003). Micro and radio waves penetrate through clouds and increase data availability even in poor illumination conditions as active sensors are independent of sunlight for measurements. However, the only operational product currently available for Antarctica is provided at a very coarse spatial resolution (25 km) (Picard, 2021), which is insufficient for the characterisation of meter-scale drainage features.

Clouds hamper the observation of terrestrial targets with optical satellites and alternatives are needed in Antarctica. Microwave and SAR observations offer an opportunity for reliably monitoring water tracks – and therefore the biodiversity they support – because of their ability to sense through clouds. The main challenge in this field is to derive a new operational product at sub-meter spatial resolution and on daily to weekly basis for accurate assessments. With increasing availability of SAR sensors on orbital satellites, such as COSMO SkyMed (0.8 m), Radarsat-2 (1 m), and TerraSAR-X (0.6 m), high spatio-temporal resolution observations are available for ongoing detection and monitoring of water tracks and soil moisture in Antarctica. Likewise, optical sensors on drones may be employed in regional areas for small-scale monitoring and for validation of satellite products (Levy et al., 2020). Open-source tools for processing SAR data are now available (e.g., SNAP tool by the European Space Agency - ESA) allowing the delivery of reliable products in near-real time. Developments with machine learning algorithms can be transferred to Antarctica for reliable and automated retrievals of soil moisture and water tracks features (Collingwood et al., 2018; Zhang et al., 2018).

2.3. Assessing the Human Footprint

Only 32% of Antarctica's total area is considered wilderness or largely undisturbed by direct human activities (Leihy et al., 2020). Up to 5000 researchers per annum temporarily reside in the 90 active Antarctic and sub-Antarctic research stations during summer months and nearly 74,000 tourists visited Antarctica during 2019/2020 season (IAATO, 2021). Human impacts on ecosystems and biodiversity can be destructive. Locally in Antarctica, human activities introduce species (Bergstrom, 2022; Hughes et al., 2011b), disturb fauna and vegetation, compact soil (O'Neill et al., 2013), cause sewage and hydrocarbon contamination (Camenzuli & Freidman, 2015), and compete for space (Putzke et al., 2020). Cumulative impacts are magnified by human activities being mostly constrained to ice-free areas (Brooks et al., 2019a), and will increase with climate change (Bennett et al., 2015), intensified research activities (i.e., Figure 3) and expanding tourism (Brooks et al., 2019a; Lee et al., 2017). Monitoring the current and growing extent of humans in Antarctica is critical for assessing compliance with the Antarctic Treaty System, as well as projected ecological consequences and identifying where protection and management is needed to mitigate these.

Figure 3: Research personnel and extensive moss carpets in an ice-free area in South Shetland Islands. Photo by Andrew Netherwood.

Evaluations using historical archives of data on the biodiversity impacts of human activities in Antarctica emphasise the need for systematic monitoring on the human footprint and preservation of pristine and wild areas through the Treaty and the ASPAs (Hughes et al., 2011a). However, few studies have directly utilised remote sensing observations for identifying the human footprint and derived impacts in Antarctica. From Google Earth base maps Brooks et al. (2019a) estimated that at least 0.48% of Antarctica's total area is affected by the human footprint. In general, remote sensing can support assessments of human impacts on local climate/environment and microclimates; disturbance of permafrost and moss beds; ship and ice breaker tracks; soil erosion, compaction, and contamination; oil spills and pollution; light and atmospheric pollution and the direct impacts of research activities (Rümmler et al., 2021). The commissioning and decommissioning of bases, as well as installation of clean energy facilities may be evaluated with remote sensing to provide baseline information on changes due to these activities (Bollard et al., 2022).

Challenges remain for mapping human footprints in Antarctica, and by extension the impacts on Antarctic biodiversity, with remote sensing. First, the ability to detect changes at adequate scales and pace relevant for monitoring and management is currently unexplored. Contemporary multispectral sensors onboard drones and cube satellites with high spatial resolution (< 0.5 m), allow the accurate identification of buildings, structures, tracks, campsites, and facilities (Bollard et al., 2022). However, these high-quality observations (for instance from PlanetScope, SkySat and ESA CubeSats) have varied temporal resolutions, ranging from daily to every 5 days revisit frequency. These data gaps are further increased by cloud cover (Roy et al., 2021) and observation frequency may not be able to capture the pace of human induced changes in Antarctica. Second, mapping ongoing human presence does not directly inform the scale of human impacts in the landscape. These are often spatially co-occurring, e.g., pollution and damaged vegetation occurs in areas with concentrated human settlement (Pertierra et al., 2017). However, the long-term consequences of other human impacts, such as the introduction of non-native species (Tin et al., 2009) or the increase of black carbon content around research facilities and popular tourist-landing sites (Cordero et al., 2022) remain unknown or vary depending on where they occur.

Detecting these impacts is less feasible than detecting the more obvious, long term environmental impacts. One significant opportunity for detecting human footprint changes is automated detection algorithms. These would be highly efficient with machine learning tools, compared to manually digitising thousands of satellite images for training of classification algorithms. Another opportunity may be available by expanding global settlement maps, such as the World Settlement Footprint (Esch et al., 2022; Marconcini et al., 2020) and the Global Urban Footprint (Esch et al., 2017) datasets to Antarctica. Critical questions remain on how to quantify and qualify human impacts and how to evaluate the effectiveness of ASPAs remotely. For instance, before and after the implementation of a conservation area, can we remotely detect any changes that support ASPAs to continue? How can we capture objective evidence of human disturbances from remote sensing?

2.4. Mapping Ice-free Areas

Ice-free terrestrial areas are home to most of Antarctica's biodiversity (Terauds & Lee, 2016), but cover a relatively small portion of the continent (<1%) (Brooks et al., 2019b; Burton-Johnson et al., 2016). These rocky habitats, free of permanent ice, provide essential breeding grounds for penguins, seabirds, seals, invertebrates, and vegetation (Figure 4). There will be considerable ecological consequences of projected ice-free area expansions with rising temperatures and subsequent ice melting (Lee et al., 2017). For instance, macroalgae and fungi rapidly colonise newly formed ice-free benthic substrates following glacier retreats and seasonal ice melt (Quartino et al., 2013; Tsuji et al., 2013). A continent-wide understanding of Antarctic biodiversity will rely upon an understanding how ice-free areas are predicted to change and the implications for terrestrial biodiversity (see Lee et al., in this issue). In addition, mapping the extension and expansion of ice-free areas, which includes carbon-rich permafrost, would contribute to a better understanding on carbon stocks and fluxes associated to these sensitive environments (DeConto et al., 2012; Wadham et al., 2019). These habitats are spatially fragmented in Antarctica, and to date the only way they have been comprehensively identified and mapped has been via remote sensing observations. However, determining their extent from space is a challenging task because of Antarctica's intense cloud coverage, low solar elevation angles (<20˚) and seasonal snow cover. It is critical to overcome these technical challenges to accurately quantify ice free areas and to understand terrestrial Antarctic biodiversity.

Figure 4: Hawker Island, East Antarctica - Ice free areas of Antarctica are hot spots of biodiversity, including seabirds and vegetation. Photo by John van den Hoff.

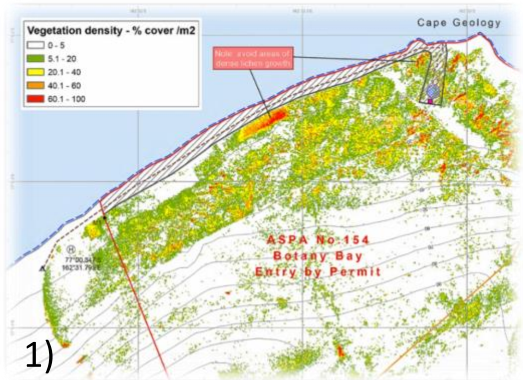
Several remote sensing approaches have been developed for mapping rock outcrops in ice-free areas and are currently available as data products in the Scientific Committee for Antarctic Research (SCAR) Antarctic Digital Database (ADD) (British Antarctic Survey, 2021). A widely used legacy product was generated by manually digitising cartographic maps and historical satellite observations dating from 1960 to 2019 (Gerrish et al., 2020). However, this approach is subjective to interpretation and combines multiple datasets with different scales and accuracies. A new approach uses an automated classification to delineate rock outcrops from Landsat-8 images at 30 m spatial resolution and showed that ice-free areas may occupy only 0.25% of the Antarctic continent (Burton-Johnson et al., 2016). However, when combining these two products, the resultant ice-free area is twice as large (0.5%) (Brooks et al., 2019a), illustrating potential inaccuracies to be addressed in each product.

Three significant challenges arise due to the dynamics of the system and to persistent environmental effects. First, the currently available products do not consider weekly to seasonal variations in snow/ice cover and may be not representative of temporal changes, current conditions, and trends in ephemeral ice-free areas of Antarctica. Second, shadows and rocks are spectrally similar, often leading to misclassification issues, which can be improved for low solar elevation angles and extreme topography (Kang et al., 2018). Third, intensive cloud coverage in Antarctica requires visual validation to ensure the accuracy of products derived from optical imagery and automated classification procedures, which is impractical and subjective. The next big opportunities for reliably mapping these biodiversity-rich ice-free areas from satellites include exploring SAR instruments, such as IceEye, TanDEM-X, TerraSAR-X and PAZ constellations to identify meter-scale rock outcrops through clouds and varying illumination conditions (Schmid et al., 2017) and to identify daily to seasonal snow cover over ice free areas (Tsai et al., 2019). Harnessing these high-quality observations with the implementation of automated procedures will allow the accurate retrieval of continuous and fine-scale ice-free maps in Antarctica.

3. Tools Required for Future Research

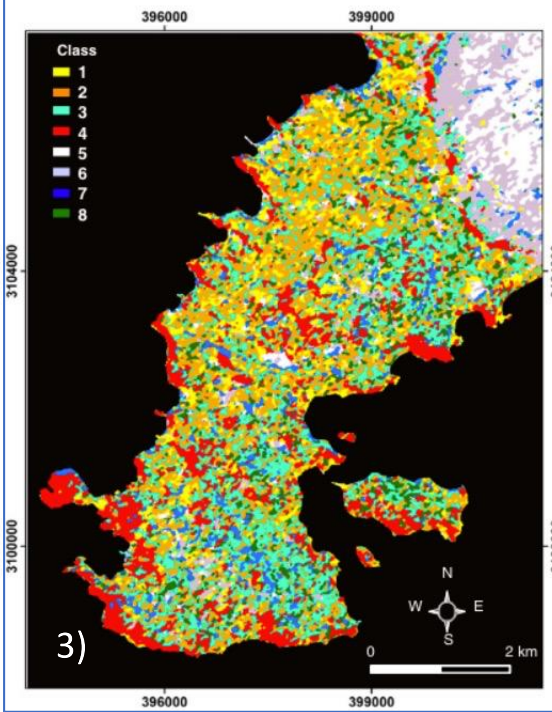
Scale and resolution are an overarching remote sensing challenge for biodiversity conservation in Antarctica (Chown et al., 2015). Earth observation satellite sensors (e.g., Landsat and Sentinel constellations) provide high radiometric quality imagery (> 12 bits), and global coverage adequate for mapping of water tracks and detection of ice-free areas but are insufficient for small-scale targets such as fragmented moss beds and human footprints. Automated and intelligent algorithms, such as machine learning tools, allied with a robust uncertainty assessment and validation, should be further explored for continuous monitoring of these targets. Conversely, the surge in low-earth orbit nano-satellite sensors (PlanetScope, SkySat, etc.), are revealing a range of opportunities for sub-meter scale monitoring (Arthur et al., 2020). These commercial observations may be freely available for research purposes, which can unlock a variety of environmental assessments including more frequent (daily to weekly), evaluation of vegetation distribution and human footprints in ice-free areas. Integration of these platforms with drone imagery is likely to open a new field of research, and data fusion algorithms are now being explored (Alvarez-Vanhard et al., 2021; Backes & Teferle, 2020; Gray et al., 2018; Miranda et al., 2020; Santangeli et al., 2020).

While nano-satellites sensors provide a wealth of information within the visible spectrum, an additional set of narrower spectral bands would allow better resolve of vegetation species and other targets. For instance, the inclusion of one or two near-infrared (NIR) bands are of critical use for moss health information, since healthy versus stressed mosses present different spectral characteristics in these bands (Malenovský et al., 2017; Turner et al., 2019). Conversely, hyperspectral sensors are useful for the reliable identification of photosynthetic organisms in microbial mats and snow algae and even to detect soil moisture properties (Levy et al., 2014; Levy et al., 2020; Malenovský et al., 2017). Innovative technological advances have allowed miniaturised hyperspectral sensors (ESA/HyperScout) on low-earth orbit (Esposito et al., 2019; European Space Agency, 2020), yielding a wealth of environmental information yet to be explored in polar areas. Harnessing hyperspectral characteristics from fine-scale observations will likely increase the amount of data to be ingested and therefore, algorithms need to be fast enough for optimal processing capabilities. Advanced techniques, such as data fusion and machine learning algorithms are rapidly evolving, allowing us to overcome current data gaps and to fully explore the potential of multiple platforms and observations. Machine learning algorithms require intensive training and testing, but are easily and rapidly implemented on large and robust datasets (Tuia et al., 2022). Currently, drone imagery may provide the most reliable and finest scale observation for vegetation and human footprint mapping. However, the temporal resolution required for continuous and long-term field assessments is hampered by adverse operational conditions such as weather and accessibility. Studies exploring the fusion of drones and fine-scale satellite observations are emerging (Alvarez-Vanhard et al., 2021; Gray et al., 2018) and may be the path towards a systematic monitoring program in Antarctica.

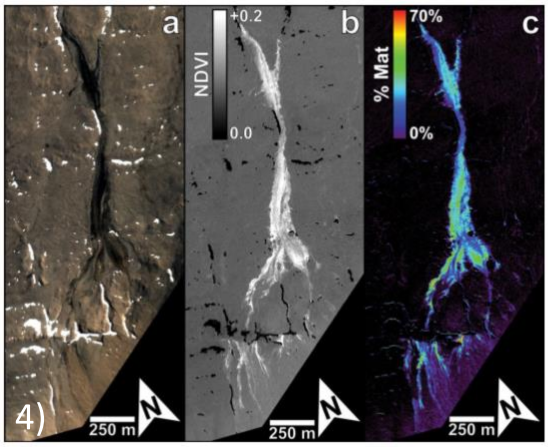


Bollard et al., (2022) mapped vegetation **(1)** in Botany Bay (ASPA 154) and identified human presence and footprint **(2)** at Cape Evans, Ross Island (ASPA 155) with sub-centimetre resolution drone images.

Schmid et al., (2017) classified landcover substrates on Fildes Peninsula **(3)** with Synthetic Aperture Radar (SAR) observations. Ice free areas (classes 1,2,3 and 4) in yellow, orange, cyan and red include coarse sediments, pebbles, stones, and rock outcrops. Ice or snow (5 and 6) are in white and purple, liquid water (7) in blue and vegetation (8) in green.



Burton-Johnson et al., (2016) automatic delineation of ice free areas of Antarctica (brown) from SCAR-ADD database **(5)**.



Salvatore et al., (2020) detected water tracks and microbial mats in the Fryxell Valley **(4)** with WorldView-2 (a) true colour composite, (b) Normalised Difference Vegetation Index (NDVI) and (c) mat abundance.

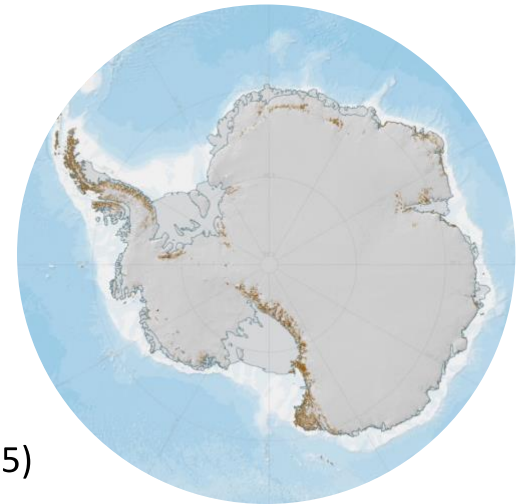


Figure 5: Remotely-sensed products developed for ice-free areas of Antarctica. Panel 1 and 2 extracted from Bollard et al., 2022; Panel 3 extracted from Schmid et al., 2017; Panel 4 extracted from Salvatore et al., 2020; and Panel 5 extracted from the SCAR-ADD online database.

Although remote sensing, computational resources and algorithm capabilities have greatly advanced in the past 20 years, ground truth datasets are still critical for calibration and validation of products and algorithms. Nevertheless, most studies report a lack of ground-based assessments in support of satellite data and product development, particularly in Antarctica. To help address this issue, field spectroscopy campaigns could be systematically implemented for validation exercises and to upscale spectral characteristics to airborne sensors. Despite multiple satellite platforms providing an unprecedented amount of satellite data for earth observation, cloud cover remains a major obstacle resulting in persistent data gaps. Cloud-filling algorithms are being developed and successfully implemented on visible and thermal imagery, with promising results to reconstruct satellite data (Barth et al., 2020b). Data Interpolating Empirical Orthogonal Functions (DINEOF) and Convolutional Neural Networks (CNN) have been of particular interest for ocean colour and temperature remote sensing (Barth et al., 2020a; Sirjacobs et al., 2011). Conversely, a decision tree approach employed to reconstruct land cover data has had promising results and should be explored for optical satellite images in ice-free areas (Holloway et al., 2019). In addition, SAR datasets are increasingly available and present an opportunity for development of a range of monitoring products in Antarctica (Collingwood et al., 2018; Sharma et al., 2022), overcoming data gaps due to clouds and low solar elevation angles. Furthermore, specialised remote sensing skills and advanced methods, including machine learning (Tuia et al., 2022) are prerequisites for synthesising the massive amount of satellite datasets increasingly available. Although existing satellite databases can be freely explored (Bindschadler et al., 2008; Scambos et al., 2007), combining datasets for multi-platform approaches is a massive challenge and requires coordinated effort between government, industry, and academia. Research, industry, and science organisations in Australia are already accomplishing an Open Data Cube program and its extension to Antarctica remains a possibility (Dhu et al., 2019; Gavin et al., 2018).

4. Conclusions

Remote sensing is an ever-evolving research field that has forever transformed the way we observe and monitor our planet and its ecosystems. Satellite and aerial observations have revolutionised biodiversity conservation studies and became an indispensable tool for continuous and systematic assessments for decision making science. Antarctic biodiversity conservation has the potential to benefit significantly from these technologies. We have identified multiple challenges to fully harness that benefit and provided insight into how potential solutions may develop with dedicated focus from remote-sensing and statistical research communities. In addition, we recommend satellite-imagery users to explore data archives freely available for research purposes, including those acquired by nano-satellites – with future capabilities in high temporal, spectral and spatial sensing. The projected increase in nanosatellite constellations offer a new and exciting tool for the development of biodiversity assessment and biological monitoring programs which will accelerate and guide conservation action and address environmental changes (Curnick et al., 2021). Nevertheless, we still lack the ground truthing data to validate algorithms and to train for remote detection of impacts. Given the high cost of Antarctic field work, optimal monitoring, and value-of-information approaches to ground-truthing will be necessary to fill this gap.

Scientific communities have a unique opportunity in Antarctica: a huge continent with high biodiversity values, dedicated to peace and science, with very little human settlement, starting from a relatively low current level of satellite-derived product availability. Ice-free areas of Antarctica are home to unique species and ecosystems, about which scientists from around the globe are still learning. Antarctica has offered international collaborative opportunities for researchers to investigate significant gaps in biology and ecology of ice-free areas. Baseline and change detection observations can be derived at relatively low cost from satellites, when compared to ground-based assessments, which can extend our knowledge for tackling some of the most pressing scientific questions in Antarctica. Mastering advanced remote sensing technologies, statistical and data processing capabilities as well as visualisation tools will be imperative for advancing any biodiversity conservation science in the decades to come.

5. Acknowledgements

The authors acknowledge Laura Gerrish (British Antarctic Survey, United Kingdom), Dr Shaun Brooks (Commonwealth Scientific Industrial Research Organization, Australia) and Dr Fraser Morgan (Landcare Research, New Zealand) for valuable feedback and discussions. This research was funded by QUT Centre for Data Science and ARC SRIEAS Grant SR200100005 Securing Antarctica's Environmental Future.

6. References

Abram, N. J., Mulvaney, R., Wolff, E. W., Triest, J., Kipfstuhl, S., Trusel, L. D., Vimeux, F., Fleet, L., & Arrowsmith, C. (2013). Acceleration of snow melt in an Antarctic Peninsula ice core during the twentieth century. *Nature geoscience*, *6*(5), 404-411. https://doi.org/10.1038/ngeo1787

Alvarez-Vanhard, E., Corpetti, T., & Houet, T. (2021). UAV & satellite synergies for optical remote sensing applications: A literature review. *Science of Remote Sensing*, *3*, 100019. https://doi.org/10.1016/j.srs.2021.100019

Amesbury, M. J., Roland, T. P., Royles, J., Hodgson, D. A., Convey, P., Griffiths, H., & Charman, D. J. (2017). Widespread Biological Response to Rapid Warming on the Antarctic Peninsula. *Current Biology*, *27*(11), 1616-1622.e1612. https://doi.org/10.1016/j.cub.2017.04.034

Arthur, J. F., Stokes, C., Jamieson, S. S., Carr, J. R., & Leeson, A. A. (2020). Recent understanding of Antarctic supraglacial lakes using satellite remote sensing. *Progress in Physical Geography: Earth and Environment*, *44*(6), 837-869. https://doi.org/10.1177/0309133320916114

Backes, D. J., & Teferle, F. N. (2020). Multiscale Integration of High-Resolution Spaceborne and Drone-Based Imagery for a High-Accuracy Digital Elevation Model Over Tristan da Cunha [Original Research]. *Frontiers in Earth Science*, *8*(319). https://doi.org/10.3389/feart.2020.00319

Ball, B., Convey, P., Feeser, K., Nielsen, U., & Van Horn, D. (2021). Environmental harshness mediates the relationship between aboveground and belowground communities in Antarctica. *Soil Biology and Biochemistry*, *164*, 108493. https://doi.org/10.1016/j.soilbio.2021.108493

Ball, B. A., & Levy, J. (2015). The role of water tracks in altering biotic and abiotic soil properties and processes in a polar desert in Antarctica. *Journal of Geophysical Research: Biogeosciences*, *120*(2), 270-279. https://doi.org/10.1002/2014JG002856

Barrett, J. E., Virginia, R. A., Hopkins, D. W., Aislabie, J., Bargagli, R., Bockheim, J. G., Campbell, I. B., Lyons, W. B., Moorhead, D. L., Nkem, J. N., Sletten, R. S., Steltzer, H., Wall, D. H., & Wallenstein, M. D. (2006). Terrestrial ecosystem processes of Victoria Land, Antarctica. *Soil Biology and Biochemistry*, *38*(10), 3019-3034. https://doi.org/10.1016/j.soilbio.2006.04.041

Barth, A., Alvera Azcárate, A., Licer, M., & Beckers, J.-M. (2020a). A convolutional neural network with error estimates to reconstruct sea surface temperature satellite observations (DINCAE). EGU General Assembly Conference Abstracts, https://doi.org/10.5194/gmd-13-1609-2020

Barth, A., Alvera-Azcárate, A., Licer, M., & Beckers, J.-M. (2020b). DINCAE 1.0: a convolutional neural network with error estimates to reconstruct sea surface temperature satellite observations. *Geoscientific Model Development*, *13*(3), 1609-1622. https://doi.org/10.5194/gmd-13-1609-2020

Barthels, M. (2020). *Want to learn how to survive on Mars? Look to Antarctica.* Future US, Inc. Retrieved 13/10/2021 from https://www.space.com/mars-human-exploration-lessons-from-antarctica.html

Bennett, J. R., Shaw, J. D., Terauds, A., Smol, J. P., Aerts, R., Bergstrom, D. M., Blais, J. M., Cheung, W. W., Chown, S. L., Lea, M.-A., Nielsen, U. N., Pauly, D., Reimer, K. J., Riddle, M. J., Snape, I., Stark, J. S., Tulloch, V. J., & Possingham, H. P. (2015). Polar lessons learned: long-term management based on shared threats in Arctic and Antarctic environments. *Frontiers in Ecology and the Environment*, *13*(6), 316-324. https://doi.org/10.1890/140315

Bergstrom, D. M. (2022). Maintaining Antarctica's isolation from non-native species. *Trends in Ecology & Evolution*, *37*(1), 5-9. https://doi.org/10.1016/j.tree.2021.10.002

Bergstrom, D. M., Wienecke, B. C., van den Hoff, J., Hughes, L., Lindenmayer, D. B., Ainsworth, T. D., Baker, C. M., Bland, L., Bowman, D. M., & Brooks, S. T. (2021). Combating ecosystem collapse from the tropics to the Antarctic. *Global Change Biology*, *27*(9), 1692-1703. https://doi.org/10.1111/gcb.15539

Bindschadler, R., Vornberger, P., Fleming, A., Fox, A., Mullins, J., Binnie, D., Paulsen, S. J., Granneman, B., & Gorodetzky, D. (2008). The Landsat Image Mosaic of Antarctica. *Remote sensing of environment*, *112*(12), 4214-4226. https://doi.org/10.1016/j.rse.2008.07.006

Bird, C. N., Dawn, A. H., Dale, J., & Johnston, D. W. (2020). A Semi-Automated Method for Estimating Adélie Penguin Colony Abundance from a Fusion of Multispectral and Thermal Imagery Collected with Unoccupied Aircraft Systems. *Remote Sensing*, *12*(22), 3692. https://doi.org/10.3390/rs12223692

Bokhorst, S., Convey, P., van Logtestijn, R., & Aerts, R. (2022). Temperature impact on the influence of penguin-derived nutrients and mosses on non-native grass in a simulated polar ecosystem. *Global Change Biology*, *28*(3), 816-828. https://doi.org/10.1111/gcb.15979

Bollard, B., Brooks, J. D., Jones, M. R. L., Robertson, J., Betschart, S., Kung, O., Craig Cary, S., Lee, C. K., & Pointing, S. B. (2015). Application of an unmanned aerial vehicle in spatial mapping of terrestrial biology and human disturbance in the McMurdo Dry Valleys, East Antarctica [Article]. *Polar Biology*, *38*(4), 573-578. https://doi.org/10.1007/s00300-014-1586-7

Bollard, B., Doshi, A., Gilbert, N., Poirot, C., & Gillman, L. (2022). Drone Technology for Monitoring Protected Areas in Remote and Fragile Environments. *Drones*, *6*(2), 42. https://doi.org/10.3390/drones6020042

British Antarctic Survey. (2017). *Antarctica and climate change*. Retrieved 22/12/2021 from https://www.bas.ac.uk/data/our-data/publication/antarctica-and-climate-change/

British Antarctic Survey. (2021). *Scientific Committee for Antarctic Research (SCAR) Antarctic Digital Database (ADD)* Retrieved 23/12/2021 from http://www.add.scar.org

Brooks, S., Jabour, J., van den Hoff, J., & Bergstrom, D. (2019a). Our footprint on Antarctica competes with nature for rare ice-free land. *Nature Sustainability*, *2*(3), 185-190. https://doi.org/10.1038/s41893-019-0237-y

Brooks, S. T., Tejedo, P., & O'Neill, T. A. (2019b). Insights on the environmental impacts associated with visible disturbance of ice-free ground in Antarctica. *Antarctic Science*, *31*(6), 304-314. https://doi.org/10.1017/S0954102019000440

Buelow, H. N., Winter, A. S., Van Horn, D. J., Barrett, J. E., Gooseff, M. N., Schwartz, E., & Takacs-Vesbach, C. D. (2016). Microbial Community Responses to Increased Water and Organic Matter in the Arid Soils of the McMurdo Dry Valleys, Antarctica. *Frontiers in microbiology*, *7*, 1040-1040. https://doi.org/10.3389/fmicb.2016.01040

Burton-Johnson, A., Black, M., Fretwell, P. T., & Kaluza-Gilbert, J. (2016). An automated methodology for differentiating rock from snow, clouds and sea in Antarctica from Landsat 8 imagery: a new rock outcrop map and area estimation for the entire Antarctic continent. *The Cryosphere*, *10*(4), 1665-1677. https://doi.org/10.5194/tc-10-1665-2016

Calviño-Cancela, M., & Martín-Herrero, J. (2016). Spectral Discrimination of Vegetation Classes in Ice-Free Areas of Antarctica. *Remote Sensing*, *8*(10), 856. https://doi.org/10.3390/rs8100856

Camenzuli, D., & Freidman, B. L. (2015). On-site and in situ remediation technologies applicable to petroleum hydrocarbon contaminated sites in the Antarctic and Arctic. *Polar Research*, *34*(1), 24492. https://doi.org/10.3402/polar.v34.24492

Cannone, N., Guglielmin, M., Malfasi, F., Hubberten, H. W., & Wagner, D. (2021). Rapid soil and vegetation changes at regional scale in continental Antarctica. *Geoderma*, *394*, 115017. https://doi.org/10.1016/j.geoderma.2021.115017

Cassaro, A., Pacelli, C., Aureli, L., Catanzaro, I., Leo, P., & Onofri, S. (2021). Antarctica as a reservoir of planetary analogue environments. *Extremophiles*, *25*. https://doi.org/10.1007/s00792-021-01245-w

Chown, S. L., Clarke, A., Fraser, C. I., Cary, S. C., Moon, K. L., & McGeoch, M. A. (2015). The changing form of Antarctic biodiversity. *Nature*, *522*(7557), 431-438. https://doi.org/10.1038/nature14505

Cimino, M. A., Fraser, W. R., Irwin, A. J., & Oliver, M. J. (2013). Satellite data identify decadal trends in the quality of Pygoscelis penguin chick-rearing habitat. *Global Change Biology*, *19*(1), 136-148. https://doi.org/10.1111/gcb.12016

Clem, K. R., Fogt, R. L., Turner, J., Lintner, B. R., Marshall, G. J., Miller, J. R., & Renwick, J. A. (2020). Record warming at the South Pole during the past three decades. *Nature climate change*, *10*(8), 762-770. https://doi.org/10.1038/s41558-020-0815-z

Collingwood, A., Charbonneau, F., Shang, C., & Treitz, P. (2018). Spatiotemporal Variability of Arctic Soil Moisture Detected from High-Resolution RADARSAT-2 SAR Data. *Advances in Meteorology*, *2018*, 5712046. https://doi.org/10.1155/2018/5712046

Cook, J. M., Tedstone, A. J., Williamson, C., McCutcheon, J., Hodson, A. J., Dayal, A., Skiles, M., Hofer, S., Bryant, R., McAree, O., McGonigle, A., Ryan, J., Anesio, A. M., Irvine-Fynn, T. D. L., Hubbard, A., Hanna, E., Flanner, M., Mayanna, S., Benning, L. G., van As, D., Yallop, M., McQuaid, J. B., Gribbin, T., & Tranter, M. (2020). Glacier algae accelerate melt rates on the south-western Greenland Ice Sheet. *The Cryosphere*, *14*(1), 309-330. https://doi.org/10.5194/tc-14-309-2020

Cordero, R. R., Sepúlveda, E., Feron, S., Damiani, A., Fernandoy, F., Neshyba, S., Rowe, P. M., Asencio, V., Carrasco, J., Alfonso, J. A., Llanillo, P., Wachter, P., Seckmeyer, G., Stepanova, M., Carrera, J. M., Jorquera, J., Wang, C., Malhotra, A., Dana, J., Khan, A. L., & Casassa, G. (2022). Black carbon footprint of human presence in Antarctica. *Nature Communications*, *13*(1), 984. https://doi.org/10.1038/s41467-022-28560-w

Curnick, D. J., Davies, A. J., Duncan, C., Freeman, R., Jacoby, D. M. P., Shelley, H. T. E., Rossi, C., Wearn, O. R., Williamson, M. J., & Pettorelli, N. (2021). SmallSats: a new technological frontier in ecology and conservation? *Remote Sensing in Ecology and Conservation*. https://doi.org/10.1002/rse2.239

DeConto, R. M., Galeotti, S., Pagani, M., Tracy, D., Schaefer, K., Zhang, T., Pollard, D., & Beerling, D. J. (2012). Past extreme warming events linked to massive carbon release from thawing permafrost. *Nature*, *484*(7392), 87-91. https://doi.org/10.1038/nature10929

Dhu, T., Giuliani, G., Juárez, J., Kavvada, A., Killough, B., Merodio, P., Minchin, S., & Ramage, S. (2019). National open data cubes and their contribution to country-level development policies and practices. *Data*, *4*(4), 144. https://doi.org/10.3390/data4040144

Dunn, M. J., Adlard, S., Taylor, A. P., Wood, A. G., Trathan, P. N., & Ratcliffe, N. (2021). Un-crewed aerial vehicle population survey of three sympatrically breeding seabird species at Signy Island, South Orkney Islands. *Polar Biology*, *44*(4), 717-727. https://doi.org/10.1007/s00300-021-02831-6

Eifert, H., Salvatore, M. R., Spitzbart, B., Lynch, H., & Szutu, B. (2020, December 01, 2020). *Tracking Meltwater Source Availability in Taylor Valley, Antarctica Through Automated Snow Detection* https://ui.adsabs.harvard.edu/abs/2020AGUFMC047.0009E

Esch, T., Brzoska, E., Dech, S., Leutner, B., Palacios-Lopez, D., Metz-Marconcini, A., Marconcini, M., Roth, A., & Zeidler, J. (2022). World Settlement Footprint 3D - A first three-dimensional survey of the global building stock. *Remote sensing of environment*, *270*, 112877. https://doi.org/10.1016/j.rse.2021.112877

Esch, T., Heldens, W., Hirner, A., Keil, M., Marconcini, M., Roth, A., Zeidler, J., Dech, S., & Strano, E. (2017). Breaking new ground in mapping human settlements from space–The Global Urban Footprint. *ISPRS Journal of Photogrammetry and Remote Sensing*, *134*, 30-42. https://doi.org/10.1016/j.isprsjprs.2017.10.012

Esposito, M., Conticello, S. S., Pastena, M., & Carnicero Domínguez, B. (2019). In-orbit demonstration of artificial intelligence applied to hyperspectral and thermal sensing from space. *SPIE Proceedings. CubeSats and SmallSats for Remote Sensing III*, *11131*. https://doi.org/10.1117/12.2532262

European Space Agency. (2020). *HyperScout-2 for the FSSCAT mission*. Retrieved 07/04/2022 from https://incubed.phi.esa.int/portfolio/hyperscout-2/

Evans, S. G., Godsey, S. E., Rushlow, C. R., & Voss, C. (2020). Water Tracks Enhance Water Flow Above Permafrost in Upland Arctic Alaska Hillslopes. *Journal of Geophysical Research: Earth Surface*, *125*(2), e2019JF005256. https://doi.org/10.1029/2019JF005256

Fretwell, P. T., & Trathan, P. N. (2021). Discovery of new colonies by Sentinel2 reveals good and bad news for emperor penguins. *Remote Sensing in Ecology and Conservation*, *7*(2), 139-153. https://doi.org/10.1002/rse2.176

Gavin, D., Dhu, T., Sagar, S., Mueller, N., Dunn, B., Lewis, A., Lymburner, L., Minchin, S., Oliver, S., & Ross, J. (2018). Digital Earth Australia-From Satellite Data to Better Decisions. IEEE International Geoscience and Remote Sensing Symposium, Valencia, Spain. https://doi.org/10.1109/IGARSS.2018.8518160

George, S. F., Fierer, N., Levy, J. S., & Adams, B. (2021). Antarctic Water Tracks: Microbial Community Responses to Variation in Soil Moisture, pH, and Salinity. *Frontiers in microbiology*, *12*, 616730-616730. https://doi.org/10.3389/fmicb.2021.616730

Gerrish, L., Fretwell, P., & Cooper, P. (2020). *High resolution vector polygons of Antarctic rock outcrop (7.3) [Data set].* https://doi.org/10.5285/cbacce42-2fdc-4f06-bdc2-73b6c66aa641

Gooseff, M. N., Barrett, J. E., & Levy, J. S. (2013). Shallow groundwater systems in a polar desert, McMurdo Dry Valleys, Antarctica. *Hydrogeology Journal*, *21*(1), 171-183. https://doi.org/10.1007/s10040-012-0926-3

Gray, A., Krolikowski, M., Fretwell, P., Convey, P., Peck, L. S., Mendelova, M., Smith, A. G., & Davey, M. P. (2020). Remote sensing reveals Antarctic green snow algae as important terrestrial carbon sink. *Nature Communications*, *11*(1), 2527. https://doi.org/10.1038/s41467-020-16018-w

Gray, A., Krolikowski, M., Fretwell, P., Convey, P., Peck, L. S., Mendelova, M., Smith, A. G., & Davey, M. P. (2021). Remote Sensing Phenology of Antarctic Green and Red Snow Algae Using WorldView Satellites. *Frontiers in Plant Science*, *12*(877). https://doi.org/10.3389/fpls.2021.671981

Gray, P. C., Ridge, J. T., Poulin, S. K., Seymour, A. C., Schwantes, A. M., Swenson, J. J., & Johnston, D. W. (2018). Integrating Drone Imagery into High Resolution Satellite Remote Sensing Assessments of Estuarine Environments. *Remote Sensing*, *10*(8), 1257. https://doi.org/10.3390/rs10081257

Holloway, J., Helmstedt, K. J., Mengersen, K., & Schmidt, M. (2019). A decision tree approach for spatially interpolating missing land cover data and classifying satellite images. *Remote Sensing*, *11*(15), 1796. https://doi.org/10.3390/rs11151796

Hughes, K. A., Fretwell, P., Rae, J., Holmes, K., & Fleming, A. (2011a). Untouched Antarctica: mapping a finite and diminishing environmental resource. *Antarctic Science*, *23*(6), 537-548. https://doi.org/10.1017/S095410201100037X

Hughes, K. A., Lee, J. E., Tsujimoto, M., Imura, S., Bergstrom, D. M., Ware, C., Lebouvier, M., Huiskes, A. H. L., Gremmen, N. J. M., Frenot, Y., Bridge, P. D., & Chown, S. L. (2011b). Food for thought: Risks of non-native species transfer to the Antarctic region with fresh produce. *Biological Conservation*, *144*(5), 1682-1689. https://doi.org/10.1016/j.biocon.2011.03.001

Hughes, K. A., Pescott, O. L., Peyton, J., Adriaens, T., Cottier-Cook, E. J., Key, G., Rabitsch, W., Tricarico, E., Barnes, D. K. A., Baxter, N., Belchier, M., Blake, D., Convey, P., Dawson, W., Frohlich, D., Gardiner, L. M., González-Moreno, P., James, R., Malumphy, C., Martin, S., Martinou, A. F., Minchin, D., Monaco, A., Moore, N., Morley, S. A., Ross, K., Shanklin, J., Turvey, K., Vaughan, D., Vaux, A. G. C., Werenkraut, V., Winfield, I. J., & Roy, H. E. (2020). Invasive non-native species likely to threaten biodiversity and ecosystems in the Antarctic Peninsula region. *Global Change Biology*, *26*(4), 2702-2716. https://doi.org/10.1111/gcb.14938

Huovinen, P., Ramírez, J., & Gómez, I. (2018). Remote sensing of albedo-reducing snow algae and impurities in the Maritime Antarctica. *ISPRS Journal of Photogrammetry and Remote Sensing*, *146*, 507-517. https://doi.org/10.1016/j.isprsjprs.2018.10.015

IAATO. (2021). *Data & Statistics*. https://iaato.org/information-resources/data-statistics/

Jenouvrier, S., Holland, M., Iles, D., Labrousse, S., Landrum, L., Garnier, J., Caswell, H., Weimerskirch, H., LaRue, M., Ji, R., & Barbraud, C. (2020). The Paris Agreement objectives will likely halt future declines of emperor penguins. *Global Change Biology*, *26*(3), 1170-1184. https://doi.org/10.1111/gcb.14864

Jorgenson, J. C., Jorgenson, M. T., Boldenow, M. L., & Orndahl, K. M. (2018). Landscape Change Detected over a Half Century in the Arctic National Wildlife Refuge Using High-Resolution Aerial Imagery. *Remote Sensing*, *10*(8), 1305. https://www.mdpi.com/2072-4292/10/8/1305

Kang, J., Cheng, X., Hui, F., & Ci, T. (2018). An Accurate and Automated Method for Identifying and Mapping Exposed Rock Outcrop in Antarctica Using Landsat 8 Images. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *11*(1), 57-67. https://doi.org/10.1109/JSTARS.2017.2755502

Kennicutt, M. C., Chown, S. L., Cassano, J. J., Liggett, D., Massom, R., Peck, L. S., Rintoul, S. R., Storey, J. W. V., Vaughan, D. G., Wilson, T. J., & Sutherland, W. J. (2014). Polar research: Six priorities for Antarctic science. *Nature*, *512*(7512), 23-25. https://doi.org/10.1038/512023a

King, D. H., Wasley, J., Ashcroft, M. B., Ryan-Colton, E., Lucieer, A., Chisholm, L. A., & Robinson, S. A. (2020). Semi-Automated Analysis of Digital Photographs for Monitoring East Antarctic Vegetation [Methods]. *Frontiers in Plant Science*, *11*(766). https://doi.org/10.3389/fpls.2020.00766

Kingslake, J., Ely, J. C., Das, I., & Bell, R. E. (2017). Widespread movement of meltwater onto and across Antarctic ice shelves. *Nature*, *544*(7650), 349-352. https://doi.org/10.1038/nature22049

Langford, Z. L., Gooseff, M. N., & Lampkin, D. J. (2015). Spatiotemporal dynamics of wetted soils across a polar desert landscape. *Antarctic Science*, *27*(2), 197-209. https://doi.org/10.1017/S0954102014000601

LaRue, M., Brooks, C., Wege, M., Salas, L., & Gardiner, N. (2022). High-resolution satellite imagery meets the challenge of monitoring remote marine protected areas in the Antarctic and beyond. *Conservation Letters*, *n/a*(n/a), e12884. https://doi.org/10.1111/conl.12884

LaRue, M., Iles, D., Labrousse, S., Salas, L., Ballard, G., Ainley, D., & Saenz, B. (2019). A possible Adélie penguin sub-colony on fast ice by Cape Crozier, Antarctica. *Antarctic Science*, *31*(4), 189-194. https://doi.org/10.1017/S095410201900018X

LaRue, M. A., Ainley, D. G., Pennycook, J., Stamatiou, K., Salas, L., Nur, N., Stammerjohn, S., & Barrington, L. (2020). Engaging 'the crowd' in remote sensing to learn about habitat affinity of the Weddell seal in Antarctica. *Remote Sensing in Ecology and Conservation*, *6*(1), 70-78. https://doi.org/10.1002/rse2.124

Lavender, S., Haria, K., Cooksley, G., Farman, A., & Beaton, T. (2016). Understanding the future market for NovaSAR-S flood mapping products using data mining and simulation. Living Planet symposium, ESA, Prague, Czech Republic, https://doi.org/https://ui.adsabs.harvard.edu/abs/2016ESASP.740E.380L/abstract

Leduc-Leballeur, M., Picard, G., Macelloni, G., Mialon, A., & Kerr, Y. H. (2020). Melt in Antarctica derived from Soil Moisture and Ocean Salinity (SMOS) observations at L band. *The Cryosphere*, *14*(2), 539-548. https://doi.org/10.5194/tc-14-539-2020

Lee, J. R., Raymond, B., Bracegirdle, T. J., Chadès, I., Fuller, R. A., Shaw, J. D., & Terauds, A. (2017). Climate change drives expansion of Antarctic ice-free habitat. *Nature*, *547*(7661), 49-54. https://doi.org/10.1038/nature22996

Leihy, R. I., Coetzee, B. W. T., Morgan, F., Raymond, B., Shaw, J. D., Terauds, A., Bastmeijer, K., & Chown, S. L. (2020). Antarctica's wilderness fails to capture continent's biodiversity. *Nature*, *583*(7817), 567-571. https://doi.org/10.1038/s41586-020-2506-3

Levy, J. (2021). Episodic basin-scale soil moisture anomalies associated with high relative humidity events in the McMurdo Dry Valleys, Antarctica. *Antarctic Science*, *33*(5), 533-547. https://doi.org/10.1017/S0954102021000341

Levy, J., Nolin, A., Fountain, A., & Head, J. (2014). Hyperspectral measurements of wet, dry and saline soils from the McMurdo Dry Valleys: soil moisture properties from remote sensing. *Antarctic Science*, *26*(5), 565-572. https://doi.org/10.1017/S0954102013000977

Levy, J. S., Cary, S. C., Joy, K., & Lee, C. K. (2020). Detection and community-level identification of microbial mats in the McMurdo Dry Valleys using drone-based hyperspectral reflectance imaging. *Antarctic Science*, *32*(5), 367-381. https://doi.org/10.1017/S0954102020000243

Levy, J. S., Fountain, A. G., Gooseff, M. N., Welch, K. A., & Lyons, W. B. (2011). Water tracks and permafrost in Taylor Valley, Antarctica: Extensive and shallow groundwater connectivity in a cold desert ecosystem. *GSA Bulletin*, *123*(11-12), 2295-2311. https://doi.org/10.1130/b30436.1

Malenovský, Z., Lucieer, A., King, D. H., Turnbull, J. D., & Robinson, S. A. (2017). Unmanned aircraft system advances health mapping of fragile polar vegetation. *Methods in Ecology and Evolution*, *8*(12), 1842-1857. https://doi.org/10.1111/2041-210X.12833

Marconcini, M., Metz-Marconcini, A., Üreyen, S., Palacios-Lopez, D., Hanke, W., Bachofer, F., Zeidler, J., Esch, T., Gorelick, N., Kakarla, A., Paganini, M., & Strano, E. (2020). Outlining where humans live, the World Settlement Footprint 2015. *Scientific Data*, *7*(1), 242. https://doi.org/10.1038/s41597-020-00580-5

May, J. L., Parker, T., Unger, S., & Oberbauer, S. F. (2018). Short term changes in moisture content drive strong changes in Normalized Difference Vegetation Index and gross primary productivity in four Arctic moss communities. *Remote sensing of environment*, *212*, 114-120. https://doi.org/10.1016/j.rse.2018.04.041

McCarthy, A. H., Peck, L. S., Hughes, K. A., & Aldridge, D. C. (2019). Antarctica: The final frontier for marine biological invasions. *Global Change Biology*, *25*(7), 2221-2241. https://doi.org/10.1111/gcb.14600

McCarthy, N. (2021). *How expensive is the NASA Mars rover Perseverance mission?* Retrieved 13/10/2021 from https://www.weforum.org/agenda/2021/02/mars-nasa-space-exploration-cost-perseverance-viking-curiosity/

McMahon, C. R., Howe, H., van den Hoff, J., Alderman, R., Brolsma, H., & Hindell, M. A. (2014). Satellites, the All-Seeing Eyes in the Sky: Counting Elephant Seals from Space. *PLOS ONE*, *9*(3), e92613. https://doi.org/10.1371/journal.pone.0092613

Meredith, M., Sommerkorn, M., Cassotta, S., Derksen, C., Ekaykin, A., Hollowed, A., Kofinas, G., Mackintosh, A., Melbourne-Thomas, J., & Muelbert, M. (2019). Polar Regions In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, & M. T. P. Zhai, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge, UK and New York, NY, USA, pp. 203-320. 10.1017/9781009157964.005

Miranda, V., Pina, P., Heleno, S., Vieira, G., Mora, C., & E.G.R. Schaefer, C. (2020). Monitoring recent changes of vegetation in Fildes Peninsula (King George Island, Antarctica) through satellite imagery guided by UAV surveys. *Science of The Total Environment*, *704*, 135295. https://doi.org/10.1016/j.scitotenv.2019.135295

Moeslund, J., Zlinszky, A., Ejrnæs, R., Brunbjerg, A. K., Bøcher, P., Svenning, J.-C., & Normand, S. (2019). LIDAR explains diversity of plants, fungi, lichens and bryophytes across multiple habitats and large geographic extent. *Ecological Applications*, *29*, e01907. https://doi.org/10.1002/eap.1907

Moreau, S., Mostajir, B., Bélanger, S., Schloss, I. R., Vancoppenolle, M., Demers, S., & Ferreyra, G. A. (2015). Climate change enhances primary production in the western Antarctic Peninsula [Article]. *Global Change Biology*, *21*(6), 2191-2205. https://doi.org/10.1111/gcb.12878

National Aeronautics and Space Administration. (2021). *Earth's Cryosphere Is Vital for Everyone. Here's How NASA Keeps Track of Its Changes*. NASA's Earth Science News Team. Retrieved 22/11/2021 from https://climate.nasa.gov/news/3079/earths-cryosphere-is-vital-for-everyone-heres-how-nasa-keeps-track-of-its-changes/

Norwegian Polar Institute. (2021). *Global climate change*. Norwegian Polar Institute. Retrieved 22/12/2021 from https://www.npolar.no/en/themes/global-climate-change/

Nowogrodzki, A. (2020). Eleven tips for working with large data sets. *Nature*, *577*(7789), 439-441. https://doi.org/10.1038/d41586-020-00062-z

O'Neill, T. A., Balks, M. R., & López-Martínez, J. (2013). Visual recovery of desert pavement surfaces following impacts from vehicle and foot traffic in the Ross Sea region of Antarctica. *Antarctic Science*, *25*(4), 514-530. https://doi.org/10.1017/S0954102012001125

Page, T. (2019). *To Antarctica and beyond*. Cable News Network. Retrieved 13/10/2021 from https://edition.cnn.com/interactive/2019/10/world/antarctica-and-beyond-scn/

Pertierra, L. R., Hughes, K. A., Vega, G. C., & Olalla-Tárraga, M. Á. (2017). High Resolution Spatial Mapping of Human Footprint across Antarctica and Its Implications for the Strategic Conservation of Avifauna. *PLOS ONE*, *12*(1), e0168280. https://doi.org/10.1371/journal.pone.0168280

Pfeifer, C., Rümmler, M.-C., & Mustafa, O. (2021). Assessing colonies of Antarctic shags by unmanned aerial vehicle (UAV) at South Shetland Islands, Antarctica. *Antarctic Science*, *33*(2), 133-149. https://doi.org/10.1017/S0954102020000644

Picard, G. (2021). *Surface melting in Antarctica derived from Passive microwave data*. Retrieved 08/03/2022 from https://snow.univ-grenoble-alpes.fr/melting/

Picard, G., & Fily, M. (2006). Surface melting observations in Antarctica by microwave radiometers: Correcting 26-year time series from changes in acquisition hours. *Remote sensing of environment*, *104*(3), 325-336. https://doi.org/10.1016/j.rse.2006.05.010

Power, S. N., Salvatore, M. R., Sokol, E. R., Stanish, L. F., & Barrett, J. E. (2020). Estimating microbial mat biomass in the McMurdo Dry Valleys, Antarctica using satellite imagery and ground surveys. *Polar Biology*, *43*(11), 1753-1767. https://doi.org/10.1007/s00300-020-02742-y

Putzke, J., Vieira, F. C. B., & Pereira, A. B. (2020). Vegetation recovery after the removal of a facility in Elephant Island, Maritime Antarctic. *Land Degradation & Development*, *31*(1), 96-104. https://doi.org/10.1002/ldr.3431

Quartino, M. L., Deregibus, D., Campana, G. L., Latorre, G. E. J., & Momo, F. R. (2013). Evidence of Macroalgal Colonization on Newly Ice-Free Areas following Glacial Retreat in Potter Cove (South Shetland Islands), Antarctica. *PLOS ONE*, *8*(3), e58223. https://doi.org/10.1371/journal.pone.0058223

Robinson, S. A., King, D. H., Bramley-Alves, J., Waterman, M. J., Ashcroft, M. B., Wasley, J., Turnbull, J. D., Miller, R. E., Ryan-Colton, E., Benny, T., Mullany, K., Clarke, L. J., Barry, L. A., & Hua, Q. (2018). Rapid change in East Antarctic terrestrial vegetation in response to regional drying. *Nature climate change*, *8*(10), 879-884. https://doi.org/10.1038/s41558-018-0280-0

Robinson, S. A., Klekociuk, A. R., King, D. H., Pizarro Rojas, M., Zúñiga, G. E., & Bergstrom, D. M. (2020). The 2019/2020 summer of Antarctic heatwaves. *Global Change Biology*, *26*(6), 3178-3180. https://doi.org/10.1111/gcb.15083s

Roy, D. P., Huang, H., Houborg, R., & Martins, V. S. (2021). A global analysis of the temporal availability of PlanetScope high spatial resolution multi-spectral imagery. *Remote sensing of environment*, *264*, 112586. https://doi.org/10.1016/j.rse.2021.112586

Royles, J., Amesbury, Matthew J., Convey, P., Griffiths, H., Hodgson, Dominic A., Leng, Melanie J., & Charman, Dan J. (2013). Plants and Soil Microbes Respond to Recent Warming on the Antarctic Peninsula. *Current Biology*, *23*(17), 1702-1706. https://doi.org/10.1016/j.cub.2013.07.011

Royles, J., & Griffiths, H. (2015). Invited review: climate change impacts in polar regions: lessons from Antarctic moss bank archives. *Global Change Biology*, *21*(3), 1041-1057. https://doi.org/10.1111/gcb.12774

Rümmler, M.-C., Esefeld, J., Hallabrin, M. T., Pfeifer, C., & Mustafa, O. (2021). Emperor penguin reactions to UAVs: first observations and comparisons with effects of human approach. *Remote Sensing Applications: Society and Environment*, 100545. https://doi.org/10.1016/j.rsase.2021.100545

Salvatore, M. R. (2015). High-resolution compositional remote sensing of the Transantarctic Mountains: application to the WorldView-2 dataset. *Antarctic Science*, *27*(5), 473-491. https://doi.org/10.1017/S095410201500019X

Salvatore, M. R., Borges, S. R., Barrett, J. E., Sokol, E. R., Stanish, L. F., Power, S. N., & Morin, P. (2020). Remote characterization of photosynthetic communities in the Fryxell basin of Taylor Valley, Antarctica. *Antarctic Science*, *32*(4), 255-270. https://doi.org/10.1017/S0954102020000176

Salvatore, M. R., & Levy, J. S. (2021). Chapter 11 - The McMurdo Dry Valleys of Antarctica: a geological, environmental, and ecological analog to the Martian surface and near surface. In R. J. Soare, S. J. Conway, J.-P. Williams, & D. Z. Oehler (Eds.), *Mars Geological Enigmas* (pp. 291-332). Elsevier. https://doi.org/10.1016/B978-0-12-820245-6.00011-2

Sanderson, K. (2010). Polar projects. *Nature*, *465*(7298), 652-653. https://doi.org/10.1038/nj7298-652a

Santangeli, A., Chen, Y., Kluen, E., Chirumamilla, R., Tiainen, J., & Loehr, J. (2020). Integrating drone-borne thermal imaging with artificial intelligence to locate bird nests on agricultural land. *Scientific Reports*, *10*(1), 10993. https://doi.org/10.1038/s41598-020-67898-3

Sassenroth, C., Hauber, E., Baroni, C., Salvatore, M. C., De Vera, J.-P., & Schmitz, N. (2021, April 01, 2021). *Polygonal frost patterned ground as a Mars analogue in Northern Victoria Land, Antarctica* https://ui.adsabs.harvard.edu/abs/2021EGUGA..2312265S

Scambos, T. A., Haran, T. M., Fahnestock, M. A., Painter, T. H., & Bohlander, J. (2007). MODIS-based Mosaic of Antarctica (MOA) data sets: Continent-wide surface morphology and snow grain size. *Remote sensing of environment*, *111*(2), 242-257. https://doi.org/10.1016/j.rse.2006.12.020

Schmid, T., López-Martínez, J., Guillaso, S., Serrano, E., D'Hondt, O., Koch, M., Nieto, A., O'Neill, T., Mink, S., Durán, J. J., & Maestro, A. (2017). Geomorphological mapping of ice-free areas using polarimetric RADARSAT-2 data on Fildes Peninsula and Ardley Island, Antarctica. *Geomorphology*, *293*, 448-459. https://doi.org/10.1016/j.geomorph.2016.09.031

Sharma, S., Tripathi, S., Ray, A., Makwana, N. D., Dave, K. R., Mathur, A. K., Kumar, R., Oza, S., Brahmbhatt, V., Hait, A., Kansara, H. R., Jyoti, R., Saini, S., & Beg, J. (2022). Establishment of SAR calibration site at Antarctica: Pre-NISAR calibration activity. *Advances in Space Research*, *69*(4), 1715-1725. https://doi.org/10.1016/j.asr.2021.05.031

Sirjacobs, D., Alvera-Azcárate, A., Barth, A., Lacroix, G., Park, Y., Nechad, B., Ruddick, K., & Beckers, J.-M. (2011). Cloud filling of ocean colour and sea surface temperature remote sensing products over the Southern North Sea by the Data Interpolating Empirical Orthogonal Functions methodology. *Journal of Sea Research*, *65*(1), 114-130. https://doi.org/10.1016/j.seares.2010.08.002

Smith, P., Arneth, A., Barnes, D. K. A., Ichii, K., Marquet, P. A., Popp, A., Pörtner, H. O., Rogers, A. D., Scholes, R. J., Strassburg, B., Wu, J., & Ngo, H. (2022). How do we best synergize climate mitigation actions to co-benefit biodiversity? [Review]. *Global Change Biology*, *28*(8), 2555-2577. https://doi.org/10.1111/gcb.16056

Sotille, M. E., Bremer, U. F., Vieira, G., Velho, L. F., Petsch, C., & Simões, J. C. (2020). Evaluation of UAV and satellite-derived NDVI to map maritime Antarctic vegetation. *Applied Geography*, *125*, 102322. https://doi.org/10.1016/j.apgeog.2020.102322

Southwell, C., & Emmerson, L. (2015). Remotely-operating camera network expands Antarctic seabird observations of key breeding parameters for ecosystem monitoring and management [Article]. *Journal for Nature Conservation*, *23*, 1-8. https://doi.org/10.1016/j.jnc.2014.11.002

Terauds, A., & Lee, J. R. (2016). Antarctic biogeography revisited: updating the Antarctic Conservation Biogeographic Regions. *Diversity and Distributions*, *22*(8), 836-840. https://doi.org/10.1111/ddi.12453

The Antarctic Treaty, 402 U.N.T.S. 71, (1961). https://treaties.un.org/pages/showDetails.aspx?objid=0800000280136dbc

Tin, T., Fleming, Z. L., Hughes, K. A., Ainley, D. G., Convey, P., Moreno, C. A., Pfeiffer, S., Scott, J., & Snape, I. (2009). Impacts of local human activities on the Antarctic environment. *Antarctic Science*, *21*(1), 3-33. https://doi.org/10.1017/S0954102009001722

Torinesi, O., Fily, M., & Genthon, C. (2003). Variability and Trends of the Summer Melt Period of Antarctic Ice Margins since 1980 from Microwave Sensors. *Journal of Climate*, *16*(7), 1047-1060. https://doi.org/10.1175/1520-0442(2003)016<1047:VATOTS>2.0.CO;2

Trochim, E. D., Prakash, A., Kane, D. L., & Romanovsky, V. E. (2016). Remote sensing of water tracks. *Earth and Space Science*, *3*(3), 106-122. https://doi.org/10.1002/2015EA000112

Tsai, Y.-L. S., Dietz, A., Oppelt, N., & Kuenzer, C. (2019). Remote Sensing of Snow Cover Using Spaceborne SAR: A Review. *Remote Sensing*, *11*(12), 1456. https://www.mdpi.com/2072-4292/11/12/1456

Tsuji, M., Fujiu, S., Xiao, N., Hanada, Y., Kudoh, S., Kondo, H., Tsuda, S., & Hoshino, T. (2013). Cold adaptation of fungi obtained from soil and lake sediment in the Skarvsnes ice-free area, Antarctica. *FEMS Microbiology Letters*, *346*(2), 121-130. https://doi.org/10.1111/1574-6968.12217

Tuia, D., Kellenberger, B., Beery, S., Costelloe, B. R., Zuffi, S., Risse, B., Mathis, A., Mathis, M. W., van Langevelde, F., Burghardt, T., Kays, R., Klinck, H., Wikelski, M., Couzin, I. D., van Horn, G., Crofoot, M. C., Stewart, C. V., & Berger-Wolf, T. (2022). Perspectives in machine learning for wildlife conservation. *Nature Communications*, *13*(1), 792. https://doi.org/10.1038/s41467-022-27980-y

Turner, D., Lucieer, A., Malenovský, Z., King, D., & Robinson, S. A. (2018). Assessment of Antarctic moss health from multi-sensor UAS imagery with Random Forest Modelling. *International Journal of Applied Earth Observation and Geoinformation*, *68*, 168-179. https://doi.org/10.1016/j.jag.2018.01.004

Turner, D. J., Malenovský, Z., Lucieer, A., Turnbull, J. D., & Robinson, S. A. (2019). Optimizing Spectral and Spatial Resolutions of Unmanned Aerial System Imaging Sensors for Monitoring Antarctic Vegetation. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *12*(10), 3813-3825. https://doi.org/JSTARS.2019.2938544

Turner, J., Barrand, N. E., Bracegirdle, T. J., Convey, P., Hodgson, D. A., Jarvis, M., Jenkins, A., Marshall, G., Meredith, M. P., & Roscoe, H. (2014). Antarctic climate change and the environment: an update. *Polar Record*, *50*(3), 237-259. https://doi.org/10.1017/S0032247413000296

Wadham, J. L., Hawkings, J. R., Tarasov, L., Gregoire, L. J., Spencer, R. G. M., Gutjahr, M., Ridgwell, A., & Kohfeld, K. E. (2019). Ice sheets matter for the global carbon cycle. *Nature Communications*, *10*(1), 3567. https://doi.org/10.1038/s41467-019-11394-4

Wege, M., Bornemann, H., Blix, A. S., Nordøy, E. S., Biddle, L., & Bester, M. N. (2021a). Distribution and Habitat Suitability of Ross Seals in a Warming Ocean [Article]. *Frontiers in Marine Science*, *8*, Article 659430. https://doi.org/10.3389/fmars.2021.659430

Wege, M., Salas, L., & LaRue, M. (2021b). Ice matters: Life-history strategies of two Antarctic seals dictate climate change eventualities in the Weddell Sea [Article]. *Global Change Biology*, *27*(23), 6252-6262. https://doi.org/10.1111/gcb.15828

Yang, J., Gong, P., Fu, R., Zhang, M., Chen, J., Liang, S., Xu, B., Shi, J., & Dickinson, R. (2013). The role of satellite remote sensing in climate change studies. *Nature climate change*, *3*(10), 875-883. https://doi.org/10.1038/nclimate1908

Zhang, W., Witharana, C., Liljedahl, A. K., & Kanevskiy, M. (2018). Deep Convolutional Neural Networks for Automated Characterization of Arctic Ice-Wedge Polygons in Very High Spatial Resolution Aerial Imagery. *Remote Sensing*, *10*(9), 1487. https://doi.org/10.3390/rs10091487