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Our footprint on Antarctica competes with nature for rare ice-free land

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Abstract/Summary Paragraph

Construction and operation of research stations present the most pronounced human impacts on the Antarctic continent across a wide range of environmental values. Despite Antarctic Treaty Parties committing themselves to the comprehensive protection of the environment, data on the spatial extent of impacts from their activities have been limited. To quantify this, we examined the area of building and ground disturbance across the entire continent using GIS mapping of satellite imagery. Here, we report the footprint of all buildings to be >390,000 m^2, with an additional disturbance footprint of >5,200,000 m^2 just on ice-free land. These create a visual footprint similar in size to the total ice-free area of Antarctica, and impact over half of all large coastal ice-free areas. Our data demonstrate human impacts are disproportionately concentrated in some of the most sensitive environments, with consequential implications for conservation management. This is the highest resolution measurement of the extent of infrastructure across the continent to-date and can be used to inform management decisions to balance sustainable scientific-use and environmental protection of the Antarctic environment.

Antarctica is the world's largest natural reserve, and the Antarctic Treaty System requires participating countries to monitor the impacts from their activities[1]. Construction, operation and abandonment of research stations in Antarctica currently cause the most prominent human impacts on a wide range of environmental values[2]. Recent research attention into how humans impact the continent has focused on threats from non-native species, climate change, and contaminants[2-5], but there has been limited consideration of the expanding development of infrastructure[6,7]. To address this gap, we used GIS mapping of satellite imagery from 2005-2016 to create the most accurate spatial dataset of human pressure across the entire Antarctic continent. The footprint of buildings[8] across all regions were measured, along with surface disturbance to ice-free land, due to these rare areas of the continent supporting the highest taxonomic and ecological diversity, and being essential habitat for iconic species such as Adélie penguins[9,10]. As we anticipate a future expansion of human impacts[7,11,12], spatially explicit information on such threats is crucial for Antarctic Treaty signatories to sustainably protect the Antarctic environment within a systematic conservation framework[6], while maintaining access to these areas for science. This information has multi-disciplinary consequences, can be used to inform conservation decision making for improved environmental management, encourage coordinated sharing of facilities[13], and to track impact and change.

The term 'footprint' is defined here as the spatial extent of human activities and associated impacts. Footprint in Antarctica can take many forms[8] with the most significant being the long-term physical modifications to terrestrial ice-free substrates/habitats ('disturbance footprint') and the placement of buildings and infrastructure across the continent ('building footprint'), including stations, runways, field huts, historical structures and abandoned sites, waste, and tourist camps. Associated with these are a spectrum of pressures including sewage discharge, hydrocarbon and heavy metal contamination, noise and visual impacts[2,8], which can all impact upon Antarctica's ecological, intrinsic, and scientific values. The paradox here is that these impacts, mainly attributed to supporting access for science, may conflict with the need to preserve untouched environments for research use as well as conservation commitments.

The cumulative growth of building and disturbance footprints in Antarctica began in 1899 with huts built by the heroic era explorers such as Scott and Shackleton. Substantial expansion, however, only began in the 1950s, initiated by the 12 original signatories to the Antarctic Treaty[14] prior to the Treaty entering into force in 1961. This growth has continued to increase, augmented by a further 41 new signatories, and a traditional expectation that building a station was required to gain decision-making Consultative Party status[15]. The current framework for comprehensive protection of the Antarctic environment is provided by the Protocol on Environmental Protection to the Antarctic Treaty (Madrid Protocol)[1], adopted in 1991. Prior to this, practices such as local dumping of waste (including hydrocarbons) and limited environmental assessments were common. Importantly, two-thirds of current stations were established before the adoption of the Protocol, with contemporary measurements of footprint reflecting this legacy.

The Madrid Protocol aims to protect the Antarctic environment, its dependent and associated ecosystems, and values[1]. Although some values are present across the whole Antarctic continent, such as those associated with ice sheets and glaciers, the small ice-free 'islands', spread across isolated coastal oases, mountain ranges, and nunataks, are the habitat for the majority of terrestrial species[16,17]. The coastal fringes of these areas are particularly important as they typically provide the best environmental envelope for flora and fauna[18], and accessibility for terrestrial-breeding marine vertebrates. Ice-free areas are also the most accessible locations for studying Antarctic landforms (e.g. fossils, soils, geomorphology)[19], further increasing the scientific value of these small areas[18]. We calculated the current total ice-free area of Antarctica to be 0.44% (54,274 km^2) and found 81% of all buildings to be within this diverse[10] environment (see *Methods* for background on this increased ice-free area estimate, up from 0.18–0.38%[20,21]). Indeed 76% of all buildings are situated in just 0.06% of Antarctica – the accessible ice-free areas within 5 km of the coast – clearly indicating that human impacts are disproportionately concentrated on the most environmentally significant areas of Antarctica.

By using GIS digitization of active and abandoned structures observed within satellite imagery (captured between October 2005 and December 2016 [median December 2011]), we mapped 158 locations with 5,342 individual vector-based ‘building’ polygons across Antarctica on both ice-covered and ice-free environments (Fig. 1). The total building footprint across Antarctica was 0.393 km^2 (Supplementary Table 1), an area equal to 73 USA football fields, a higher proportion of which were located within two hotspots of activity centred on coastlines of the Antarctic Peninsula and Ross Sea. Thirty signatory countries contributed to this total area; however, three accounted for the majority (54%).

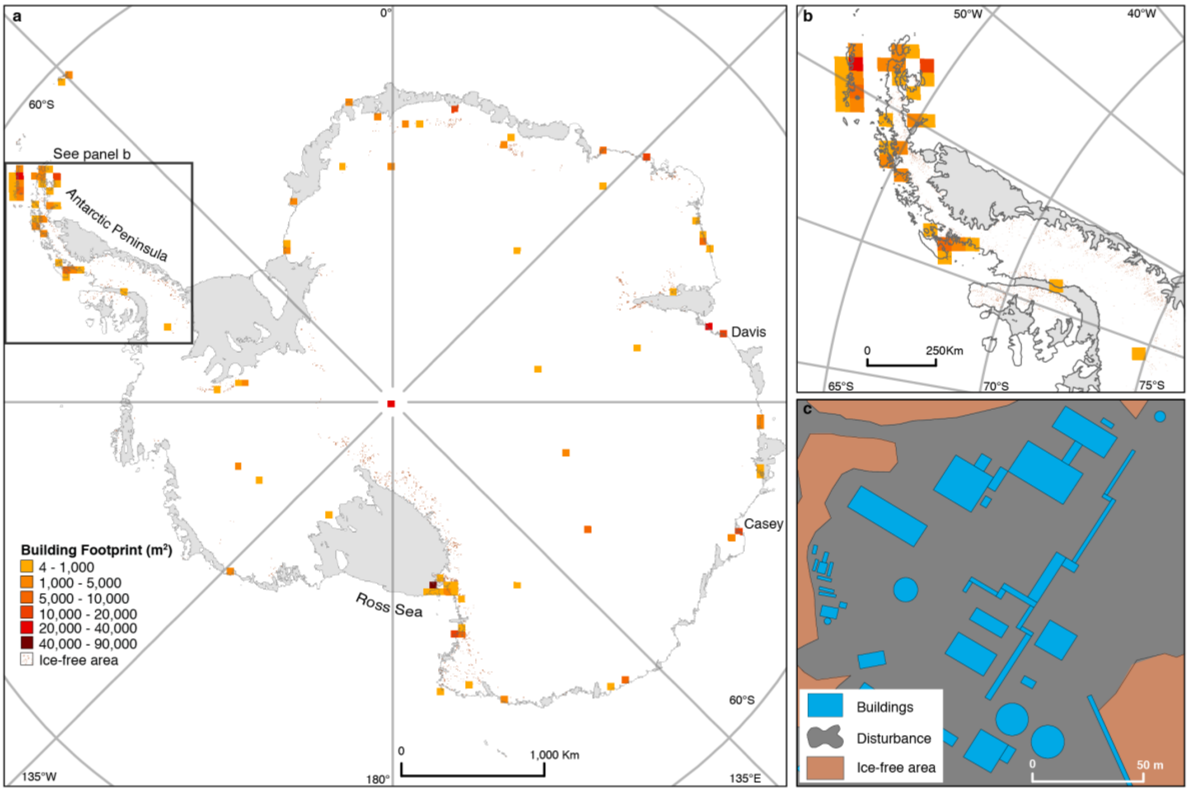

Fig. 1 Distribution of building footprint on Antarctica.
(**a**) The distribution and density of building footprint represented within 50x50km^2 cells. These cells may include multiple stations. (**b**) Shows the density of building footprint within the Antarctic Peninsula, the area acknowledged as the most developed and vulnerable to threats from climate change and non-native species. (**c**) Example of detail applied showing buildings and disturbance footprint mapped within Australia's Davis Station.

As aesthetic and wilderness values are given the same protection under the Madrid Protocol as scientific significance, we considered the visual footprint of buildings on the Antarctic landscape (Fig. 2). By applying a range of buffers according to the visible-distance of Antarctic infrastructure[22] (20 km planar km for stations, 10 km for abandoned stations and field camps, 5 km for refuges and field huts, and 5 km for automatic weather stations, historic sites, and monuments), we estimate the total visual footprint to extend up to 93,500 km^2 (including offshore visibility). When confined to onshore areas, this footprint was 58,500 km^2 (or 0.48% of Antarctica), a size similar to but larger than all ice-free areas on the continent. Ninety percent of this visual footprint was from station buildings. Although the areas shown here are considered to be the maximum visibility, and would be affected by factors including topography, the current visibility modelling that we have used[22] excludes surface modifications such as roads, runways, and maintained traverse routes which may increase this estimate once their viewshed is established.

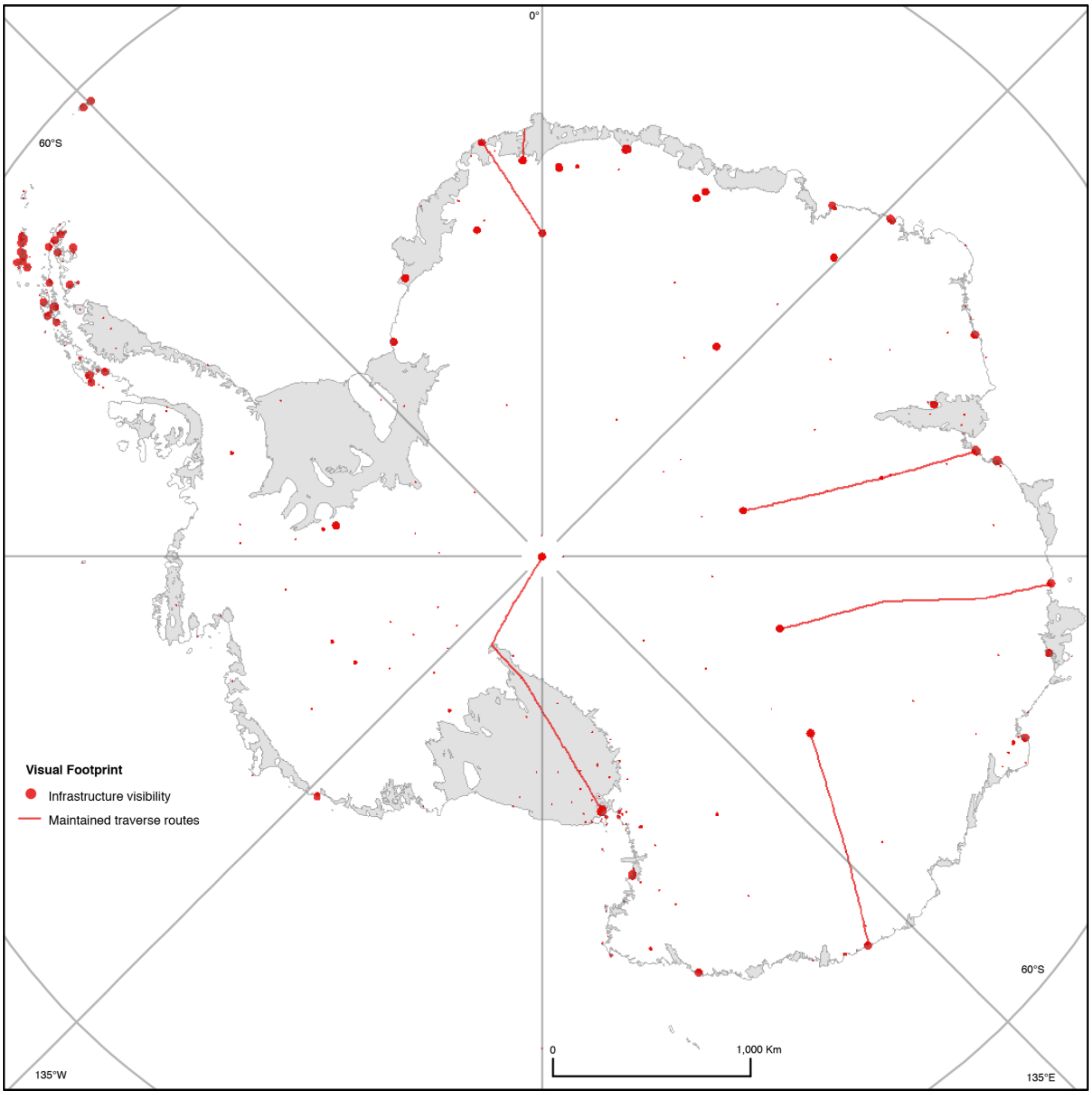

Fig. 2 Modelling of visual footprint of Antarctic infrastructure

Maximum visual footprint of Antarctic buildings in-scale applying visibility modelling by Summerson[22]. Even with conservative buffers applied at half the distances suggested by the modelling, the footprint still covers 26,400 km^2 (16,500 km^2 onshore only). While visibility distances are yet to be established for maintained traverse routes (shown here); they cover an estimated 6,169 km in distance, which would add over 12,000 km^2 to this footprint if visible from just 1 km.

The total disturbance area within ice-free environments from human activities was 5.242 km^2 (Supplementary Fig. 1). This equates to nearly 1,000 football fields, or 1,135 m^2 of disturbed ground for every person at an Antarctic research station (at peak capacity)[23]. We found some disturbance was present in more than half of all large ice-free coastal areas (>50km^2, <5km from the coast, n=15/29). Again, three countries contributed the majority (53%) of all detectable disturbance. Here, only visibly observed disturbance was mapped (e.g. roads, levelled areas, spoil piles), with further below-detection levels of disturbance expected due to the limitations of satellite imagery resolution[24], resulting in this likely being a cumulative underestimate (see *Sources of Error*). This total disturbance figure also excludes naturally and artificially remediated ground (e.g. the former Hallett Station site) where impacts associated with disturbance may still persist (e.g.[25,26]). While physical disturbance of ice-free ground does not guarantee negative biological impacts, there is evidence of detrimental effects from an increasing number of Antarctic environments and associated biota[27-29] threatening natural processes that have been ongoing for millennia. Furthermore, disturbance to ice-free areas is known to affect geomorphological, aesthetic, and wilderness values[30-33], and is associated with activity that can disturb wildlife[34].

Continent-wide, the median disturbance to building footprint ratio for facilities in all ice-free areas was 12:1 (mean 21:1, range 2:1 – 178:1). Several factors have contributed to variations in the disturbance footprint. Station configuration had a clear effect: de-centralised stations, with their buildings dispersed over a relatively large area, often have evidence of extensive road networks, while others have terrestrial runways situated away from the main station buildings (older stations, in particular, were deliberately dispersed for safety to ensure protection from fires spreading between buildings). De-centralised stations had disturbance ratios more than twice as large as centralised stations (i.e. a larger disturbance footprint for the same overall building area; mean=6.85:1 centralised, 17.0:1 de-centralised, $p < 0.001$). The effects of substrate and station size were less clear, with some aspects being inconsistent across different, but equally plausible models (see “Statistical Analysis” Supplementary

Information for model details). Within ice-free areas certain substrates are known to be vulnerable to disturbance[35,36], increasing the likelihood and rate that substrate modification occurs[31], enhancing its detectability within remote-sensed imagery. Additionally, the majority of stations are located in soil/gravel sites (n=60) rather than rock outcrops (n=17). The characteristics of softer soil environments mean they are readily utilised in earthworks and road construction which, when combined with environmental legacy impacts[31,35,36], has resulted in these locations typically having an enlarged disturbance footprint. Our data showed that centralised stations located on soil substrates had 70% higher disturbance to building area ratios compared to those located on rock (range 43% to 111% across the four plausible models; see Supplementary Information). However, based on the data available it was not clear whether substrate also had an effect with de-centralised stations, nor whether disturbance ratio varied by station size.

The biogeography of ice-free terrestrial Antarctica has been categorised into 16 Antarctic Conservation Biogeographic Regions (ACBRs)[10,20], with each ACBRs being a biologically and geographically distinct region. Half of all the terrestrial disturbance we quantified occurred in just two of these ACBRs – South Victoria Land and NW Antarctic Peninsula (Supplementary Table 2). The latter is recognised as part of the most biologically diverse area of the continent[18]. Two other ACBRs (Adélie Land and East Antarctica, known for their bryophyte flora and Adélie penguin colonies[37,38]) have relatively small ice-free areas and consequently had the highest percentage of disturbed ice-free land (both ~0.067%). Although the relative footprint area may appear small, the fine scale of our dataset (smallest site = $2m^2$) surpasses the resolution of any continent-wide habitat or biodiversity mapping. Therefore, local areas of footprint may disproportionately affect significant sites within a bioregion (e.g. Casey Station is situated within some of the most well-developed and extensive vegetation in continental Antarctica[10,38]). The layering of our data with high-resolution habitat datasets, as they become available, will enable further analyses.

Our dataset is the most comprehensive inventory of infrastructure across Antarctica and establishes a baseline, contributing to the Madrid Protocol's recognised need for regular and effective monitoring of environmental impacts by Antarctic Treaty countries. To date physical footprint data[8], beyond analyses based on point locations[39], were only available for a few stations[6,40,41], despite multiple calls for continent-wide measurements[40,42,43]. The availability of this dataset will also benefit efforts to map the global 'human footprint'[39,44]. As higher resolution imagery and data from ground-truthing become available our estimates will be refined.

A primary goal of the Madrid Protocol is protection of Antarctic values within a systematic geographical framework, this has yet to be achieved, with only ~1.5% of ice-free areas formally designated as Antarctic Specially Protected Areas (ASPAs)[20]. Our data, coupled with increasing information about the spatial distribution of environmental values and other threats[3,45], can be used to inform and rectify this situation[6]. For example, within the Marie Byrd Land bioregion 16,200m^2 of terrestrial disturbance was detected but there are no ASPAs; similarly within the Northeast Antarctic Peninsula the area of disturbance was nearly twice the size of the protected area. While the current ASPA coverage is already recognised as not providing equal representation in all bioregions[4,6,20], the uneven distribution of disturbance identified by this study will further help inform future protected area designations.

With the tension between increasing pressure for access to the continent[12], and an international commitment to protect the Antarctic environment, cognisance of the current state of our footprint on Antarctica is essential for achieving a sustainable balance of the two. Here, our analysis can be used to inform and objectively assess strategies employed by Antarctic national programs and tourism operators to achieve this goal. Such strategies include identifying and setting limits on station areas to prevent disturbance-creep into intact natural environments; using existing ice-free disturbed areas more efficiently (e.g. rationalisation and in-filling); aiming for low disturbance to building ratios; focusing operations in more resilient environments[19]; locating new facilities on ice-covered land; and for ongoing monitoring and reporting. These strategies may be particularly useful at sites where multiple parties are active; here our data can play an important role in the further designation and management of Antarctic Specially Managed Areas. Parties may also use these data to identify areas for focused restoration efforts of disturbed sites to reduce their current footprint and support effective environmental impact assessment, in particular understanding the environmental reference state in the location(s) of proposed activities. Finally, as scientific cooperation for projects is often fundamental and demonstrably successful in Antarctica, our findings should provide a useful incentive for better co-operation to allow international sharing of existing facilities and a higher level of importance for environmental impacts when planning new facilities, substantially assisting in the reduction of future footprint expansion.

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Materials & Correspondence

Requests for materials and correspondence should be directed to Shaun Brooks.

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Author Contributions

S.T.B. and D.M.B. initiated the research. S.T.B. led the development, GIS mapping and analysis, and writing of the manuscript. All authors contributed to further conceptual and content development, interpretation of the data, and drafting of the manuscript.

Competing Interests

We declare no competing interests.

List of Supplementary Information

Materials and Methods

Table 1. List of Footprint by location

Table 2. Footprint measured for each Antarctic Conservation Bioregion

Table 3. Summary of all models examined.

Fig. 1. Continent disturbance footprint

Fig. 2. Plot of disturbance to building footprint ratios for centralised and decentralised station configurations.

Fig. 3. Footprint mapping example

Fig. 4. Point locations of additional current and past infrastructure

Fig. 5. Footprint digitizing flowchart

Methods

Ice-free areas

Ice-free areas of Antarctica were determined within a GIS (ArcMap™ 10.3) by using established 'rock outcrop' datasets from the Antarctic Digital Database (ADD). In the footprint assessment conducted for this project, omissions of ice-free areas around research stations and ASPAs, that affected our analysis, were identified from both recent maps: high-resolution rock outcrop (SCAR ADD, https://www.add.scar.org/, downloaded 1 Dec 2017) and high-resolution rock outcrop from Landsat 8 (https://doi.org/10.5285/f7947381-6fd7-466f-8894-25d3262cbcf5, downloaded 1 Dec 2017). Differences between the maps were confirmed by comparing satellite imagery against the datasets' polygons. One example of this is provided by the 5.2km^2, entirely ice-free, Yukidori Valley (APSA 141). The former dataset correctly classified 75% of the ice-free area, compared to just 0.5% by the latter. Due to the inconsistencies between the two rock outcrop versions, the two datasets were merged by running the 'Union' function with the two layers within ArcMap. This was found to accurately capture ice-free areas more consistently, with a total area of 54,274 km^2 and 6,864 km^2 within five kilometres of a coastline-only version of the ADD Medium Resolution Coastline dataset. Percentages were calculated using a total land area for the Antarctic continent of 12,188,650 km^2 (SCAR Antarctic Digital Database, http://www.add.scar.org). While our estimate of ice-free areas may be conservative by being larger than existing estimates (44,900 km^2 and 21,745 km^2)[21], it ensured more accurate representation within our fine-scale analyses.

Footprint Assessment

The locations of all known buildings and sites of terrestrial disturbance in Antarctica were compiled from maintained lists including:

- COMNAP Antarctic Facilities Lists (2014, 2016, 2017); (https://www.comnap.aq/Members/SiteAssets/SitePages/Home/COMNAP%20Antarctic%20Facilities%20List%2031%20March%202017.xlsx)
- IAATO Peninsula tourism landing sites; (https://iaato.org/documents/10157/323623/Antarctic+Peninsula+Sites.pdf)
- AntON/WMO automated weather stations (AWS); (https://www.ats.aq/documents/ATCM40/ip/ATCM40_ip117_e.doc)
- NGA lighthouses; (https://msi.nga.mil/MSISiteContent/StaticFiles/NAV_PUBS/.../Pub111/Pub111bk.pdf)
- Antarctic Treaty historic sites and monuments (HSMs); and(www.ats.aq/documents/recatt/att580_e.pdf);
- Aircraft landing sites. (https://www.usap.gov/USAPgov/sciencesupport/GIS/documents/USAP_grundberg_fixedwing_v7.pdf; https://www.phys.hawaii.edu/elog/anita_notes/090805_112626/Field_Sites_08-09.pdf; https://www.usap.gov/USAPgov/sciencesupport/GIS/documents/FixedWingLandingFacilitesMap_2010-11.pdf).

This compilation was followed by a review of current national program websites to search for further information on field huts, refuges, and camps, as well as searching historical literature (e.g. [46]) for disused and abandoned stations.

Two main datasets were created, one containing the disturbance footprint, defined as 'visually detectable substrate disturbance within ice-free environments caused by compaction, clearing, earthworks and other landscape modification from human activities'; and building footprint, defined as 'the spatial area covered by built features'[8]. We found rectified nadir imagery with a resolution sufficient to identify and map buildings and/or disturbance at 104 national Antarctic facilities listed past and present with the Council of Managers of National Antarctic Programs (COMNAP) [23] and a further 54 locations of huts, camps, HSMs, abandoned sites, and lighthouses identified during our review. Footprint datasets were achieved by using aerial imagery as a base map, and manually digitizing discernable features into vector files in ArcMap (Supplementary Fig. 3). Sites that were discovered during the review but could not be digitized because of either insufficient satellite resolution (e.g. Druzhnaya-4), were too small to see (e.g. AWS), are buried in snow (e.g. Siple Station), or have been removed (e.g. World Park Base), were recorded as additional point layers in the dataset (Supplementary Fig. 4). The mapping was done using a Lambert Azimuthal equal area projection, centered on the South Pole, with the digitized files saved unprojected, based on a WGS84 horizontal datum.

The majority (93.5%) of the base maps used were accessed through Google Earth™ using primarily Digital Globe images, then CNES/Airbus, CNES/Astrium, and Landsat/Copernicus. The remaining base map sources included NSIDC Operation Icebridge images and national program mapping. When images from multiple dates were available a preference was applied to using the most recent image, followed by highest resolution, then least snow cover present. All images used were captured between October 2005 and December 2016. In nine instances, imagery from two dates was used, as snow cover obscured disturbance on more recent or higher resolution images. All Google Earth™ base map images were extracted and automatically rectified using El-Shayal Smart GIS software before being introduced to ArcMap. To obtain maximum resolution, aerial images were captured at an equivalent eye elevation between 100–343 meters. Overlapping mosaics of multiple images were used to cover larger stations that extended beyond the extent captured at this altitude (*e.g.* Supplementary Fig. 5).

The building footprint dataset was created by manually digitizing the area of features on ice and ice-free areas (see Supplementary Fig. 3). These included stations built on ice caps and ice shelves. As this layer mapped all discernable 'built' environments, it is expected to have included temporary items such as shipping containers, equipment storage and tents, and potentially, large vehicles such as trucks and buses. Vehicles that were obvious were not included, with the exception of aircraft wreckage. The resulting digitized layer was saved into a File Geodatabase Feature Class with 5359 individual polygons mapped.

The footprint of terrestrial disturbance was digitized using the same approach as by Brooks [24] (see Supplementary Fig. 3). Only disturbance visible from the imagery was mapped within ice-free areas south of 60º S. These included natural surfaces that appeared to be disturbed and compacted to a similar extent to gravel roads and other levelled areas, paved areas, and areas of earthworks including where spoil from road clearing is deposited. Without ground-truthing, we predict this method detected the heaviest levels of substrate modification, with substantially more lighter levels of disturbance actually present (see *Sources of Error*). We also conservatively excluded features which were not visible; such as sections of road obscured by snow cover. Terrestrial disturbance was, however, assumed directly under building footprints in all ice-free areas. This assumption is based upon the need for a building's foundations, the effects created by light obstruction, wind channeling, and snow drifts. The resultant digitized layer was saved into a File Geodatabase Feature Class with 767 individual polygons mapped. Disturbance and building footprint data associated with this project are stored at data.aad.gov.au (doi: 10.4225/15/5ae7af0fb9fcf).

Sources of Error

Within our dataset digitizing errors were expected to introduce the most error in the results. To check for error, the estimated building footprint layer for five stations was compared with known building sizes held by the Australian Antarctic Data Centre (http://data.aad.gov.au/aadc/portal/drill_down.cfm?gid=1). Of the 66 buildings cross-referenced, the new dataset had a mean area error of +2%, a mean measurement difference of +13.7m^2 (median +3m^2) (range -93 to +572m^2). As this project measured all visible built features across station environments (including fuel storage, pipes, and temporary structures), the total building footprint area provided could exceed some 'permanent building' or 'under roof' measurements published elsewhere. Furthermore, the measurements provided represent what was present on the date of the imagery, and buildings may have been built/removed, or disturbance created/rehabilitated, since.

A systematic validation of our disturbance estimates against on-ground measurements was not possible, due to the scale of our analyses and the fact that no on-ground measurements exist for the vast majority of the locations. In general, we expect that our disturbance values are underestimates, because of the limitations of the available image resolution and obscured ground surfaces (*e.g.* snow cover). As an anecdotal example, the long-term ecological monitoring project at McMurdo Station[35] measured on-ground disturbance at 2.5 km^2 whereas our estimate was 1.16 km^2. This is consistent with previous findings[24] which also demonstrated an underestimation of disturbance from aerial imagery following ground-truthing. Here, many features that may be obvious on-the-ground, such as walking tracks, were generally below the limit of detection with our methods. While we also conducted an in-depth review of remote locations (away from stations), some sites may have been overlooked.

As found in other studies using Google Earth™ images in research (e.g. [47]), error in the planimetric accuracy (the correct longitudinal/latitudinal placement of a feature on the Earth's surface) was expected to be small (<5m). Because this study was focused on land areas, minor location inaccuracies were considered to be inconsequential. It is acknowledged that image resolution, rectification, projection, distortion, and different image sources have the potential to introduce error. Additionally, some facilities (and disturbance) were known to be buried in ice/snow preventing their accurate detection. The outcome of these errors, combined with the cross-referencing results, suggest the disturbance footprint estimates presented here are likely to be conservative.

Statistical Analysis

All area estimates were calculated using ArcMap, based on using the digitized polygons and the Lambert Azimuthal equal area projection, centered on the South Pole. To provide the visual footprint results, we applied visibility distances modeled by Summerson[22] to the infrastructure mapped by this project. This involved applying buffers within a GIS to points of buildings of 20 km for stations, 10 km for abandoned stations and field camps, and 5 km for refuges and field huts, automatic weather stations, historic sites, and monuments. These buffer areas were then merged, dissolved to avoid overlapping measurements, and clipped to the ADD Antarctic medium resolution coastline to provide onshore/offshore measurements.

This model was based on planar distances, with acknowledgment that local topography may decrease (or increase) the distance specific infrastructure is visible, especially in sloping coastal areas where the majority of stations are located. To consider such error we also ran the modelling with more conservative buffers (10 km for stations, 5 km for abandoned stations and field camps, 2.5 km for refuges and field huts, and 1 km for automatic weather stations, historic sites, and monuments), with results provided in the caption for Fig. 2. Although more sophisticated visibility modelling incorporating topography is a step closer with the Reference Elevation Model of Antarctica (REMA) now providing a high-resolution DEM, the height of all infrastructure above ground level would need to be established to enable such analyses.

Large contiguous ice-free areas were identified by creating a layer aggregating rock outcrop polygons (ADD high-resolution rock outcrop) that were within a maximum distance of 1km of each other. This layer was then clipped to areas within 5km of a coastline-only version of the ADD Antarctic medium resolution coastline. Result were obtained through running queries against presence/absence of disturbance footprint within these layers.

Disturbance to building footprint ratios were calculated by dividing the disturbance area measured against the building area for COMNAP-listed locations within ice-free environments. These analyses required some exclusion of outlying data. The ratios provided for the continent included runways (n=68) but excluded stations where no disturbance was detected beyond the building footprint (n=13). These exclusions were sites of low intensity use (*e.g.* field huts), stations with buildings situated on and off ice, and where image resolution was insufficient to determine substrate disturbance. For the mean soil/gravel and rock outcrops ratios, runways were excluded as they create disproportionately large amounts of disturbance, with few buildings, producing high ratios that do not provide useful information in the context of the environmental management of a station area. One other outlier on King George Island was removed as it was a very small station (building footprint = 66m^2), with a road network possibly attributed to nearby stations, creating an unrepresentative ratio. For the ratio-trend analysis of 1,000m^2-10,000m^2 stations, we chose to exclude McMurdo because it is over eight times larger than the next-largest station, and its relationship of buildings to disturbance did not fit the general trend of the remaining locations. Station configuration (centralised/decentralised) was determined by assessing each location against a set of criteria. Here, centralised stations were classified as being concentrated around a single location, with similar distances between structures, and had minimal road networks extending beyond buildings. Decentralised stations had either non-concentrated layouts (often linear, or with several arms extending out), buildings were dispersed, roadways extended beyond the station area (often to remote buildings), or had separate runways. Station substrates (soil/gravel or rock outcrop) were determined by reviewing satellite images of the stations, descriptions within literature and Treaty documents, and eliciting expert advice from Treaty-inspection personnel.

To investigate whether disturbance to building ratios were affected by substrate (soil/gravel sites or rock outcrops), station building footprint, or station configuration (centralized or not) we fitted generalised linear models (GLMs) with negative-binomial distributions, using the mgcv package[48] in R 3.5.1[49]. We assumed that substrate and station size effects might vary with station configuration, and so we examined a set of models that included all combinations of the three variables as main effects, along with all combinations involving configuration as an interaction term. Models were compared using Akaike's information criterion (AIC)[50]. Four model structures yielded similar AIC scores that were better than all other models

(Supplementary Table 3). We considered these four models to be equally plausible (difference of AIC scores less than 2)[50] and based our interpretation and discussion on all four. The fits of these four models to the data are shown in Supplementary Fig. 2.

Additional data sources in figures:

Figures 1 & 2 and Supplementary Figures 1 & 4 are projected in WGS 1984 Antarctic Polar Stereographic, centred on the geographic South Pole. These use Antarctic Digital Database coastlines and rock outcrop layers, detailed previously in *Ice-free Areas* (http://www.add.scar.org). The maps were produced by S.T.B. in November 2018.

Data Availability

The data associated with this manuscript is stored and accessible at the Australian Antarctic Data Centre, Australia: Brooks, S.T. (2018, updated 2018) Our Footprint on Antarctica - Buildings, disturbance Australian Antarctic Data Centre - doi:10.4225/15/5ae7af0fb9fcf. A summarised excerpt of the GIS data is also available in Supplementary Table 1.

Methods-only References

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Supplementary Tables

Supplementary Table 1. Footprint measurements for locations. See seperate spreadsheet.

Supplementary Table 2. Footprint measured for each Antarctic Conservation Bioregion

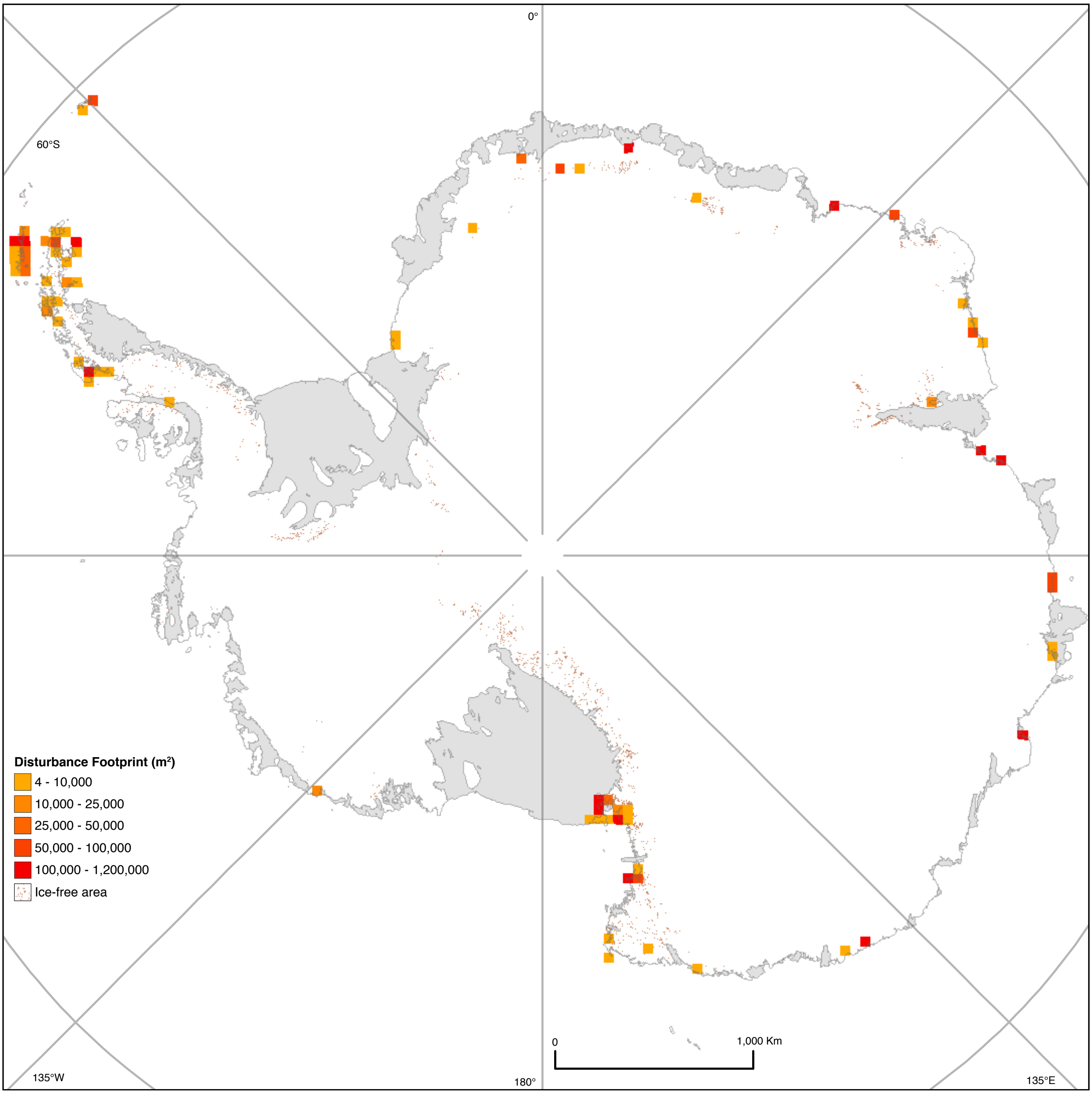
ACBR identifier	ACBR name	Total ACBR area (km^2)	Building Footprint (m^2)	Disturbance Footprint (km^2)	% of ACBR covered by disturbance footprint
ACBR1	North-east Antarctic Peninsula	1215	13157	0.6392	0.053
ACBR2	South Orkney Islands	160	682	0.0673	0.042
ACBR3	North-west Antarctic Peninsula	5183	62638	1.2109	0.023
ACBR4	Central South Antarctic Peninsula	4962	112	0.0013	0.000
ACBR5	Enderby Land	2188	20915	0.4157	0.019
ACBR6	Dronning Maud Land	5523	16523	0.2348	0.004
ACBR7	East Antarctica	1109	35520	0.7254	0.065
ACBR8	North Victoria Land	9431	19126	0.2127	0.002
ACBR9	South Victoria Land	10038	87953	1.4759	0.015
ACBR10	Transantarctic Mountains	18480	1183	0.0067	0.000
ACBR11	Ellsworth Mountains	2859	0	0	0.000
ACBR12	Marie Byrd Land	1128	1437	0.0162	0.001
ACBR13	Adelie Land	178	7164	0.1186	0.067
ACBR14	Ellsworth Land	217	0	0	0.000
ACBR15	South Antarctic Peninsula	2875	0	0	0.000
ACBR16	Prince Charles Mountains	5992	9141	0.1170	0.002

Based on ACBR polygon layer (data.aad.gov.au, doi:10.4225/15/5729930925224).

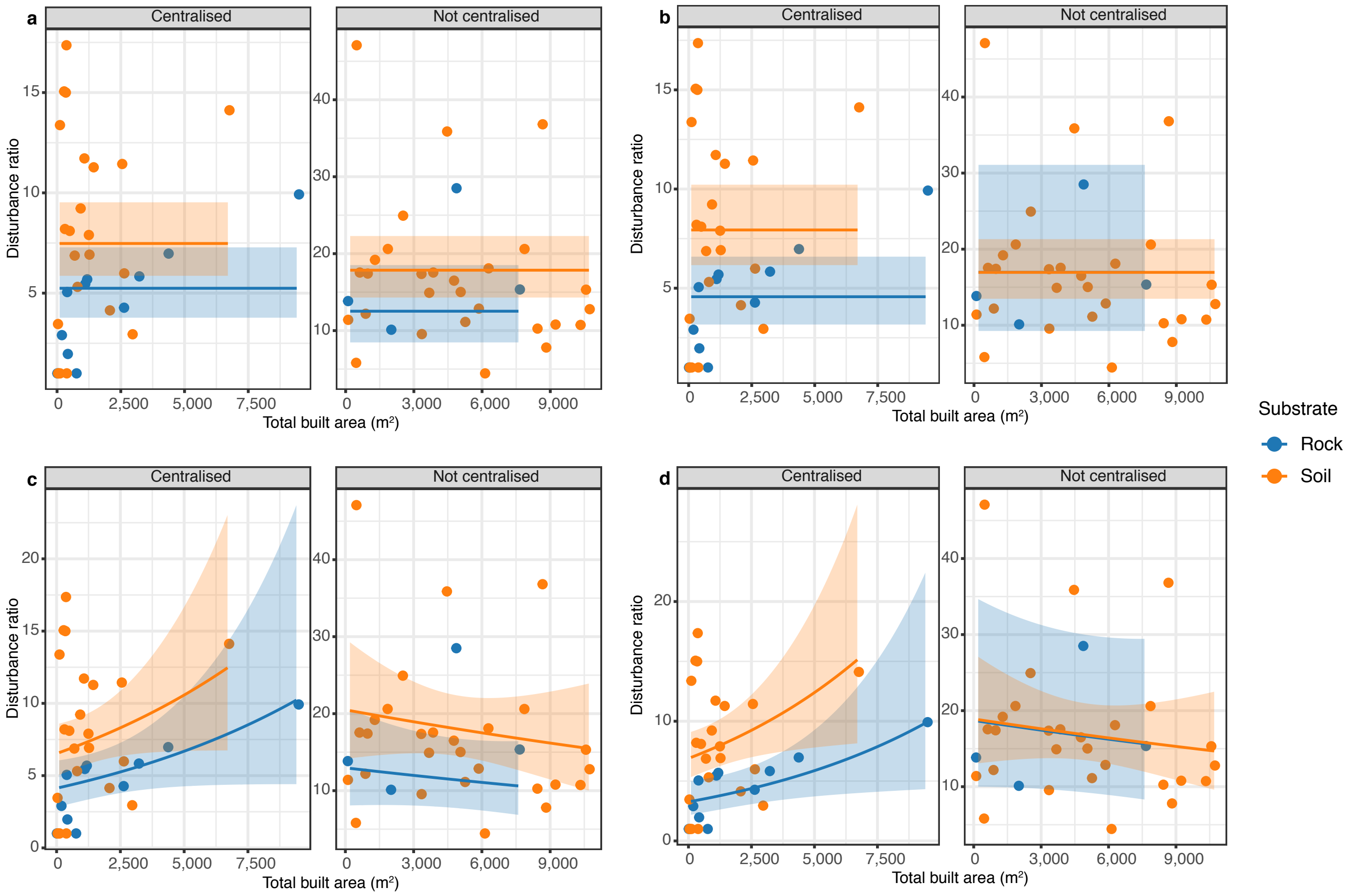
Supplementary Table 3. Summary of all models examined.
“Model terms” indicates the model structure (+ indicates main effects, * indicates interaction terms). AIC gives the Akaike information criterion for the model, and delta AIC gives the difference of that model from the best. The four models indicated by # were all considered plausible, and used for further analysis.

Model	Model terms	AIC	delta AIC
A	Intercept only	1399.9	27.9
B	configuration	1375.1	3.1
C	substrate	1397.4	25.4
D	size	1397.5	25.6
E#	substrate + configuration	1373.8	1.8
F	substrate + size	1394.5	22.5
G	configuration + size	1377.1	5.1
H	substrate + configuration + size	1375.6	3.6
I#	substrate * configuration	1373.8	1.8
J	size * configuration	1377.0	5.1
K	substrate * configuration + size	1375.3	3.3
L#	configuration * size + substrate	1373.6	1.6
M#	substrate * configuration + configuration * size	1372.0	0

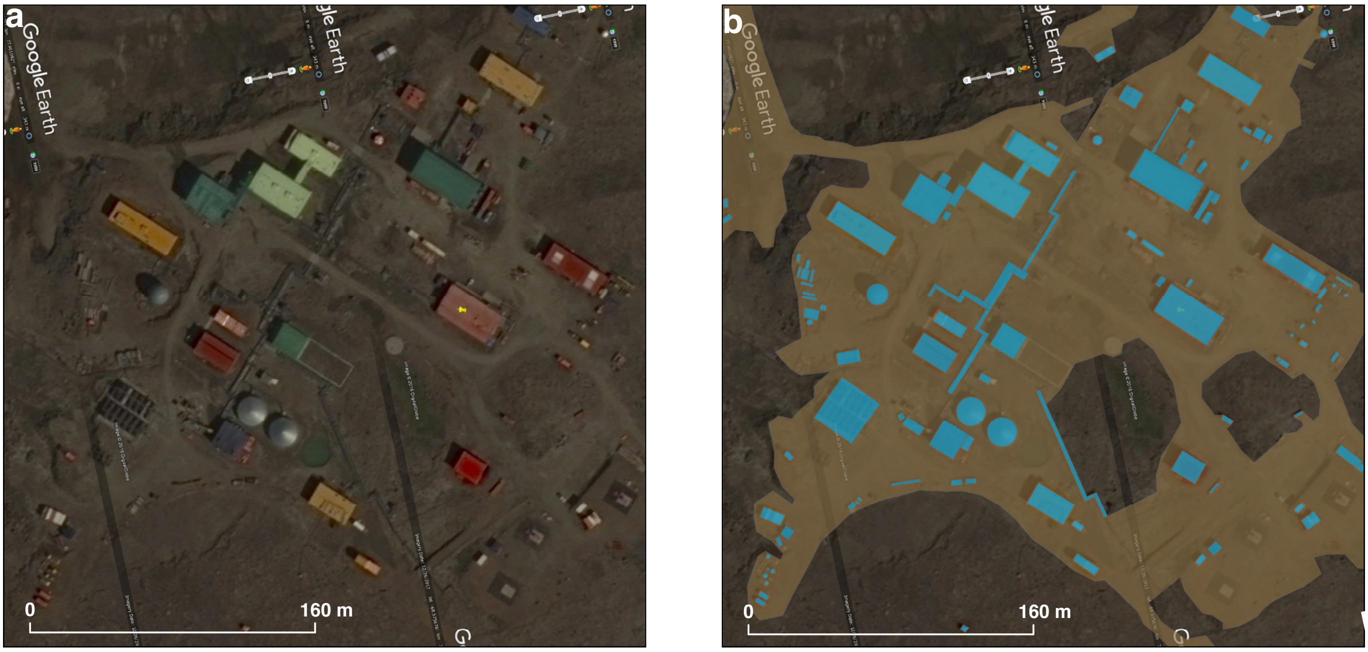
Supplementary Figures



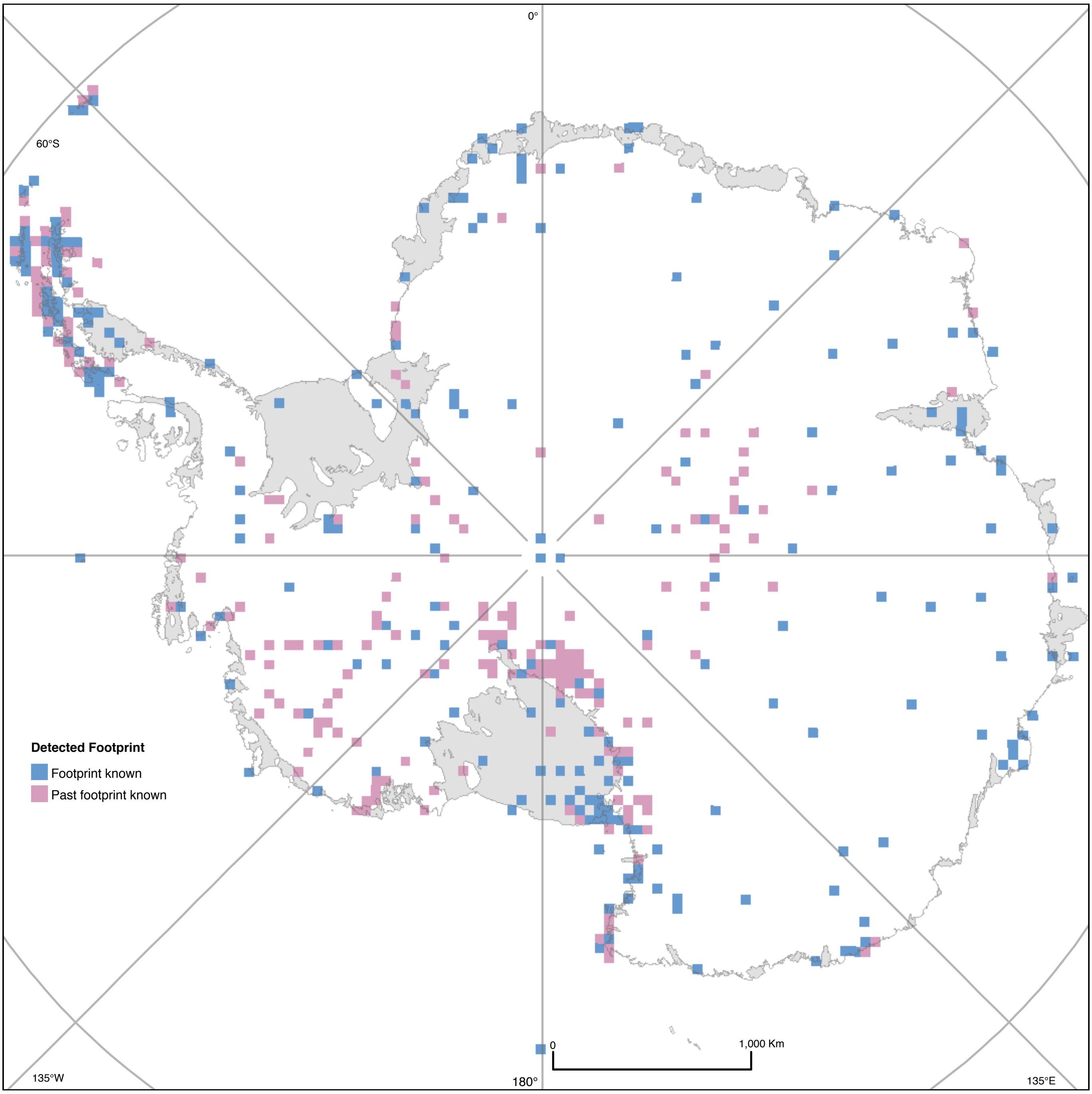
Supplementary Fig. 1. Continent disturbance footprint presented in 50x50km^2 cells.



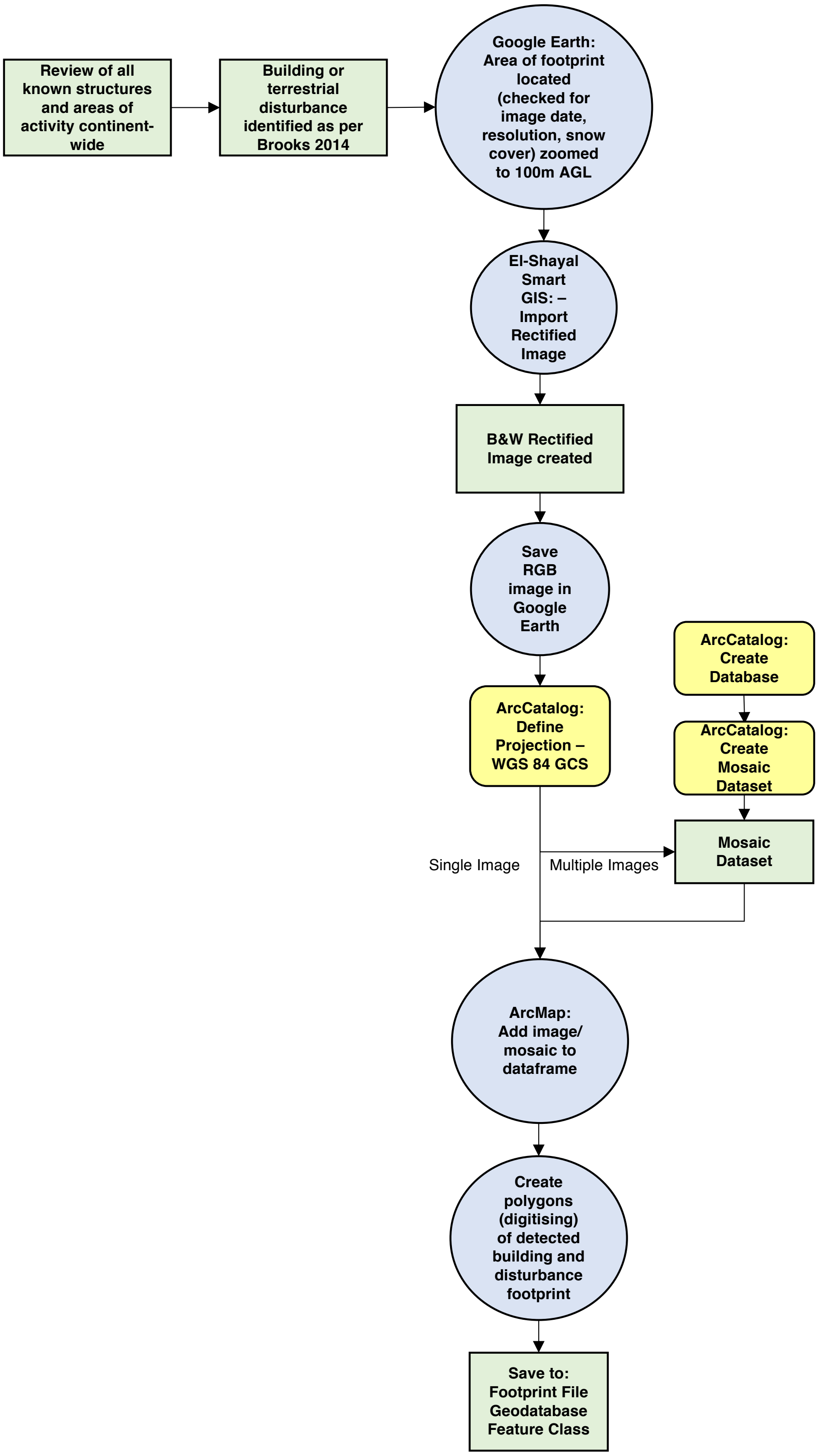
Supplementary Fig. 2. Plot of Disturbance to Building Footprint ratios for centralised and decentralised station configurations. The four panels show the fits of the four plausible models to the data (see Statistical Analysis section). The shaded bands show 95% confidence intervals. The models are **a**) E, **b**) I, **c**) L, and **d**) M (see Supplementary Table 3). Note: differing y-axis scales.



Supplementary Fig. 3. Footprint mapping example.
(**a**) Example of initial base layer of mosaicked images, extracted from Google Earth™ for Australia's Davis Station, and (**b**) resultant GIS vector polygons following digitization of buildings (blue) and disturbance (brown) footprint detected in the original images. Credit: Google, 2016, Digital Globe (panel a and b).



Supplementary Fig. 4. Point locations of additional current and past infrastructure.
During this study additional areas of infrastructure and activity were identified but were omitted from the measurement data because satellite image resolution was insufficient to enable mapping, the objects were too small to see, or the objects have been removed or buried. The point locations of these are also provided with the dataset. Blue cells represent locations where data indicates footprint is present, and magenta cells show sites where footprint was previously known to be, with its current status unknown or removed.



Supplementary Fig. 5. Footprint digitising flowchart.
This identifies the strategy used to capture footprint data from Google Earth™ through to creation of polygon shapefiles.