drones

MDPI

Communication

Drone Technology for Monitoring Protected Areas in Remote and Fragile Environments

Barbara Bollard [1,*], Ashray Doshi [1], Neil Gilbert [2], Ceisha Poirot [3] and Len Gillman [1]

[1] Drone Lab, School of Engineering, Computer and Mathematical Sciences, Auckland University of Technology, 55 Wellesley St. East, Auckland 1010, New Zealand; ashray.doshi@aut.ac.nz (A.D.); len.gillman@aut.ac.nz (L.G.)
[2] Director, Constantia Consulting Ltd., 310 Papanui Road, Christchurch 8052, New Zealand; neil@constantiaconsulting.net
[3] Antarctica New Zealand, GM Policy, Environment and Safety, 38 Orchard Road, Christchurch 8053, New Zealand; c.poirot@antarcticanz.govt.nz
* Correspondence: barbara.bollard@aut.ac.nz

Abstract: Protected Areas are established to protect significant ecosystems and historical artefacts. However, many are subject to little structured monitoring to assess whether the attributes for which they have been protected are being maintained or degraded. Monitoring sensitive areas using ground surveys risks causing damage to the values for which they are being protected, are usually based on limited sampling, and often convey insufficient detail for understanding ecosystem change. Therefore, there is a need to undertake quick and accurate vegetation surveys that are low impact, cost effective and repeatable with high precision. Here we use drone technology to map protected areas in Antarctica to ultra-high resolution and provide baseline data for future monitoring. Our methods can measure micro-scale changes, are less expensive than ground-based sampling and can be applied to any protected area where fine scale monitoring is desirable. Drone-based surveys should therefore become standard practice for protected areas in remote fragile environments.

Keywords: Antarctica; unmanned aerial vehicle; remote sensing; vegetation mapping; protected areas; fragile environments; environmental monitoring

check for updates

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

Academic Editor: Diego González-Aguilera

Received: 31 December 2021
Accepted: 6 February 2022
Published: 9 February 2022

1. Introduction

For maintaining an effective network of protected areas, it is particularly important to be able to determine whether or not the values for which the areas are protected remain intact and that management controls are successful in achieving the aims and objectives prescribed in the management plans. Habitat loss and degradation due to increased human pressure within protected areas can be substantial. The key problem is often inadequate funding for their management [1]. Therefore, more efficient monitoring tools that reduce management costs have the potential to make significant contributions to nature protection. The cost of monitoring protected areas in extreme and remote environments is particularly significant. Low altitude, high spectral and spatial resolution remote sensing technologies have the potential to increase the accuracy of monitoring while decreasing costs. Therefore, they provide a potentially important methodological advance for conservation.

Here we investigate the utility of drone-based platforms to provide cost efficient and accurate baseline vegetation maps for monitoring. The Antarctic continent is one of the most remote and extreme environments on Earth, and therefore our study sites, located within this continent, provide an excellent testing ground for the practical use of this technology.

The governance and management of Antarctica and the Southern Ocean are undertaken under the auspices of a set of internationally agreed treaties that commenced with the adoption of the Antarctic Treaty in 1959. The Protocol on Environmental Protection to the Antarctic Treaty adopted in 1991 provides for the designation of terrestrial and marine sites as Antarctic Specially Protected Areas (ASPAs). ASPAs are designated to protect areas of outstanding environmental, scientific, historic, aesthetic or wilderness values, (Protocol Annex V, Article 3(1)). Currently, a total of 72 ASPAs have been designated across Antarctica. The protected areas system in Antarctica has come under scrutiny in recent years with several deficiencies identified [2,3]. Human activity posing a risk to biodiversity is increasingly concentrated within, and in close proximity, to designated ASPAs, and many appear to be inadequately protected [3]. Surprisingly, for a region as remote as the Antarctic, the outlook for biodiversity conservation appears to be no better than that for the rest of the planet [4–7]. Antarctica has experienced an overall growth in tourism visitation with 74,401 tourists visiting in the 2019–2020 season, which equates to growth of 134% since the 2010–2011 season [8].

Personal observations in 2017 and 2019 of areas within the Botany Bay ASPA 154 suggest widespread die-back of moss beds and in 2019 there was evidence of significant damage due to trampling of vegetation in the Canada Glacier ASPA. However, without accurate vegetation maps it is not possible to discern whether vegetation in these areas is undergoing short-term fluctuation or whether there are more serious irreversible declines in the health of the ecosystems. Manual surveying of protected areas in remote locations such as Antarctica is very time consuming, provides limited detail that is useful for monitoring change and can induce additional damage to the ecosystem being monitored. For example, the original survey conducted for the Botany Bay ASPA required multiple expeditions to the continent between 2000 and 2009 with large teams and involved 190 plots. Yet, despite the substantial investment in the survey, it is not possible to reproduce these plots for direct comparison of the vegetation because they were not permanently marked due to ASPA restrictions or accurately located on maps. Even if the plots were permanently marked, they would not necessarily capture fine scale changes, or retreating vegetation boundaries, if these changes were not coinciding with sample plots.

Cost constraints on monitoring protected areas are not confined to Antarctica. Monitoring protected areas wherever they occur, but especially those in extreme and remote environments, will always be limited in extent and resolution due to the high cost of ground-based sampling. Therefore, there is a need to be able to undertake quick and accurate vegetation surveys that are low impact, cost effective and repeatable with high precision. Drone technology offers a possible solution due to its potential to gather data with minimal foot traffic and due to its potential to provide comprehensive three-dimensional maps that accurately delineate vegetation and other relevant features. The use of both fixed-wing and rotary-wing drones has expanded significantly in recent years and the remote sensing equipment that can be attached to them has a wide range of scientific and operational application [9–11]. In Antarctica, drone research has primarily focused on studying breeding behaviour of marine mammals [12] and nesting penguins [13], and not on systematic environmental mapping of cryptic vegetation as presented in this research.

The Committee for Environmental Protection (CEP) was established by the 1991 Protocol on Environmental Protection to the Antarctic Treaty (the Protocol) as the primary environmental advisory body to the Antarctic Treaty Consultative Meeting (ATCM). Over a series of meetings between 2014 and 2018, the CEP debated the use of drones in Antarctica. The CEP saw the need to balance the scientific and operational benefits of drones with the largely untested environmental impacts, not least regarding the potential disturbance to Antarctic wildlife. The CEP's discussions are summarised and reviewed by Leary [14].

In 2018, the CEP recommended that the ATCM adopt Environmental Guidelines for operation of Remotely Piloted Aircraft Systems (RPAS) in Antarctica [15]. The Guidelines are targeted at small to medium-sized drones ($\leq$25 kg in weight) and aim to assist in undertaking Environmental Impact Assessments for activities involving drones and to aid decision making for use of drones through provision of guidance based on current best available knowledge. The Guidelines address issues to be considered in the planning, operational and post-flight phases of using drones in Antarctica. The Guidelines were utilised in the planning and operation of the research reported in this paper.

This communication reports on the functionality of using drone technology in three protected areas in the Ross Sea region. We used custom built fixed wing and multirotor airframes with off-the-shelf Red, Blue, Green (RGB), multispectral and video camera sensors, and a global navigation satellite system (GNSS) survey for ground truthing aerial data.

2. Materials and Methods

2.1. Study Sites

The study sites are located within the Ross Sea region of Antarctica and are all Antarctic Specially Protected Areas (ASPAs) (Figure 1). Two of the ASPAs that were selected (ASPA 131—Canada Glacier, and ASPA 154—Botany Bay) are designated to protect native vegetation, whilst the third (ASPA 155—Cape Evans) is designated to protect historic values. These include the Terra Nova Hut, established as part of the British Antarctic Terra Nova Expedition of 1910–1913, led by Captain R.F. Scott, and the surrounding artefacts.

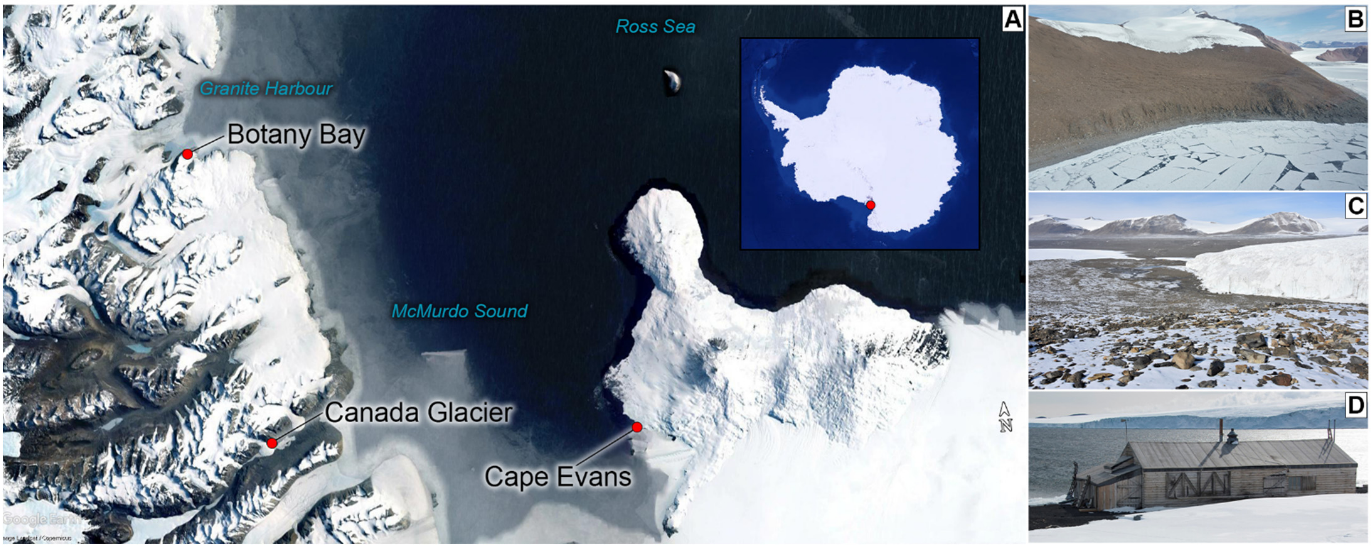

Figure 1. Location of the three Antarctic Specially Protected Areas mapped by drone. (**A**) McMurdo Sound; (**B**) photo of Botany Bay ASPA 154 taken by Ashray Doshi; (**C**) photo of Canada Glacier ASPA 131 from the top of the ASPA taken by Len Gillman; and (**D**) photo of Cape Evans ASPA 155 taken by Len Gillman.

2.1.1. Botany Bay ASPA 154

The Botany Bay ASPA was established on Cape Geology in the south-western corner of Granite Harbour, southern Victoria Land (Figure 1). The Area comprises a glacial catchment which steeply slopes to a rocky foreshore (Figure 1A) and is extremely species rich for such a high-latitude location, and it is one of the richest sites in the Ross Sea region [16].

The area includes a high diversity and abundance of lichens (at least 30 species), bryophytes (9 species) and algae (at least 85 taxa) (Figure 2A,B). In addition to the biological values described, the area contains the remains of a rock shelter and associated artefacts of historical importance (from the British Antarctic Expedition 1910–1913) (Figure 2C). This is known as Granite House, designated as Historic Site and Monument (HSM) No. 67. Measure 4 (1995) (Figure 2C).

The management plan for ASPA 154 (https://www.ats.aq/devph/en/apa-database/58 (accessed on 31 December 2021)) records that the primary reason for the designation of the site as an ASPA is to protect the Area's unusual ecological features and its exceptional scientific and historic values. The pre-existing vegetation maps are at low resolution and based on approximated density of vegetation cover, derived from a visual census of 190 plots (50 × 50 cm, 20 × 10 cm, and 8 × 4 m), which took multiple seasons with large groups of scientists starting in 2000 and ending in 2009 (Brabryn pers. comm. 2021) [16,17].

Figure 2. (**A**) Crustose and foliose lichen on rocks in the Botany Bay ASPA; (**B**) bryophytes found on rock platforms in the Botany Bay ASPA; and (**C**) Granite House, designated as Historic Site and Monument (HSM) No. 67 in the Botany Bay ASPA.

2.1.2. Canada Glacier ASPA 131

Canada Glacier ASPA is situated in Taylor Valley, McMurdo Dry Valleys on the eastern side of Canada Glacier and to the north of Lake Fryxell (Figure 1). The ASPA covers an area of approximately 1.5 km^2 and was designated because it contains some of the most diverse vegetation (bryophytes and algae) in the McMurdo Dry Valleys. The Area is designated primarily to protect scientific and ecological values. It comprises soils on sloping ice-free ground with summer ponds and small meltwater streams draining from Canada Glacier towards Lake Fryxell. Most of the bryophytes occur in a wet area (referred to as 'the flush') close to the glacier, whereas algae are abundant in the wash and down the stream to the margins of Lake Fryxell. Water availability, temperature, and UV-B have been identified as three key drivers for vegetation composition, distribution and health in Antarctica [18–21].

The management plan for ASPA 131 records that the area is of regional significance and has exceptional scientific value for ecological investigation. The pre-existing vegetation map was also at low resolution and was based on approximated density of vegetation cover derived from a visual point-sampling method (https://www.ats.aq/devph/en/apa-database/36 (accessed on 31 December 2021)).

2.1.3. Cape Evans ASPA 155

The Cape Evans ASPA is situated on the western side of Ross Island (Figure 1) and is designated in the management plan to protect the Terra Nova Hut, which was built in January 1911 by the British Antarctic Terra Nova Expedition of 1910–1913, led by Captain Robert Falcon Scott (Figure 1C). It was subsequently used as a base by the Ross Sea party of Sir Ernest Shackleton's Imperial Trans-Antarctic Expedition of 1914–1917. The current management plan includes maps of the historic artefacts (https://www.ats.aq/devph/en/apa-database/59 (accessed on 31 December 2021)).

A range of external artefacts, including two anchors from the ship Aurora of the Imperial Trans-Antarctic Expedition, two instrument shelters, several supply dumps, the Cross on Wind Vane Hill and numerous smaller artefacts, are distributed around the site.

2.2. Drone Mapping

The drone imagery was collected at each of the sites during the 2015/2016 and 2017/2018 summer seasons (late January to early February) (Antarctica NZ Events K011A and K500). A total of three to seven days was spent conducting the surveys at each site. The number of days varied due to the site complexity and size. A custom built Polarfox fixed wing drone was equipped with a SLR Sony 5100 and was flown at 120 m above ground level (AGL) at Cape Evans and Canada Glacier for greater area coverage due to its 50 min flight time. A custom-built Bhremer^{TM} Octocopter was flown at 50 to 70 m AGL (depending on the terrain) equipped with both a Sony SLR 5100 for RGB, and a MicaSense RedEdge five-band multispectral sensor for more precise flights at higher resolution vegetation mapping at all three sites. The MicaSense sensor has a focal length of 5.4 mm, a field of view of 46 degrees, image resolution of 1280 × 960 pixels, and narrow bands, blue, green, red, red-edge and near infra-red (NIR). The MicaSense sensor was mounted with a slight off-nadir viewing angle to compensate for the multirotor tilt in forward motion. Mission Planner, an open-source flight planner, was used for flight planning, with a focus on planning missions to maximise the multispectral data collection. The aircraft were under autopilot control, programmed prior to launch, and photographs were taken at regular intervals to optimise overlap. A grid-style mission was conducted with 80% side and front overlap. The drones were equipped with RTK GNSS to geotag each image trigger.

The image sets for each flight were successfully rendered into orthomosaics that were later merged at the ASPA level. The flights were flown between 10 am and 6 pm, due to the consistently high position of the sun in polar regions during the summer months. There was minimal sun glare at the sites. The drone survey covered 90% of the Canada Glacier ASPA (total hectares 151); all of Botany Bay ASPA except for the glacier (total hectares 3800); and 100% of the Cape Evans ASPA (total hectares 5.5).

To georeference the orthoimages for optimal horizontal and vertical accuracy, ground control points (GCPs) were established across the full extent of each study area but away from sensitive areas (48 GCPs at Canada Glacier, 72 GCPs at Botany Bay and 25 GCPs at Cape Evans) [22]. These targets were 25 cm crosses with marks to identify the centre point (these were all removed following the data collection). Each GCP centre was surveyed using a Septentrio® GNSS system. The base positions were surveyed in and post-processed using AUSPOS. In addition, points were recorded using a Septentrio® RTK Rover within random vegetation patches to validate and assess the accuracy of the vegetation maps. At each point, we recorded presence and absence of the taxonomic groups bryophyte, lichen and cyanobacteria in order to establish the accuracy of the drone-based mapping. This procedure may not be necessary for future monitoring.

UAV Data Collection Challenges

The use of drones on automated flight paths in Antarctica for mapping required the resolution of many technical challenges such as proximity to the magnetic pole, extreme cold, high winds and weak GPS coverage. In order to efficiently map areas on pre-programmed flight paths, standard platforms required specific mechanical and software modifications. We overcame these challenges by custom building the platforms to minimise heat loss, and customising the autopilot for waypoint navigation in high latitudes by making the navigation systems more robust to compass inconsistencies. In addition, batteries were pre-warmed to >20 °C and insulated with a polar fleece shell. An endurance penalty of 15% was applied to flight plans to account for operations in the cold.

2.3. Analysis

Both the RGB and multispectral imagery were processed with Pix4D Mapper™ using structure from motion (SfM) techniques to generate high-resolution digital surface models (DSM) and orthomosaics [10]. The GCPs were used to improve the overall model accuracy in Pix4D. The multispectral images were radiometrically corrected using the MicaSense reflectance calibration panel and correction values for each band. The final multispectral maps were five-band orthomosaics with resolution ranging from 3.5 to 5 cm per pixel, depending on altitude flown, and the RGB maps were three-band orthomosaics ranging from 0.5 to 1.0 cm pixel resolution. The RGB orthomosaic at Cape Evans was used to manually digitise, with sub-centimetre accuracy, the walking trails, heritage features and historic buildings. The multispectral orthomosaic from Botany Bay was classified in the ESRI Software, ArcMap 10.7, using the SAVI (soil-adjusted vegetation index) [23]. The equation is as follows:

$$((\mathrm{NIR} - \mathrm{Red})/(\mathrm{NIR} + \mathrm{Red} + \mathrm{L})) \times (1 + \mathrm{L})$$

where "L" is a constant value between 0 and 1 referring to the amount of green vegetation cover aimed at minimising the influence of soil brightness variations across the input image. Due to the arid Antarctic environment, and extent of dry soil, 0.5 was chosen [23].

At Canada Glacier, we experienced heavy snow fall halfway through the 2017/2018 field season and thus had accumulated patches of snow cover during some flights. To avoid misclassification of the snow patches, we used a Modified Snow Mask Index calculated in QGIS (https://qgis.org (accessed on 15 October 2021)) using the raster calculator. The equation is:

$$((\text{Green} - \text{NIR})/(\text{Green} + \text{NIR} + \text{L})) \times (1 + \text{L})$$

Then we used a modified SAVI (known as MSAVI) on the unmasked areas that were not covered in snow. The MSAVI equation is as follows:

$$(0.5) \times (2 \times (\text{NIR} + 1) - \sqrt{}((2 \times \text{NIR} + 1)2 - 8 \times (\text{NIR-Red})))$$

Once the indices were calculated we used thresholds to reclassify cells into taxonomic groups in ArcMap 10.7.

For the management plan maps, the raster resolution was converted to cell sizes of 1 m^2 before determining the cover abundance (CA) of vegetation. The "Create fishnet" tool in ArcMap 10.7 was then used to calculate the CA (within 1 × 1 m grids) over the entire ASPA. The grid was intersected with the SAVI and MSAVI maps and the percentage cover for each taxonomic group was then calculated. The categories of CA mapped for each vegetation class (total vegetation at Canada Glacier, and bryophytes, cyanobacteria and lichen at Botany Bay) were: Blank, 0–5%; Green, 6–20%; Yellow, 21–40%; Orange, 41–60%; and Red, 61–100%. The vegetation maps differed in the number of vegetation classes reported due to differences in the vegetation associations and to reflect information reported in previous ASPA Management Plans for each site.

An additional accuracy assessment was conducted using the ground-truthed points that were collected in the field. Ground truth points for areas of bryophytes, lichens and cyanobacteria were located on site during the expedition. Accuracy was calculated using Cohen's Kappa coefficient to measure of how closely the vegetation type in the classified map matched that recorded at the ground truth points, while controlling for the expected accuracy of a random classifier. Kappa is given by:

$$K = \frac{P_{observed} - P_{chance}}{1 - P_{chance}}$$

3. Results

3.1. Botany Bay ASPA 154

The drone surveys generated highly detailed maps for moss, cyanobacteria and lichen cover in the Botany Bay ASPA. These were down-sampled from less than one square centimetre per pixel to 1 × 1 m due to planning requirements for the 2018 ASPA Management Plan (Figure 3A–C). The classification model clearly illustrates the areas of vegetation throughout the protected area. Vegetation was concentrated around watercourses derived from the small glacier at the top of the ASPA. The accuracy of overall vegetation and bryophyte classification was very high (user accuracy = 0.974 and 0.900 respectively, kappa coefficient = 0.940, Table 1). Much of the lichen and cyanobacteria in this ASPA is black or grey and detection of these groups was less accurate and, in the case of lichens, most likely an overestimate of abundance (user accuracy = 0.350 and 0.776 respectively).

The maps that we generated from this project were used in the revised management plan for ASPA 154 which was submitted to the 42nd ATCM (Czech Republic, July 2019) and adopted unanimously by the Parties with no corrections [24].

Our maps of Botany Bay indicate a lesser extent of cover and lower densities of bryophyte vegetation than the previous maps. It is not clear, however, if this is due to change over time or due to the greater precision in our mapping.

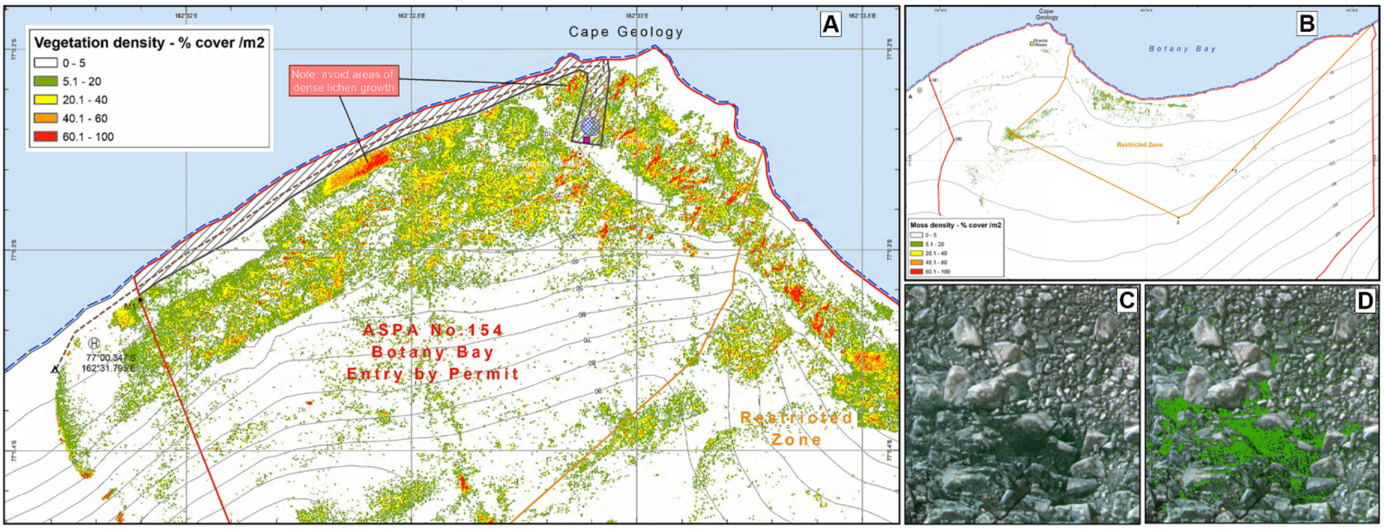

Figure 3. Botany Bay ASPA 154 (management plan maps from the Antarctic Treaty Secretariat's Antarctic Protected Area database (https://documents.ats.aq/recatt/att652_e.pdf, accessed on 2 February 2022)): (**A**) drone survey maps of total vegetation density (% within 1 m^2 cells); (**B**) bryophyte density (% within 1 m^2 cells); (**C**) photo from drone of 4 m^2 showing RGB image of bryophytes amongst rocks; (**D**) classified moss beds in green for the same area as in (**C**).

Table 1. Accuracy assessment of vegetation classification at Botany Bay ASPA including the accuracy for each class. The combined overall accuracy between the classified features and referenced data ("Overall Accuracy") and the kappa coefficient estimate of accuracy (values can range from 0 to 1, with 0 signifying that the classification is entirely random and 1 signifying entirely non-random).

Class	User Accuracy	Producer Accuracy
Bryophytes	0.900	0.990
Lichens	0.350	0.400
Cyanobacteria	0.776	0.600
No vegetation	0.992	0.977
Overall Accuracy	0.974	
Kappa Coefficient	0.940	

3.2. Canada Glacier ASPA 131

We generated a detailed vegetation map (Figure 4) in which the classification model clearly demarcated the areas of dense and sparse vegetation throughout the ASPA. Due to management planning requirements specific to this site, we did not split vegetation into sub-classes. The accuracy of the vegetation classification was again very high (kappa coefficient = 0.959, Table 2). The similarity between the kappa coefficient and overall accuracy (0.974) indicates that there is little or no bias in the land cover classes (Table 2). The vegetation was mostly concentrated around the meltwater pond and watercourses associated with Canada Glacier (Figure 4).

3.3. Cape Evans ASPA 155

We generated detailed RGB 2D and 3D orthomosaics of the Cape Evans ASPA (Figure 5A). Sub-centimetre resolution was obtained of the hut, outer buildings and artefacts. We detected individual footprints in the snow and in the gravel near the hut (Figure 5B), and slide trails created by Weddell Seal (*Leptonychotes weddellii*) movements up from the beach. The chain where the sled dogs were tied (Figure 5C) and a food cache of mutton bones were clearly defined (Figure 5D). The latter artefact was rediscovered during this event as the glacier had retreated, exposing the cache for the first time in many years.

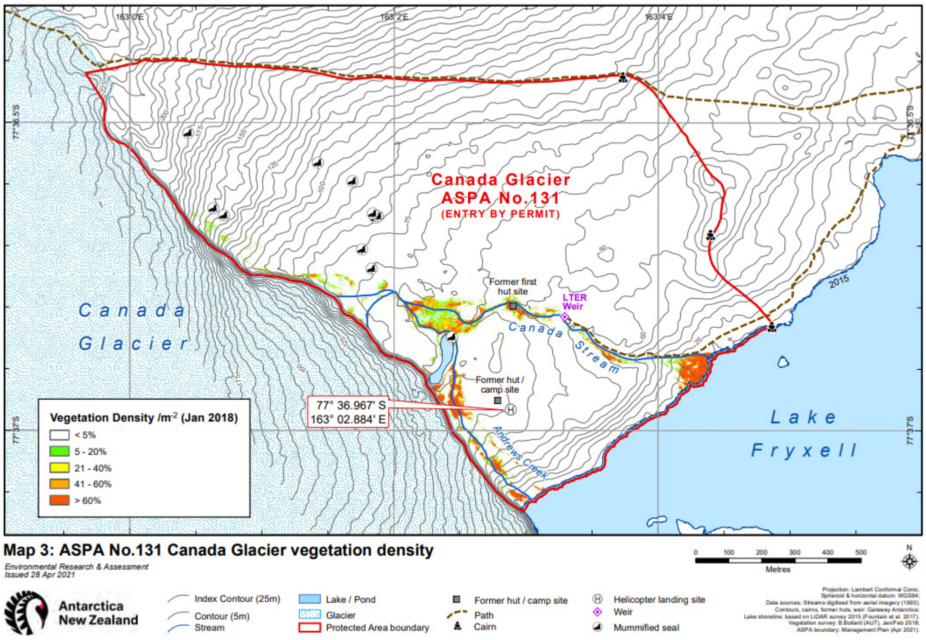

Figure 4. Canada Glacier ASPA 131 management map showing vegetation classification from the drone surveys (management plan and maps taken from the Antarctic Treaty Secretariat's Antarctic Protected Area database (https://www.ats.aq/documents/recatt%5Catt683_e.pdf, accessed on 2 February 2022)).

Table 2. Accuracy assessment of vegetation classification at Canada Glacier including the accuracy for each class. The combined overall accuracy between the classified features and referenced data ("Overall Accuracy") and the kappa coefficient estimate of accuracy.

Class	User Accuracy	Producer Accuracy
Vegetation	1.000	0.900
No Vegetation	0.967	1.000
Overall Accuracy	0.974	
Kappa Coefficient	0.959	

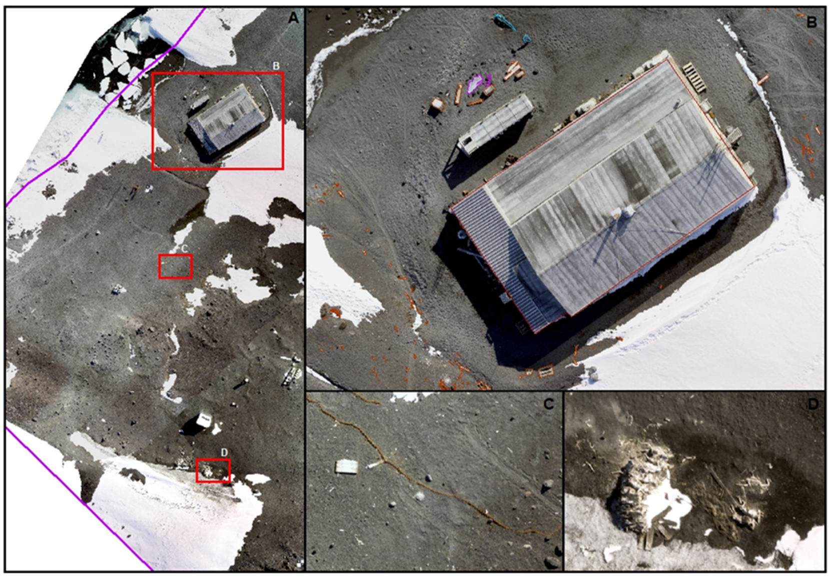

Figure 5. (**A**) RGB orthomosaic of Terra Nova Hut (Scott's hut) at Cape Evans, Ross Island, Antarctica based on drone imagery; (**B**) close up of the hut showing artefacts surrounding the building, in addition to footprints on the snow and all around the buildings; (**C**) close up of the chain that was used to tie the sled dogs; and (**D**) close up of the cache of mutton bones that was exposed during the summer season of 2015/2016.

4. Discussion

The pre-existing maps (see ASPA 154 (https://www.ats.aq/devph/en/apa-database/58 (accessed on 1 December 2021); ASPA 131 https://www.ats.aq/devph/en/apa-database/36 (accessed on 31 December 2021); and ASPA 155 https://www.ats.aq/devph/en/apa-database/59 (accessed on 31 December 2021)) for each of the three Antarctic Specially Protected Areas we surveyed were useful for the purposes of identifying the values of the sites. However, they provided little detailed information to inform management actions and nor did they provide any utility in identifying changes in vegetation cover or artefact status over time.

Our revised vegetation maps provide far higher levels of accuracy and resolution, and a much greater degree of confidence in the spatial coverage of the vegetation. Bryophytes and lichens are the key component autotrophs in the Ross Sea region, where vascular plants do not occur, and cyanobacteria is the main component within the meltwater streams and ponds. They are restricted to small areas of ice-free land where there is also sufficient summer melt water. Bryophyte vegetation was mapped with a very high degree of accuracy and therefore enables the monitoring of small changes in density and cover over short periods of time. Lichen and cyanobacteria monitoring will require modified methods due to the difficulty in demarcating the black and grey colours of these taxa from shadows, rocks and gravels.

For the first time, we have been able to demonstrate that the use of drone technology provides the means for undertaking quick protected area surveys that are low impact, inexpensive and highly repeatable. The resolution we obtained using drones (0.5 to 5 cm) compares favourably with the resolution available from satellite imagery (0.5 to 5 m) for mapping cryptic vegetation patches (where patches can range in size from 1 to 100 cm). Even with the highest resolution satellite imagery available commercially, small patches would be missed due to their limited ground sampling distance. As such, drone survey methods will be of particular value to environmental managers and policy makers; future changes in overall vegetation cover and broad taxa distributions can be easily discerned with repeat surveys. The ability to map extremely sensitive areas, such as the fragile moss beds in Antarctica, without entering the protected area, and thereby eliminating the potential for damage during the process of surveying, will be of considerable conservation utility. We have demonstrated that drone surveys can provide quantifiable information on human impacts, such as track formation, within sensitive areas. Subsequent changes to these protected areas due to either natural variability or climate forcing can now be measured with subsequent drone surveys. This approach provides a critical advancement in monitoring change, especially changes in features for which the areas are protected. The use of drone remote sensing technology will therefore enable more relevant management actions.

Our results show that the extent and density of vegetation in the protected areas we mapped is not as great as the previous management plan maps would suggest, especially for the Botany Bay ASPA. However, because of the lack of detail in the previous maps, it is not clear if this difference is due to change in the extent and density of vegetation, or simply due to the lack of precision evident in the earlier mapping or a result of climatic change. However, we now have precise vegetation maps against which future changes can be measured. Similarly, any future deterioration, movement or loss of artefacts will be detectable with subsequent mapping.

As a demonstration of the environmental and conservation benefits of using drones and to help address some of the shortfalls in protected area monitoring, we tested the utility of using remote sensing drone technology to survey three protected areas in the Ross Sea region of Antarctica. The high-quality maps we produced from incident-free flying demonstrate that drone technology can provide a level of monitoring capability to effectively track changes in protected areas, both in terms of vegetation and historical artefacts. Therefore, this technology can close a major gap in conservation management practice, especially in remote, sensitive environments such as those presented in Antarctica.

It is recommended that conservation managers take advantage of these new technological methods by including regular drone-supported surveys within conservation management plans and policies for protected areas. This will result in more accurate site mapping and provide managers with the data to monitor change over both short and long timeframes.

Author Contributions: Conceptualization, B.B., A.D., N.G., C.P. and L.G.; methodology, B.B., A.D. and L.G.; software, B.B. and A.D.; validation, B.B., A.D. and L.G.; formal analysis, B.B. and A.D.; investigation, B.B., A.D., L.G. and C.P.; resources, A.D.; data curation, B.B. and A.D.; writing—original draft preparation, B.B., A.D., N.G. and L.G.; writing—review and editing, B.B., A.D., N.G., C.P. and L.G.; visualization, B.B. and A.D.; project administration, B.B., A.D., N.G., C.P. and L.G.; funding acquisition, B.B., N.G. and A.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by a NZARI Research Grant in 2015, the Institute for Applied Ecology New Zealand and funding from the AUT Drone Lab. Antarctica New Zealand provided field logistics support for events K011 and K500.

Data Availability Statement: The data supporting the results in the paper are archived in the SCAR Antarctic Database: https://www.biodiversity.aq/ (accessed on 15 September 2018).

Acknowledgments: The authors are extremely grateful to Antarctica New Zealand for staff engagement and field logistical support for events K011 and K500, the Antarctic Heritage Trust for training and access to Scott's Hut, and to staff at Air Traffic Control Services (Mac Centre, McMurdo Station, US Antarctic Program) for supporting our UAV flight program. The research was partly funded by an NZARI Research Grant in 2015, the Institute for Applied Ecology New Zealand (AENZ) and contract funding from the AUT Drone Lab. Thank you to Steve Pointing (Department of Biological Sciences, National University of Singapore) and Mark Orams (Auckland University of Technology) for their contributions and support. Thanks to Colin Harris (Environmental Research & Assessment) for cartographic support and production of management plan maps. The authors would like to thank the following Master of GIS students for their dedication and hours of enthusiastic GIS volunteering for this project: Ryan Smith, Aamir Bonamis and Stace Ellis. The authors would like to also acknowledge and thank Rebecca Jarvis and Melinda Waterman, who were invaluable field team members in the 2015/2016 and 2018/2019 seasons, respectively. In particular, the contributions from the University of Wollongong team (Melinda Waterman and Sharon Robinson) form the basis of future publications and ongoing research collaborations.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Adams, V.M.; Iacona, G.D.; Possingham, H.P. Weighing the benefits of expanding protected areas versus managing existing ones. *Nat. Sustain.* **2019**, *2*, 404–411. [CrossRef]
2. Kevin, A. Hughes, Peter Convey, John Turner. Developing resilience to climate change impacts in Antarctica: An evaluation of Antarctic Treaty System protected area policy. *Environ. Sci. Policy* **2021**, *124*, 12–22. [CrossRef]
3. Wauchope, H.; Shaw, J.D.; Terauds, A. A snapshot of biodiversity protection in Antarctica. *Nat. Commun.* **2019**, *10*, 946. [CrossRef] [PubMed]
4. Chown, S.L.; Brooks, C.M.; Terauds, A.; Le Bohec, C.; van Klaveren-Impagliazzo, C.; Whittington, J.D.; McGeoch, M. Antarctica and the strategic plan for biodiversity. *PLoS Biol.* **2017**, *15*, e2001656. [CrossRef] [PubMed]
5. Hughes, K.A.; Ireland, L.; Convey, P.; Fleming, A.H. Assessing the effectiveness of specially protected areas for conservation of Antarctica's botanical diversity. *Conserv. Biol.* **2016**, *30*, 113–120. [CrossRef]
6. Shaw, J.; Terauds, A.; Riddle, M.J.; Possingham, H.P.; Chown, S.L. Antarctica's protected areas are inadequate, unrepresentative and at risk. *PLoS Biol.* **2014**, *12*, e1001888. [CrossRef]
7. Hughes, K.A.; Pertierra, L.R.; Walton, D.W.W. Area protection in Antarctica: How can conservation and scientific research goals be managed compatibly? *Environ. Sci. Policy* **2013**, *31*, 120–132. [CrossRef]
8. Cajiao, D.; Benayas, J.; Tejedo, P.; Leung, Y.-F. Adaptive Management of Sustainable Tourism in Antarctica: A Rhetoric or Working Progress? *Sustainability* **2021**, *13*, 7649. [CrossRef]
9. Turner, D.; Lucieer, A.; Malenovský, Z.; King, D.; Robinson, S.A. Assessment of Antarctic moss health from multi-sensor UAS imagery with Random Forest Modelling. *Int. J. Appl. Earth Obs. Geoinf.* **2018**, *68*, 168–179. [CrossRef]
10. Bollard-Breen, B.; Brooks, J.; Jones, M.; Robertson, J.; Betschart, S.; Kung, O.S.; Cary, S.C.; Lee, C.K.; Pointing, S.B. Application of an unmanned aerial vehicle in spatial mapping of terrestrial biology and human disturbance in the McMurdo Dry Valleys, East Antarctica. *Polar Biol.* **2015**, *38*, 573–578. [CrossRef]

11. Turner, D.; Lucieer, A.; Watson, C. An automated technique for generating georectified mosaics from ultra-high resolution unmanned aerial vehicle (UAV) imagery, based on structure from motion (SfM) point clouds. *Remote Sens.* **2012**, *4*, 1392–1410. [CrossRef]
12. Fudala, K.; Bialik, R.J. Breeding Colony Dynamics of Southern Elephant Seals at Patelnia Point, King George Island, Antarctica. *Remote Sens.* **2020**, *12*, 2964. [CrossRef]
13. Korczak-Abshire, M.; Kidawa, A.; Zmarz, A.; Storvold, R.; Karlsen, S.R.; Rodzewicz, M.; Chwedorzewska, K.; Znój, A. Preliminary study on nesting Adélie penguins disturbance by unmanned aerial vehicles. *CCAMLR Sci.* **2016**, *23*, 1–16.
14. Leary, D. Drones on ice: An assessment of the legal implications of the use of unmanned aerial vehicles in scientific research and by the tourist industry in Antarctica. *Polar Record* **2017**, *53*, 343–357. [CrossRef]
15. ATCM. Environmental Guidelines for Operation of Remotely Piloted Aircraft Systems (RPAS) in Antarctica (v 1.1). Adopted by Means of Resolution 4 (2018) by the 41st Antarctic Treaty Consultative Meeting, Buenos Aires. 2018. Available online: http://www.iau.gub.uy/wp-content/uploads/2019/07/Environmental-guidelines-for-operation-of-Remotely-Piloted-Aircraft-Systems.pdf (accessed on 30 December 2021).
16. Seppelt, R.; Turk, R.; Green, A.; Moser, G.; Pannewitz, S.; Sanchos, L.; Schroeter, B. Lichen and moss communities of Botany Bay, Granite Harbour, Ross Sea, Antarctica. *Antarct. Sci.* **2010**, *22*, 691–702. [CrossRef]
17. Schroeter, B.; Green, T.G.A.; Pannewitz, S.; Schlensog, M.; Sancho, L. Summer variability, winter dormancy: Lichen activity over 3 years at Botany Bay, 77S latitude, continental Antarctica. *Polar Biol.* **2011**, *34*, 13–22. [CrossRef]
18. Clarke, L.J.; Robinson, S.A.; Hua, Q.; Ayre, D.J.; Fink, D. Radiocarbon bomb spike reveals biological effects of Antarctic climate change. *Glob. Chang. Biol.* **2012**, *18*, 301–310. [CrossRef]
19. Newsham, K.K.; Robinson, S.A. Responses of plants in polar regions to UVB exposure: A meta-analysis. *Glob. Chang. Biol.* **2009**, *15*, 2574–2589. [CrossRef]
20. Wasley, J.; Robinson, S.A.; Lovelock, C.E.; Popp, M. Some like it wet—Biological characteristics underpinning tolerance of extreme water stress events in Antarctic bryophytes. *Funct. Plant Biol.* **2006**, *33*, 443–455. [CrossRef]
21. Wasley, J.; Robinson, S.A.; Turnbull, J.D.; King, D.H.; Wanek, W.; Popp, M. Bryophyte species composition over moisture gradients in the Windmill Islands, East Antarctica: Development of a baseline for monitoring climate change impacts. *Biodiversity* **2012**, *13*, 257–264. [CrossRef]
22. Agüera-Vega, F.; Carvajal-Ramírez, F.; Martínez-Carricondo, P. Assessment of photogrammetric mapping accuracy based on variation ground control points number using unmanned aerial vehicle. *Measurement* **2017**, *98*, 221–227. [CrossRef]
23. Huete, A.R. A soil-adjusted vegetation index (SAVI). *Remote Sens. Environ.* **1988**, *25*, 295–309. [CrossRef]
24. ATCM (2019) ATCM Antarctic Treaty Consultative Meeting XLII, Final Report. 2019. Available online: https://www.ats.aq/devAS/Info/FinalReports?lang=e (accessed on 31 December 2021).