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# Antarctica's wilderness fails to capture continent's biodiversity

https://doi.org/10.1038/s41586-020-2506-3

Received: 21 January 2019

Accepted: 3 May 2020

Published online: 15 July 2020

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Recent assessments of Earth's dwindling wilderness have emphasized that Antarctica is a crucial wilderness in need of protection[1,2]. Yet human impacts on the continent are widespread[3–5], the extent of its wilderness unquantified[2] and the importance thereof for biodiversity conservation unknown. Here we assemble a comprehensive record of human activity (approximately 2.7 million records, spanning 200 years) and use it to quantify the extent of Antarctica's wilderness and its representation of biodiversity. We show that 99.6% of the continent's area can still be considered wilderness, but this area captures few biodiversity features. Pristine areas, free from human interference, cover a much smaller area (less than 32% of Antarctica) and are declining as human activity escalates[6]. Urgent expansion of Antarctica's network of specially protected areas[7] can both reverse this trend and secure the continent's biodiversity[8–10].

Wilderness areas are important in the Earth system for maintaining biodiversity and large-scale ecosystem services[1,11]. They also provide baselines for assessing current and future anthropogenic environmental impacts elsewhere[12]. Catastrophic declines in Earth's wilderness have led to urgent calls for action to secure it, including the establishment of comprehensive conservation targets[13]. The protection of Antarctica has been identified as crucial to this action[2]. Antarctica has an important role in the global climate system, has unusual and surprisingly extensive biodiversity, and, despite its isolation, is under growing pressure from humans[3,4,14].

Arguments have been made that, from a legal theoretical perspective, the whole of Antarctica can be considered a wilderness with the highest global level of conservation protection[2,15,16]. However, such theoretical assessments are rendered empirically inaccurate by the escalating extent of human impacts[5,17–19], and the Antarctic Specially Protected Areas (ASPAs) mechanism under the Protocol on Environmental Protection to the Antarctic Treaty (hereafter 'the Protocol'). This mechanism affords Antarctic Treaty Parties the ability to provide added protection to sites[7,8,10].

These contrasting perspectives on Antarctic wilderness conservation reflect the fact that the actual area of wilderness on the continent remains unknown, as does the extent to which it captures Antarctic biodiversity, which is largely restricted to ice-free areas[20]. Moreover, no attempt has been made to quantify the areas that remain free from human interference across the continent—a prerequisite of the Protocol—and that can be described as 'inviolate areas'. These deficiencies remain despite widespread recognition of the importance of Antarctic wilderness[2,9], assumptions that it is crucial for the region's biodiversity[21] and commitments by the Antarctic Treaty Parties to protect environmental and wilderness values (article 3, paragraph 1 of the Protocol)[7] and to identify and protect areas that are to be kept inviolate from human interference (Annex V to the Protocol)[7].

Policymakers are therefore unable to deliver fully their international obligations under the Protocol, leaving this important wilderness, and potentially its biodiversity, insecure. This policy standstill is the subject of frequent discussion[6,10,22,23]. ASPA designations and discussions in the Antarctic Treaty's Committee for Environmental Protection (CEP) also confirm this. Only one ASPA has been established explicitly for its wilderness value (ASPA 123)[24], and although two small ASPAs have been established as inviolate areas (ASPAs 129, 165)[24], they have previously been subject to human activity. Moreover, despite widespread discussion of how Antarctic wilderness areas should be defined and what constitutes an inviolate area[25,26], the CEP has not reached formal conclusions about these questions, and they remain largely absent from its priorities[27]. Consequently, Antarctic wilderness values remain unprotected from the impacts of growing scientific activity and infrastructure, and from tourism.

Here, we provide the means to resolve these problems by adopting a quantitative, ecological informatics approach. We compile, in a spatially explicit framework, all of the available human activity records for the continent, going back to its discovery 200 years ago, and then apply these data to different definitions proposed for wilderness in a global and Antarctic context, the requirements for inviolate areas, and an assessment of the representation of Antarctic biodiversity in wilderness and inviolate areas. In doing so, we provide evidence to resolve the policy implementation impasse and set in motion the protection of this globally important wilderness, including inviolate features that the Antarctic Treaty Parties are obliged to consider, before rapidly escalating human activity and changing environmental conditions[2,4] impose yet further limits on these options.

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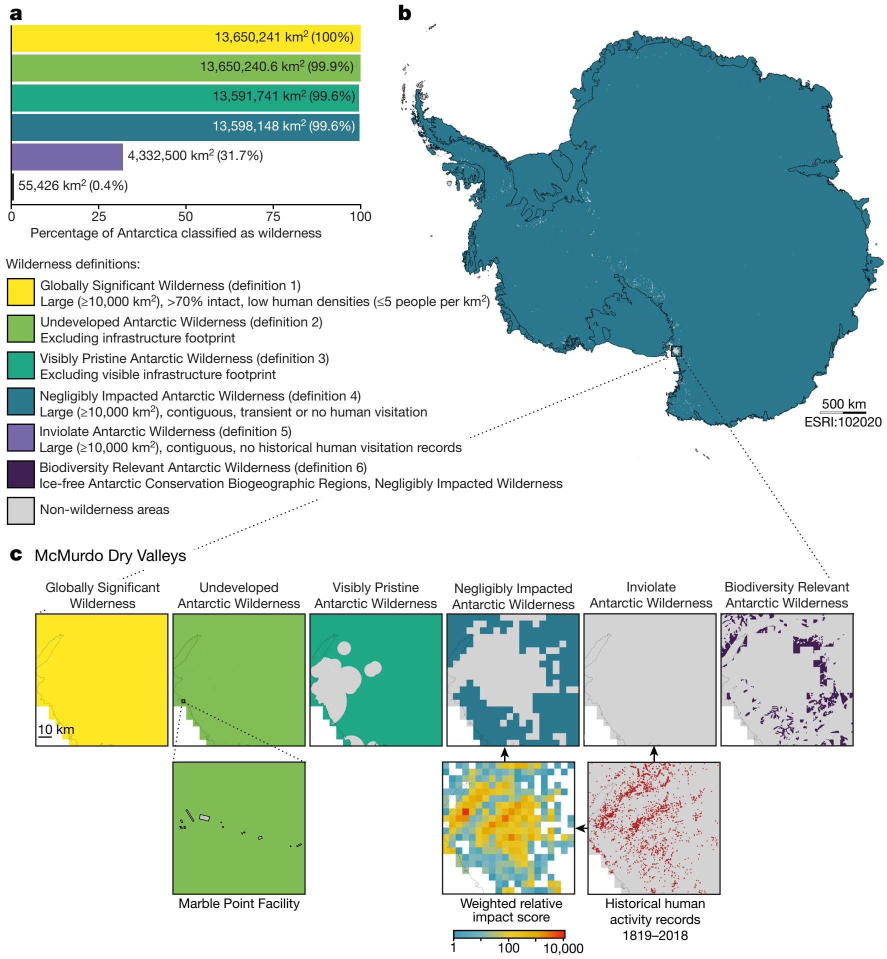


**Fig. 1 | Antarctic wilderness areas. a**, Comparison of the extent of Antarctic wilderness using six global and regional definitions of wilderness. For each set of wilderness criteria, we estimated the percentage of the total Antarctic land area (including ice shelves) classified as wilderness. Except for the Inviolate and Biodiversity Relevant Antarctic Wilderness definitions, which identify areas of outstanding wilderness value, these definitions identify nearly the entire Antarctic continent as wilderness. **b**, Negligibly Impacted Antarctic Wilderness: large (≥10,000 km$^2$), contiguous wilderness areas where human visitation is likely to have had a negligible impact on sites. **c**, Extent of wilderness (colours as in **a**) and non-wilderness areas (grey) in the McMurdo Dry Valleys region of Antarctica using six definitions of wilderness. Historical human activity records (red points) were used to estimate the relative impact of human visitation on each 25-km$^2$ cell across Antarctica and define areas of Negligibly Impacted and Inviolate Antarctic Wilderness.

## Identifying Antarctic wilderness areas

We assembled an extensive record of ground-based human activity across the Antarctic continent and its immediate offshore islands, from publications, tourism data and scientific databases, spanning 1819–2018 (~2.7 million activity records; Extended Data Figs. 1, 2; see 'Data availability' section). These human activity data were reported or recorded in a variety of formats, necessitating protocols to ensure compatibility for use on a 25-km$^2$ equal-area grid of Antarctica (excluding marine cells) to define areas of visitation (Extended Data Table 1). We used this visitation grid, and data on the spatial extent of Antarctica and its ice-free areas[28], the peak human populations of Antarctic facilities[29] and the human infrastructure footprint[18], to calculate the total wilderness area across the continent using six quantitative global and regional definitions of wilderness (see Methods).

Globally Significant Wilderness (definition 1): outside Antarctica, these areas are defined as those at least 10,000 km$^2$, mostly intact (at least 70% of historical habitat extent) and with low human population densities (5 or fewer people per km$^2$)[1]. Because Antarctica has no industrial, urban or agricultural land use[30], the entire continent, by this definition, qualifies as a Globally Significant Wilderness area, being more than 10,000 km$^2$ in size (13,650,241 km$^2$), 100% intact in terms of its historical habitat extent and with a peak human population annually (in summer) of around 5,000 individuals[29], or approximately 0.00037 people per km$^2$ (Fig. 1a).

Undeveloped Antarctic Wilderness (definition 2): Antarctic wilderness areas are often defined as those areas remote from or lacking human infrastructure[31,32]. To calculate the area of wilderness using this definition, we subtracted an estimate of the infrastructure footprint of Antarctica[18] from the total land area. Using this definition, 99.99% (13,650,240.6 km$^2$) of the continent is wilderness (Fig. 1a).

Visibly Pristine Antarctic Wilderness (definition 3): the absence of visible evidence of human activity has also been used as a definition of Antarctic wilderness areas[9,10,15,30]. To calculate the Visibly Pristine Antarctic Wilderness area, we subtracted an estimate of the total visual footprint (that is, areas within a visible distance of human infrastructure; 58,500 km$^2$)[18] from the total land area, resulting in a wilderness area estimate of 99.57% (13,591,741 km$^2$) of the Antarctic land area (Fig. 1a).

The above wilderness definitions focus on the absence of permanent landscape modifications, such as infrastructure or agricultural clearing. They ignore, however, the substantial and cumulative impacts that even transitory human activity can have on Antarctic sites[21,31,33]. These impacts arise because of the sensitivity of many Antarctic landscapes, especially to repeated activity[33,34], and their reduced rates of recovery from disturbance due to the generally slow life histories of

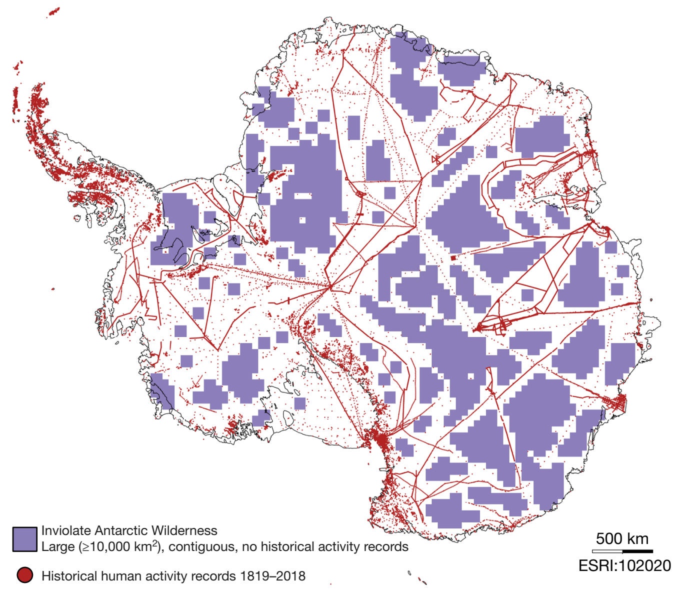


**Fig. 2 | Inviolate Antarctic Wilderness areas (definition 5).** Large (≥10,000 km$^2$), contiguous, putatively inviolate areas free from human interference across Antarctica (purple squares). Lines of historical visitation records (red points, $n$ = 2,698,429 records) indicate visited sites along transverse routes.

the indigenous terrestrial biota[35,36]. Moreover, human activities on the continent are rapidly diversifying and growing[5,17,19]. Thus, ignoring transitory human activity, as do the three previous wilderness definitions, provides an inflated estimate of the extent of the Antarctic wilderness.

Negligibly Impacted Antarctic Wilderness (definition 4): our fourth definition of Antarctic wilderness defines wilderness strictly as any contiguous land area of 10,000 km$^2$ or more where the cumulative impacts of human visitation are likely to have been negligible or non-existent. Using the 25-km$^2$ visitation grid of Antarctica, we evaluated the relative impact of human visitation in each grid cell. To account for differences in the impact that human visitation has on ice-free and ice-covered areas, due to the slow physical recovery of disturbed ice-free sites and the fact that most of Antarctica's terrestrial biota occupies ice-free habitats[20,36], the number of visitation records was weighted by the proportion of ice-free area per cell and the proportion of ice-free area in the eight adjacent cells (Extended Data Fig. 1a). Cells with an impact score below a set threshold value were considered to be negligibly impacted by human visitation. The relationship between the impact scores and sites likely to have been impacted by human activity was validated using field camp sites in the McMurdo Dry Valleys (Fig. 1c; Extended Data Fig. 1b–d; Extended Data Table 2). Large (at least 10,000 km$^2$), contiguous areas of negligibly impacted or unvisited cells were defined as wilderness areas. Under this definition, Antarctica's wilderness encompasses 99.62% (13,598,148 km$^2$) of the continent's surface area (Fig. 1). Most of the non-wilderness areas (that is, sites likely to have been impacted by historical human activity) are situated near scientific stations, ice-free areas and coastal sites (Fig. 1b).

Thus, irrespective of which of these four definitions of wilderness is adopted, the vast majority (99.57–100% total land area; Fig. 1) of the Antarctic continent can be considered wilderness, making Antarctica the world's second-largest intact terrestrial wilderness after the boreal forests of the Northern Hemisphere[1,13]. Protecting an area of this size (~13.6 million km$^2$), particularly with regard to limiting further development or extensive visitation, is, however, very difficult under the Antarctic Treaty System because of the extensive geopolitical, tourism and scientific interest in the region[37,38]. Antarctica is open for visitation unless decided otherwise, and decisions to close areas or to prohibit certain types of activities require consensus among all 29 Consultative Parties to the Antarctic Treaty. The largest terrestrial area currently protected is 26,286 km$^2$ (ASMA 5)[24], less than 0.2% of the size of the Negligibly Impacted Antarctic Wilderness. Analogous efforts to secure large marine protected areas in Antarctica have been met with considerable opposition[39]. Policymakers have an obligation to protect Antarctic wilderness areas (article 3, paragraph 1 of the Protocol and Annex V to the Protocol)[7], but given the complexity of doing so, it is therefore important to consider, on a wilderness continent, which areas have the most outstanding wilderness value.

## Areas of outstanding wilderness value

Although consensus about what constitutes 'areas of outstanding aesthetic and wilderness value' (Annex V to the Protocol)[7] in an Antarctic context is lacking[31,40], Antarctica's remoteness from human habitation, pristine condition and intrinsic value as the last untrampled place on Earth are frequently cited values that have been used to justify its scientific, recreational and conservation value[2,6,9,23,37]. From a perspective of environmental conservation, high-value wilderness areas may include (i) those areas in the most pristine condition or (ii) those with the most biodiversity[1,11]. Thus, we assess which wilderness areas are likely to be high-value regions from both perspectives, and in particular recognizing that pristine sites ('areas kept inviolate from human interference') are enshrined in Antarctic law (Annex V to the Protocol)[7]. Indeed, Antarctica's putatively inviolate areas are considered exceptionally valuable as baselines for assessing growing human impacts on the environment[22], and thus in need of urgent protection[6], even though no quantitative data exist on where, or how extensive, these areas might be.

Inviolate Antarctic Wilderness (definition 5): we assessed the extent of inviolate areas across Antarctica by identifying large (at least 10,000 km$^2$), contiguous areas with no historical human visitation records. We found that human activity has been broadly distributed across the continent, leading to a fragmented Inviolate Wilderness, although large areas (up to 812,500 km$^2$) of contiguous, putatively unvisited areas exist in East Antarctica and adjacent to the Filchner Ice Shelf (Fig. 2). In total, the Inviolate Antarctic Wilderness comprises 31.86% of the Negligibly Impacted Antarctic Wilderness, or 31.74% (4,332,500 km$^2$) of the continent (Fig. 1a).

Two important caveats for our assessment are its conservatism with regard to the availability of activity data and its dependency on the spatial scale of the analysis. Scientific data coverage favours western countries (for example, Soviet-era data are not well represented), fails to capture very recent scientific activity that has not yet resulted in data output, and omits proposed expeditions which, from their announcements, seem certain to cross areas identified here as wilderness or inviolate[41]. From the accumulation curve of visited sites for which human activity data are available (Extended Data Fig. 3a), we estimate that the visited area of Antarctica would increase by 25.3%, from 625,575 km$^2$ to 838,022 km$^2$, if twice the number of activity records were available (about 5.4 million records). Notably, we modelled the extent of human visitation at a relatively high spatial resolution (25-km$^2$), whereas a coarser-resolution analysis of the same data would exponentially decrease the area of Antarctica defined as 'unvisited' (Extended Data Fig. 3b). Conversely, a finer-resolution analysis would result in more unvisited area across Antarctica.

Biodiversity Relevant Antarctic Wilderness (definition 6): to determine whether Antarctica's wilderness captures major biodiversity features, and thus is of high biodiversity value, several biodiversity spatial layers were used. These are Antarctica's ice-free, relatively biodiversity-rich (compared to permanently ice-covered areas) ecoregions (known as Antarctic Conservation Biogeographic Regions (ACBRs)[28]), Important Bird Areas (IBAs)[42], biodiversity-relevant ASPAs and species locality records captured by the Antarctic Terrestrial

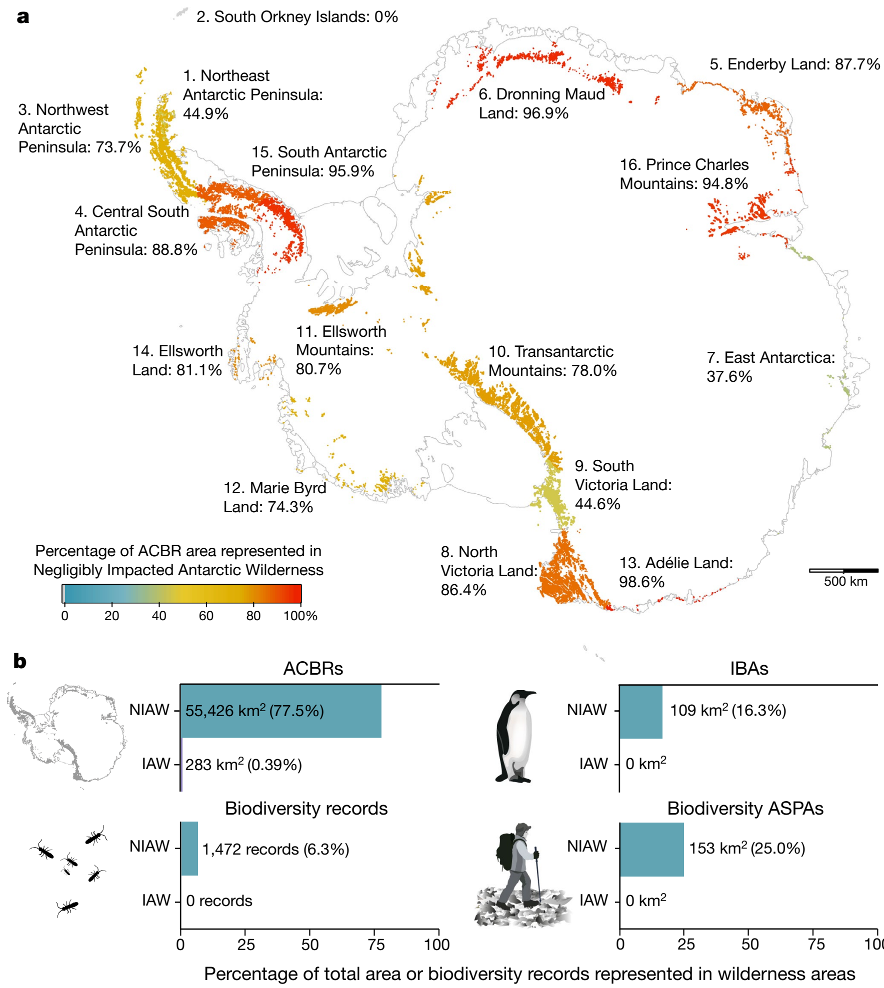


**Fig. 3 | Biodiversity Relevant Antarctic Wilderness. a**, Percentage of each ice-free ACBR represented in the Negligibly Impacted Antarctic Wilderness area (Extended Data Table 3). **b**, Percentages of the total ice-free ACBRs, IBAs, biodiversity records in the Antarctic Terrestrial Biodiversity Database and biodiversity-relevant ASPAs represented in the Negligibly Impacted Antarctic Wilderness (NIAW) and Inviolate Antarctic Wilderness (IAW) areas (Extended Data Table 4).

Biodiversity Database. The biodiversity layers were overlaid onto the Negligibly Impacted Antarctic Wilderness and the Inviolate Antarctic Wilderness, and representation calculated as a proportion of overlap.

Ice-free ACBRs are well represented within the Negligibly Impacted Antarctic Wilderness, with 55,426 km$^2$ (77.5%) of their 71,537 km$^2$ of surface area represented (Fig. 3). The South Orkney Islands (ACBR 2) is the only ACBR not represented within Antarctica's Negligibly Impacted Wilderness because these islands are small and discontiguous from the rest of the continent and, therefore, do not meet the criteria for inclusion in the Negligibly Impacted Antarctic Wilderness. Of the remaining ACBRs, the amount of their total area represented within the Negligibly Impacted Wilderness varies widely, from less than 38% to more than 98%, although the wilderness captures at least 75% of most ACBRs (Fig. 3a).

Biodiversity records are poorly represented within Negligibly Impacted Antarctic Wilderness areas, with less than 7% (1,472 records) of the more than 23,000 species records in the Antarctic Terrestrial Biodiversity Database recorded in wilderness areas (Fig. 3b). Only 16.3% (109 km$^2$) of the terrestrial IBAs (667 km$^2$) and 25.0% (153 km$^2$) of the biodiversity-relevant ASPAs are represented within the Negligibly Impacted Wilderness (Fig. 3b).

The Inviolate Antarctic Wilderness does not capture any sites of high biodiversity value (Fig. 3b). Ice-free ACBRs are largely excluded from this wilderness, with only 283 km$^2$ (0.39%) of their area represented (Fig. 3b). Antarctica's IBAs, ASPAs and species occurrence records in the Antarctic Terrestrial Biodiversity Database are entirely unrepresented in the Inviolate Wilderness (Fig. 3b) because historically the collection of an occurrence record has necessarily required human visitation to a site.

## Discussion

Our results show that the Antarctic wilderness encompasses nearly the entire continent (Fig. 1), but excludes much of its important biodiversity (Fig. 3). Continued human presence throughout the most biodiverse areas of Antarctica over the past 200 years has affected these areas in both obvious ways (for example, infrastructure, vegetation trampling, sealing[18,34]) and more subtle ways (for example, microbial contamination, wildlife and soil disturbance, pollution, human-mediated dispersal of indigenous and alien species[17,19,31,36,43]). For this reason, many of Antarctica's most valuable biodiversity sites, such as its IBAs, are not well represented within the Negligibly Impacted Antarctic Wilderness (Fig. 3). Such a situation is unique globally. Intact wilderness elsewhere on the globe is valued for its biodiversity and ecosystem services, including its roles in water catchment, food security, recreation, carbon storage and sequestration, and as a megafaunal refuge[1,2,13].

Human activity has also been extensive across Antarctica, leading to a fragmented and diminishing set of pristine, inviolate areas free from human interference (Fig. 2). Recognizing that inviolate areas need to be visited to ascertain their biodiversity value, thus rendering them less so by the current definition, we do not yet know whether Antarctica's inviolate areas are generally depauperate in terms of biodiversity. Recent investigations of life in ice, snow and airborne assemblages have revealed surprising microbial diversity and likely extensive habitat across glaciated regions[44,45]. Overcoming the shortfall in biodiversity data, without compromising the pristine condition of Antarctic inviolate areas, presents a unique challenge—one that is beginning to be addressed through the application of remote-sensing technologies and models to explore new areas and assess biodiversity[46,47].

Human activity in Antarctica is in theory more easily regulated than elsewhere because it is restricted to science and tourism, with few other human activities or permanent inhabitants[30]. Evidence-based planning for, and designation of, new protected areas, with explicit consideration of the trade-offs between the benefits of science and tourism and the importance of retaining pristine wilderness areas or regaining their biodiversity value through the spatial restriction of human activity, could therefore readily be implemented. Inviolate areas are also presently isolated from current and forecast anthropogenic impacts[20,48], making a strong case for their inclusion in ASPAs. Such planning is well within the grasp of modern conservation science. Given rapidly expanding and diversifying human activity in Antarctica[5,10,19], along with the general absence of Antarctica's wilderness and inviolate areas from its protected area system and of wilderness values from Environmental Impact Assessments, it is also urgent. The outcomes could provide the Parties to the Antarctic Treaty with the mechanism required to implement their commitments to[7], and recently demonstrated enthusiasm for[49], the protection of the Antarctic environment.

## Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-020-2506-3.


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## Methods

### Historical human activity

We used publications and scientific databases to assemble an extensive record of ground-based human activity across the Antarctic continent and its offshore islands (south of 60°S) from 1819 to 2018 (see Data availability; Extended Data Fig. 1a). We identified 2,698,429 activity records from 363 sources, of which 2,009,819 were unique site coordinates. Records of human activity included scientific sampling sites, traverses, infrastructure and tourism. They excluded aerial surveys, remote-sensed data and data from social networking and public image-hosting services (such as Twitter, Flickr and Facebook). Human activity data were available in three source formats: geographic coordinates, maps or place-name records. Where available, we converted geographic coordinates from various source formats to the South Pole Lambert Azimuthal Equal Area projected coordinated system (ESRI:102020), using the sp package (ver. 1.3-1)[50] in R (ver. 3.4.1)[51]. To extract activity data from digitized maps, we projected maps in ArcGIS (ver. 10.6)[52], using high-resolution spatial layers of the Antarctic coastline and exposed rock outcrops, sourced from the Scientific Committee on Antarctic Research (SCAR) Antarctic Digital Database (ADD, ver. 7)[53]. Markers were then placed on map features of interest to extract activity localities.

Although place-name records varied widely in scale within and across sources (for example, Cape Roberts hut vs. Transantarctic Mountains), they were the best-available records in several cases, such as for historical expeditions[54]. To infer the accuracy of place-name records, we sorted places by feature-type into two approximate size classes: fine-resolution features (roughly, ≤25 km$^2$; for example, Casey Station) and coarse-resolution features (>25 km$^2$; for example, Dronning Maud Land; see Extended Data Table 1 for sorting protocol). We used this 25-km$^2$ resolution because it is the finest resolution we adopted for the whole-of-continent analysis. Coordinates for fine-resolution features were sourced from the SCAR Composite Gazetteer of Antarctica[55] and included in the human activity data set. We excluded place-name records for coarse-resolution features, such as mountain ranges, coasts and lands. Because islands and archipelagos vary greatly in size, yet have readily delineated boundaries, the areas of visited islands were calculated to sort them into fine-resolution and coarse-resolution classes. We used the spatialEco (ver. 0.0.1-7)[56] R package to identify islands in the high-resolution coastline polygon of Antarctica[55] that intersected with the SCAR Gazetteer coordinates for visited islands. The areas of visited islands were calculated using the raster (ver. 2.5-8)[57] R package, and the SCAR Gazetteer coordinates for visited islands or island groups ≤25 km$^2$ were included in the human activity data set.

Historical activity records under-represent human activity because some activities were undocumented, un-digitized or unpublished (for example, exploratory field expeditions), or the visit was not captured in the literature search. Moreover, although Parties to the Antarctic Treaty are expected to monitor human impacts, few do so, and no centralized comprehensive repository of human activity exists[58]. Tourist data are generally better reported because they are coordinated through the International Association of Antarctica Tour Operators (IAATO), but some private expedition data remain unreported, further indicating that the actual area of human impact is probably larger than estimated here. Our assessment is, therefore, a conservative estimate of human visitation across Antarctica. Likewise, data on the magnitude of human impacts at each site, such as the number of people per visit, length of stay, infrastructure installed, activity or transport type, were not consistently reported across data sources. To avoid making assumptions about the relative impacts of different activities across sites, we used the number of independent visitation records per site as a measure of visitation impact. We sourced data from multiple databases to maximize the spatial and temporal coverage of the activity data set. This approach captured data sets with different sampling frequencies, precluding a reliable analysis of visitation impact from the density of records per site. For example, several recent traverses recorded geo-positioning data at high temporal resolutions (~10 min), resulting in many records for relatively transitory site visits (Extended Data Fig. 2a). To estimate the number of independent visits to Antarctic sites and to standardize sampling protocols across data sets, we sorted the human activity data sets into multiple-event and single-event data sets. Multiple-event data sets included large databases that collated records from numerous field campaigns (for example, ref. [54]). For these data, we counted the number of records per cell on a 25-km$^2$ grid of Antarctica, projected using the South Pole Lambert Azimuthal equal area projection and the R packages raster[57] and rgdal (ver. 1.3-4)[59]. For single-event data sets, including all traverse data and scientific records from a single field expedition, we counted only one record per data set per cell. We then added the multiple-event and single-event counts to create a high-resolution (25-km$^2$) visitation grid of Antarctica (Extended Data Fig. 2b).

To exclude marine areas and areas north of 60°S from the visitation grid, we created a land mask of Antarctica by converting a high-resolution Antarctic coastline spatial polygon[53] into a 0.01-km$^2$ grid of Antarctica, where cells overlapping land areas (including ice shelves) had a value of one, and non-land cells had a value of zero. We then aggregated this land grid to the resolution of the visitation grid (25-km$^2$) and assigned marine areas (that is, those cells with no overlap with land) NA values in the visitation grid. This rasterization and aggregation method was applied to optimize the resolution of the land mask so that cells with even a small overlap with land were retained in the visitation grid, and to improve the computation time of the analysis. For all subsequent analyses, we used the visitation grid, instead of the activity coordinates, as a representation of the spatial extent of visitation across Antarctica because grid cells provide a spatial buffer around the activity coordinates to account for unreported, small-scale activities (for example, movements around a camp site).

### Visitation impact weights

Although more spatially restricted than scientific activity, tourism activities typically support larger numbers of visitors to Antarctic sites each year[30]. To account for this discrepancy in visitation pressure, we weighted the tourist visitation records by the degree of difference between the average number of landed tourists per field activity per year and the average number of scientists per field activity. The mean number of tourists and their support staff participating in land-based activities from fifteen field seasons between 2003 and 2019, was calculated from tourism data collected by IAATO[60]. Land-based tourism activities included aircraft and small boat landings, hiking, camping, climbing and skiing data, but excluded water activities, such as kayaking, boat cruising and snorkelling. Tourism data recorded the cumulative number of tourists and staff per activity type per site per year. We used data on the number of scientists and their support staff per field expedition (that is, excluding station populations) from the United States Antarctic program[61] from 2003-2016 to estimate the mean number of scientists participating in field activities. On average, 716.42 tourists and their staff and 7.31 scientists and their staff visited Antarctic sites. Tourism activities had therefore, on average, 98 times the number of visitors per activity than scientific activities. The tourism records in the human activity database were multiplied by this factor (98) to weight these records by the relative number of people per site visit. Our calculation of human impact is not, however, highly sensitive to the value of this tourism weight because any value >20 would classify tourism sites as likely to have been impacted by visitation (see equation below).

Transitory activities can have substantial long-term effects on Antarctic sites because of the slow rates of ecological and physical recovery after disturbance[6,31,34,36,62–65]. Ice-free areas are particularly vulnerable to the impacts of physical disturbance, pollution, vegetation trampling and wildlife disturbance, and are at greater risk of non-native species establishment than glaciated areas[48,66]. To account for the differences in risk that human visitation poses to ice-free and ice-covered areas, we weighted the number of independent visitation records in the visitation grid by the proportion of ice-free area in each cell, and the proportion of ice-free area in the eight adjacent cells. Because of their slower rates of recovery after disturbance and increased vulnerability to invasion, completely ice-free cells were weighted here as an order of magnitude more likely to be impacted by human visitation than completely ice-covered cells. The proportion of ice-free area per cell was calculated by converting the high-resolution Antarctic exposed rock outcrops polygon[53] into a 0.05 $km^2$ grid of Antarctica, where cells overlapping ice-free areas had a value of one, and glaciated cells had a value of zero. We then aggregated this exposed rock grid to the resolution of the visitation grid (25-$km^2$), where the value of every cell was equal to the proportion of ice-free cell area.

The proportion of ice-free area in the eight adjacent cells is a measure of ice-free area connectivity, included here as an additional weight because non-native species are more likely to establish and spread in connected ice-free areas[20,67]. To calculate the proportion of directly adjacent cells that were ice-free, the 'adjacent' function in the raster R package[57] was used to identify the eight neighbouring cells of every cell in the 25-$km^2$ ice-free area grid, and calculate the overall proportion of ice-free area in these adjacent cells. Because the connectivity of ice-free areas is expected to have a smaller effect on the impact of visitation than the extent of ice-free area at a given site, an exponential weight of base 2 was used to model the effect of ice-free area connectivity on human visitation impacts. Thus, entirely connected ice-free areas (that is, those with eight completely ice-free neighbouring cells) were weighted as twice as likely to be impacted by visitation as unconnected cells. The following formula was, therefore, used to calculate the weighted relative impact (WRI) score for each cell:

$$\mathrm{WRI} = N \times 10^{\mathrm{IF}} \times 2^{\mathrm{AIF}},$$

where $N$ is the number of independent visitation records per cell, IF is the proportion of ice free area per cell and AIF is the proportion of ice-free area in the eight adjacent cells.

### Identification of impacted and negligibly impacted sites

To delineate between sites that are likely to have already been impacted by historical human visitation, and sites that are either historically inviolate (unvisited), or where visitation has occurred at such low levels or in glaciated regions where its environmental impacts are likely to have been negligible, we defined a threshold WRI score to classify impacted and negligibly impacted sites. Antarctic sites in the WRI score of >20 were considered to have been impacted by historical human visitation. This threshold considered completely ice-free sites, surrounded by ice-free neighbouring cells, with two or more independent visitation records as impacted. Alternatively, entirely ice-covered sites required more than twenty independent visitation records to be considered impacted by human activity.

To test whether the WRI scores predict the occurrence of field camp sites in the McMurdo Dry Valleys region and, therefore, independently identify sites likely to have been impacted by human activity, we used a binomial generalized linear model with a logit link function. The locations of 18 seasonal field camp and helicopter landing sites were sourced from the Council of Managers of National Antarctic Programs (COMNAP) Antarctic facilities list[29] and the McMurdo Dry Valleys Antarctic Specially Managed Areas (ASMA) manual[68] (Extended Data Table 2). The presence or absence of field sites was modelled as a dependent variable of the WRI scores (Extended Data Fig. 1b,c). We calculated the bootstrapped 95% confidence interval (CI) for the binomial regression coefficient from 1999 random non-parametric samples of the McMurdo Dry Valleys WRI scores (Extended Data Fig. 1b). We found that the regression coefficient of the model fitted to the original sample was outside the 95% confidence interval for the bootstrapped coefficients (original model coefficient: 0.0023; bootstrapped 95% CI: −0.0030 to 0.0006; Extended Data Fig. 1d), therefore, the positive relationship between the WRI scores and the likelihood of observing a field camp at a given site was much stronger than would be expected by chance. The WRI scores are, therefore, a useful indicator of sites likely to have been impacted by historical human visitation to Antarctica.

### Identification of Negligibly Impacted Antarctic Wilderness areas

Globally significant wilderness areas need to be large to minimize indirect impacts from outside their boundaries[1,9]. Here, we defined Negligibly Impacted Antarctic Wilderness areas as all contiguous land areas ≥10,000 $km^2$ (based on ref. [1]) with either no record of historical human visitation or negligibly impacted sites (WRI score of ≤20; Extended Data Fig. 1a). To identify contiguous wilderness areas, the high-resolution (25-$km^2$) weighted relative impact (WRI) grid was transformed so that all land cells with a WRI score ≤20 (including unvisited cells) were assigned a value of 1, and impacted cells (WRI >20) were assigned a value of 0. A connected component labelling approach ('clump' function, raster R package[57]) was used to identify directly adjacent wilderness cells (excluding diagonal connections). Groups of contiguous wilderness cells ≥10,000 $km^2$ (that is, ≥400 connecting 25-$km^2$ cells) were considered Negligibly Impacted Antarctic Wilderness areas (Fig. 1b). To calculate the total size of the Negligibly Impacted Antarctic Wilderness, the area of intersection between Negligibly Impacted Antarctic Wilderness cells and a high-resolution Antarctic coastline spatial polygon[53] was calculated using the raster R package[57].

### Identification of wilderness areas using alternative definitions

To compare the extent of wilderness identified using historical human visitation records to the outcomes of using other quantitative wilderness criteria, we calculated the area of Antarctic wilderness using three alternative global and regional definitions of wilderness. First, Globally Significant Wilderness areas are defined as those ≥10,000 $km^2$, mostly intact (≥70% of historical habitat extent), and with low human population densities (≤5 people per $km^2$) (Globally Significant Wilderness, Definition 1)[1]. We used the high-resolution coastline of Antarctica[53] and the raster R package[57] to calculate the total land area including ice shelves. Antarctica has no large-scale anthropogenic land modifications, which elsewhere fragment wilderness areas (for example, agriculture[1,13]). Thus, we considered the entire continent to be 100% intact in terms of its historical habitat extent. To calculate the human population density of Antarctica, we divided the peak summer 2018 population of Antarctic facilities[29] by the total land area.

Permanent infrastructure degrades the wilderness value of Antarctic sites[32]. We calculated the area of Antarctica with no human infrastructure footprint (Undeveloped Antarctic Wilderness, Definition 2) and areas with no visible infrastructure (Visibly Pristine Antarctic Wilderness, Definition 3), as two alternative wilderness assessments[9,10,15,31,32]. To calculate the Undeveloped Antarctic Wilderness area (Definition 2), we subtracted the total infrastructure footprint of Antarctica, derived from remote-sensed imagery[18], from the total land area. Here, the infrastructure footprint included station buildings, field camps, huts, refuges and lighthouses[18]. Likewise, to calculate the Visibly Pristine Antarctic Wilderness area (Definition 3), we subtracted the land area of Antarctica within a visible distance of infrastructure from the total land area, using the planar spatial buffers for the visible distance of infrastructure developed by Brooks et al.[18]. That is, terrestrial areas within 20 km of station buildings, 10 km of abandoned stations and field camps and 5 km of refuges, field huts, automatic weather stations and historic sites were within the total visible footprint of Antarctica, and excluded from the Visibly Pristine Antarctic Wilderness estimate[18].

### Identification of Inviolate Wilderness areas

Here, we defined Inviolate Antarctic Wilderness areas as all contiguous land areas ≥10,000 $km^2$ (based on ref. [1]) with no record of historical human visitation. We did not apply the connected components labelling approach, used to identify contiguous Negligibly Impacted Antarctic Wilderness areas, to the inviolate areas analysis because some traverse records were spatially discontinuous (for example, records of only significant camps or sampling sites). This discontinuity resulted in a 'dashed-line' effect, where sites between two consecutive traverse records were presumably visited and, therefore, not strictly inviolate. A connected component approach would erroneously identify both sides of a 'dashed-line' as a contiguous inviolate area. Instead, we aggregated the high-resolution (25-km$^2$) visitation grid to a 10,000-km$^2$ grid of Antarctica, using the raster R package[57], where cells with a value of 1 had no visitation records and cells with a value of 0 were visited (NA for marine cells). To reduce spatial bias caused by grid placement, we repeated the aggregation procedure, offset in each $x,y$ spatial direction by 50 km. The two aggregated grids were then overlaid, with the offset thus resulting in a 2,500-km$^2$ grid of Antarctica used for the identification of inviolate areas. This grid was then used to identify contiguous inviolate areas of ≥10,000 km$^2$ (that is, consisting of four or more contiguous 2,500-km$^2$ cells). By offsetting the two 10,000-km$^2$ grids and then overlaying them, we maximized the spatial extent of each inviolate area, while also constraining the minimum size of inviolate areas.

### Identification of Biodiversity Relevant Antarctic Wilderness areas

To determine whether Antarctica's wilderness areas capture major features of biodiversity value, spatial layers of Antarctica's ice-free Antarctic Conservation Biogeographic Regions (ACBRs)[28], 220 IBAs[69], terrestrial biodiversity[70] and biodiversity-relevant ASPAs (v.4)[28] were overlaid onto the Negligibly Impacted Antarctic Wilderness and Inviolate Wilderness areas. Ice-free areas, IBAs and species-rich sites are rare across the continent and are under substantial pressure from human activity[5,37,42], making them important conservation priorities. We used the ice-free ACBRs as a spatial layer of land areas suitable for Antarctic species because areas without the presence-only biodiversity records are not necessarily depauperate of biodiversity, and the vast majority of Antarctic species occupy ice-free habitats[20]. We considered only the ASPAs that were primarily designated for their biodiversity value (that is, 'areas with important or unusual assemblages of species, including major colonies of breeding native birds or mammals' (Protocol Designation Category C), or areas that are 'representative examples of major terrestrial, including glacial and aquatic, ecosystems and marine ecosystems' (Protocol Designation Category B))[24]. We converted the wilderness and inviolate grids into spatial polygon layers of the boundaries of Antarctica's wilderness areas, using the rasterToPolygons function in the raster R package[57]. Spatial polygons of the IBAs and ACBRs and spatial points of the terrestrial biodiversity occurrence records were re-projected to the same coordinate reference system as the wilderness polygons (ESRI:102020) using the rgdal R package[59]. Representation was calculated as the area of intersection between the wilderness and inviolate areas, ACBRs, IBAs, ASPAs and the total number of biodiversity records within wilderness areas, using the raster[57] and spatialEco R packages[56]. Because some coastal wilderness cells overlap both terrestrial and marine areas, the area of intersection between the wilderness polygons and biodiversity layers was cropped by the high-resolution coastline polygon of Antarctica[53] to exclude marine areas from the final area of intersection.

Despite the increasing use of remote-sensing technologies for monitoring Antarctic biodiversity[47,71–73], to date the vast majority of biological data have been collected from ground observations. Likewise, the bird population censuses required to identify IBAs are typically conducted during field expeditions[42,74]. Inviolate Wilderness areas identified from a complete record of human activity will therefore, by definition, exclude most sites where biodiversity is known to occur (for example, those with biodiversity records, IBAs), as well as most sites where biodiversity is likely to occur (ice-free areas), where historical human visitation has been most extensive. Nonetheless, we repeated the analyses of the representation of biodiversity on the inviolate areas grid to determine whether any of the Inviolate Wilderness areas are likely to capture undocumented biodiversity (in the case of the ACBR layer) and to test the spatial completeness of the human activity data (in the case of the biodiversity records, ASPAs and IBAs). If the human visitation record is comprehensive, very few of the IBAs, biodiversity records or ASPAs should overlap with inviolate areas.

In addition to the ACBR layer of ice-free areas[28], we also calculated the overall representation of ice-free areas within the Negligibly Impacted Antarctic Wilderness and Inviolate Antarctic Wilderness areas using an alternative high-resolution exposed rock outcrop spatial layer, derived from Landsat8 satellite imagery[75]. This rock outcrop layer provides a more refined estimate of the extent and distribution of the ice-free regions of Antarctica than the ACBR layer[75]; however, it has not been delineated into biologically distinct ecoregions. We therefore used both of these datasets to capture regional patterns of ice-free area representation in wilderness and inviolate areas, and continental patterns.

All maps were created in R[51], using our data (see Data Availability), in addition to high-resolution shapefiles of the Antarctic coastline[53], Antarctic infrastructure footprint[18], point localities for field camps[68] and the Antarctic Conservation Biogeographic Regions[28].

### Sensitivity analyses

To model the scale dependency of Antarctic visitation, we examined the relationship between grid cell size (grain) and the total percentage of Antarctic land area visited, where cells containing one or more historical human visitation records were counted as visited, and cells that overlapped land areas but contained no human activity records were unvisited. We created grids of Antarctica with eight spatial resolutions (5, 10, 20, 40, 80, 160, 320 and 640 km). For each resolution, two grids were produced, where the second grid was spatially offset from the first by half of the grid dimensions in each $x,y$ spatial direction to account for any introduced bias caused by grid placement. To control for edge effects, the amount of visited or unvisited land area each cell contributed to the total sum was weighted by the proportion of land area within that cell, using the 0.01-km$^2$ land mask (see Historical human activity, above). The relationship between grid cell size and the total percentage of Antarctic land area unvisited was fitted with exponential ($r^2$: 0.95) and power-law curves ($r^2$: 0.73), and the model that explained the most variation (measured by $r^2$) was plotted (Extended Data Fig. 3b).

To predict how the total amount of visited area might change with additional data, we modelled the accumulation of visited land across Antarctica with increasing numbers of historical visitation records. We drew random subsamples from our ~2.7 million visitation records. For each subsample increment (1%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100% of the records), 20 random samples of records were drawn, without replacement, from the visitation data set. We overlaid each subsample of records onto the 25-km$^2$ visitation grid and assigned cells that were visited in the subsample records a value of 1, and cells with no visitation records in the subsample a value of 0. We then calculated the total percentage of Antarctic land area visited in each subsample grid. The relationship between subsample size and the total percentage of Antarctic land area visited by historical human activity was fitted with exponential ($r^2$: 0.57) and power-law curves ($r^2$: 0.99). To predict how the visited area of Antarctica might increase if twice the number of human activity records were available, the model that explained the most variation (measured by $r^2$) was extrapolated to 200% of the total number of visitation records (~5.4 million activity records) (Extended Data Fig. 3a).

### Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this paper.

## Data availability

The wilderness areas and historical human activity data are available at https://doi.org/10.26180/5c32bf1b041ea. The other spatial data can be obtained from their creators[18,28,53,68].

## Code availability

Computer code is available at https://doi.org/10.26180/5c32bf1b041ea.


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**Acknowledgements** We thank K. Close, G. A. Duffy, R. Harvey, K. A. Hughes, T. Robertson and D. Smith for their assistance in identifying activity data and M. A. McGeoch, H. P. Baird, J. R. Lee, L. Chapman and A. Clarke for reading a previous version of this manuscript. This research was supported by Australian Antarctic Science (AAS) grant 4482 and a Sir James McNeill Foundation Postgraduate Research Scholarship to R.I.L. F.M. was supported by a New Zealand Ministry of Business, Innovation and Employment grant (CO9X1413). A.T. was supported by AAS grant 4296.


**Author contributions** S.L.C., B.W.T.C. and R.I.L. conceived the study. R.I.L., B.W.T.C., F.M., B.R., J.D.S. and A.T. collected the human activity data. R.I.L. conducted the analyses. R.I.L., K.B. and S.L.C. drafted the initial manuscript. All authors contributed to the final manuscript.

**Competing interests** S.L.C. is the President of the Scientific Committee on Antarctic Research.

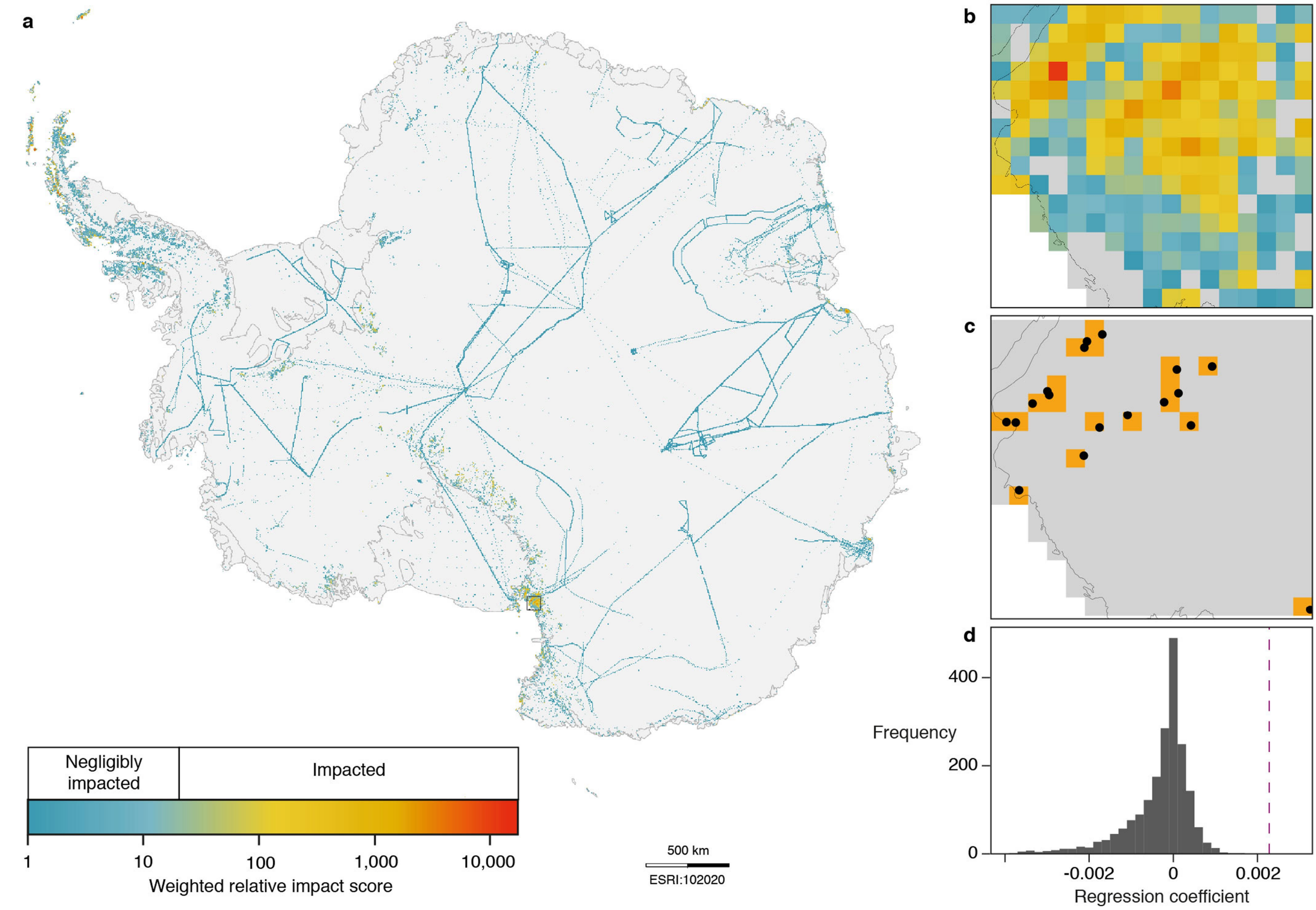
**Additional information**

**Supplementary information** is available for this paper at https://doi.org/10.1038/s41586-020-2506-3.

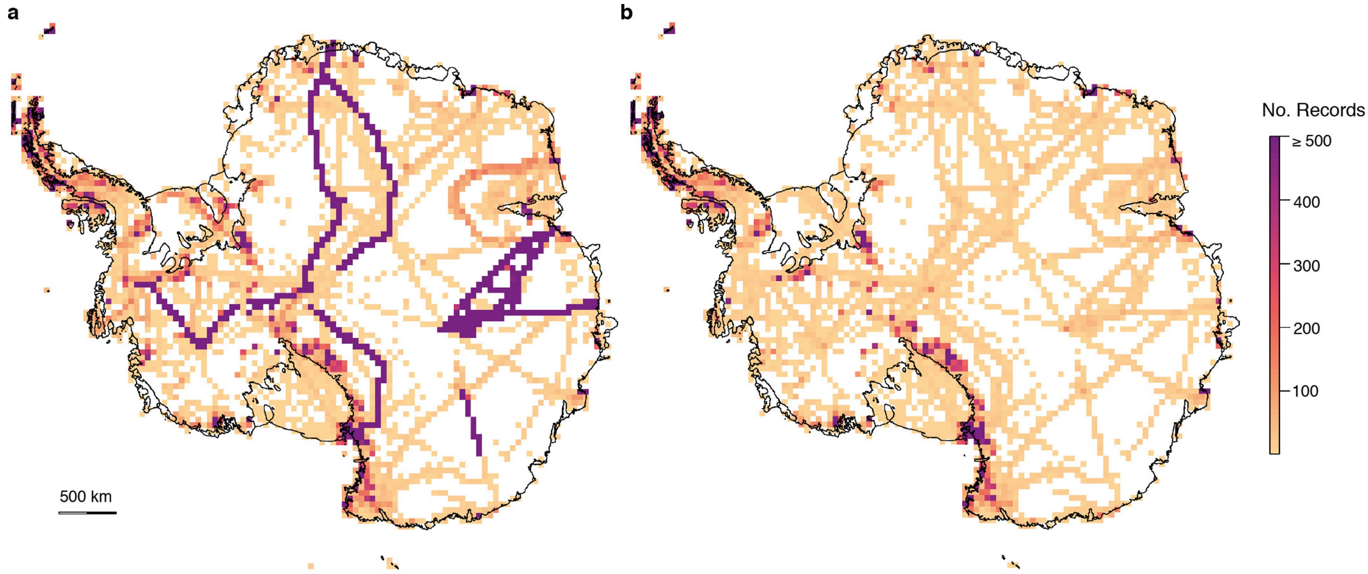

**Correspondence and requests for materials** should be addressed to S.L.C.



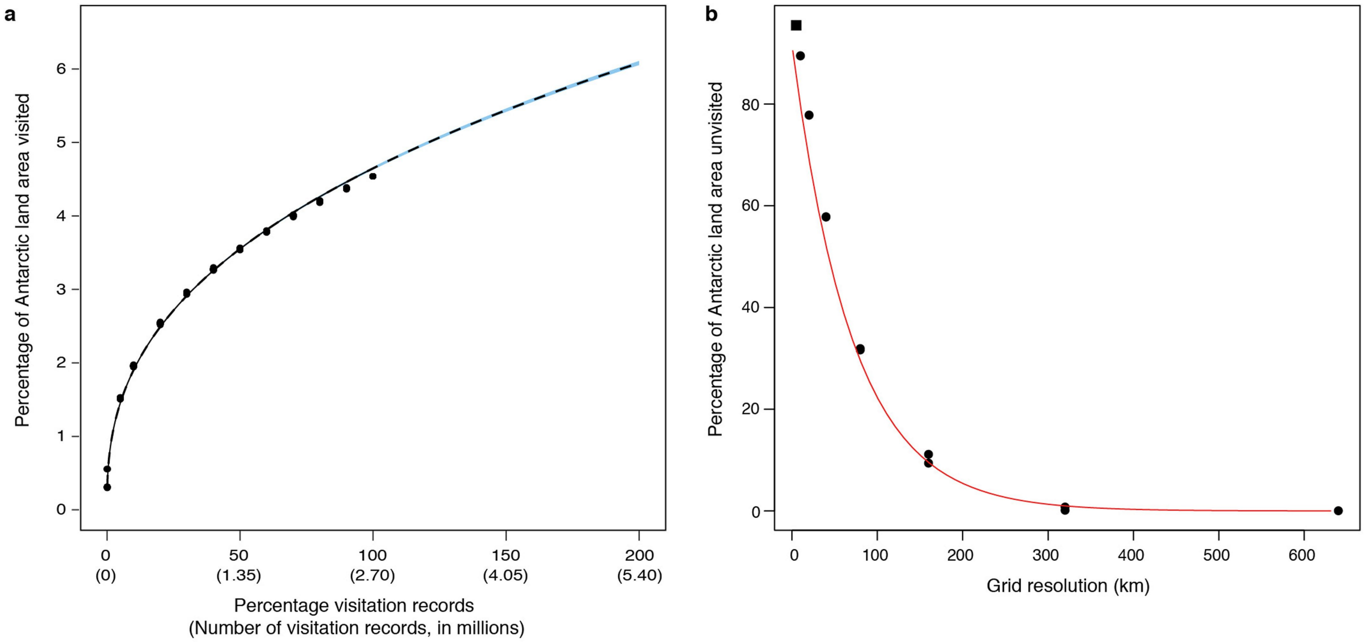
**Peer review information** *Nature* thanks Andrew Clarke and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.




**Extended Data Fig. 1 | Cumulative impact of human visitation across Antarctica. a**, Weighted relative impact (WRI) scores of the number of independent historical human visitation records per 25-km$^2$ grid cell, weighted by the proportion of ice-free area in each cell and the eight adjacent cells. Visitation to sites with WRI scores ≤20 is likely to have had a negligible impact. Cells without WRI scores (grey) have no historical visitation record in the data set and are considered here as unvisited. **b**, WRI scores for the McMurdo Dry Valleys region. **c**, Location of 18 field camps (points) in the McMurdo Dry Valleys, used to validate the WRI scores (Extended Data Table 2). **d**, Frequency distribution of 1,999 bootstrapped binomial generalized linear model regression coefficients for the relationship between WRI scores and the presence/absence of field camps in the McMurdo Dry Valleys (**b**, **c**; $n = 252$ grid cells). The dashed line indicates the regression coefficient (0.0023) for the model fit to the original sample.




**Extended Data Fig. 2 | Historical human visitation record density.** **a**, **b**, Number of historical human activity records (**a**) and number of independent historical human activity records (**b**) per 50 × 50 km cell across Antarctica from 1819 to 2018 ($n$ = 2,698,429 records). Dark purple lines (**a**) indicate the routes of recent overland traverses (for example, 2007–2008 Norwegian–US Scientific Traverse of East Antarctica), where geo-positioning data were collected automatically at high temporal resolutions (~10 min), resulting in many records for relatively transitory site visits. To standardize sampling frequencies across different data sources, independent records (**b**) count only one record per cell per data set for data sets describing a single event (for example, a traverse).




**Extended Data Fig. 3 | Sampling completeness and scale dependency of visitation records. a**, Relationship between the number of visitation records and percentage of land area visited across Antarctica at a 25-km$^2$ grid resolution, modelled using a power-law model ($f(x) = 0.78x^{0.39}$; $r^2 = 0.99$). The visitation accumulation curve is extrapolated (dashed line) to predict the percentage land area expected to be identified as visited if twice the number of visitation records (5.4 million records) were available in the data set. Points indicate the percentage of visited land, calculated using 20 random subsamples of the complete visitation records for each interval ($n = 240$ subsamples); shaded blue area indicates 95% confidence interval. **b**, Relationship between grid cell resolution and the percentage of land area across Antarctica with no visitation records (that is, unvisited areas), modelled using an exponential model ($f(x) = 91.78e^{(-0.01x)}$; $r^2 = 0.95$; $n = 15$ grids). In this study, visitation was modelled at a 5-km (25-km$^2$) resolution (square).

## Extended Data Table 1 | Place-name record categories

| Fine-resolution features | | Coarse-resolution features | |
|---|---|---|---|
| Airbase | Massif | Archipelago | Oasis |
| Airfield | Monument | Bay | Passage |
| Airway | Monolith | Channel | Peaks |
| Anchorage | Mount | Coast | Peninsula |
| AWS | Nunatak | Dome | Plain |
| Base | Observatory | Fjella | Promontory |
| Beach | Point | Fjord | Range |
| Bellows | Peak | Glacier | Ranges |
| Bluff | Pinnacles | Gulf | Region |
| Camp | Pointe | Harbor | Sea |
| Cape | Pole | Harbour | Sound |
| Cemetery | Port | Hills | Strait |
| Cliffs | Reef | Ice stream | Terre |
| Cove | Reefs | Ice Tongue | Valley |
| Field | Refuge | Ice-shelf | Valleys |
| Grave | Ridge | Icesheet | |
| Head | Rock | Island | |
| Hill | Rocks | Islands | |
| Hut | Rookery | Kyst | |
| Iceport | Runway | Land | |
| Inlet | Skiway | Plateau | |
| Island | Station | Mountains | |
| Lake | | Nunataks | |

Initial filter used to sort place-name activity records into fine-resolution (≤25 km$^2$) and coarse-resolution (>25 km$^2$) geographic feature classes. Islands and island groups were sorted independently by their size (see Methods). Where small differences in spelling or use were present, as with 'ice shelf' and 'ice-shelf', these were made consistent to a single use before analysis.

## Extended Data Table 2 | Weighted Relative Impact score validation

| | Field site | Facility | Latitude | Longitude | Pr. ice-free area | Pr. adjacent ice-free area | WRI | Impact * |
|---|---|---|---|---|---|---|---|---|
| 1 | Canada Glacier heli site | Camp | -77.62646667 | 163.0569833 | 0.76 | 0.75 | 11,604.8 | I |
| 2 | Bull pass Hut | Hut | -77.51683333 | 161.8513333 | 1.00 | 0.92 | 3,472.5 | I |
| 3 | Meserve Glacier Camp | Camp | -77.51333333 | 162.2833333 | 0.94 | 0.72 | 2,285.0 | I |
| 4 | Lake Fryxell Hut | Hut | -77.61666667 | 163.05 | 0.66 | 0.54 | 1,948.9 | I |
| 5 | F-6 Camp heli site | Heli | -77.60856667 | 163.2557167 | 0.80 | 0.67 | 1,768.4 | I |
| 6 | Don Juan camp | Camp | -77.56325 | 161.2158333 | 1.00 | 0.93 | 1,575.9 | I |
| 7 | Lake Bonney heli site | Heli | -77.71583333 | 162.4608333 | 0.77 | 0.68 | 1,293.6 | I |
| 8 | Old Lake Bonney Hut | Hut | -77.70333333 | 162.51 | 0.87 | 0.71 | 946.7 | I |
| 9 | Old New Harbor Camp | Camp | -77.575 | 163.4983333 | 0.84 | 0.58 | 798.4 | I |
| 10 | Blood Falls Camp | Camp | -77.72066667 | 162.2715 | 0.87 | 0.70 | 735.9 | I |
| 11 | Vanda Station | Camp | -77.52666667 | 161.6683333 | 0.95 | 0.87 | 701.6 | I |
| 12 | Marble Point Refueling Facility | Depot | -77.413666 | 163.679166 | 0.36 | 0.10 | 314.0 | I |
| 13 | Lower Wright Hut heli site | Heli | -77.44228333 | 161.6511667 | 0.98 | 1.00 | 152.5 | I |
| 14 | Asgard Hut | Hut | -77.58333333 | 161.6 | 0.97 | 0.67 | 133.4 | I |
| 15 | Mount Newall Radio Repeater heli site | Heli | -77.50491667 | 162.6223333 | 0.33 | 0.38 | 47.5 | I |
| 16 | Battleship Promontory camp | Camp | -76.92183333 | 161.08 | 0.33 | 0.41 | 19.9 | N |
| 17 | Brownworth Hut | Hut | -77.45 | 162.8833333 | 0.04 | 0.26 | 3.9 | N |
| 18 | Commonwealth Glacier Camp | Camp | -77.58233333 | 163.5968333 | 0.33 | 0.46 | 0.0 | N |

Field sites[29,68] used to validate the relationship between WRI scores and sites likely to have been impacted by human activity in the McMurdo Dry Valleys region (Extended Data Fig. 1). The WRI scores were calculated by multiplying visitation record data by the proportion of ice-free area per 25-km$^2$ cell and the proportion of the ice-free area in the eight adjacent cells, a measure of ice-free area connectivity. Sites with WRI scores ≤20 are considered to have experienced negligible impact from human activity. *Impact categories: I, impacted; N, negligibly impacted.

## Extended Data Table 3 | Inviolate and Negligibly Impacted Antarctic Wilderness areas

| ACBR ID | ACBR Name | Total area (km$^2$) | Inviolate Wilderness area (km$^2$) | Negligibly Impacted Wilderness area (km$^2$) | % area Negligibly Impacted Wilderness |
|---|---|---|---|---|---|
| 1 | North-east Antarctic Peninsula | 1,215 | 0 | 546 | 44.94 |
| 2 | South Orkney Islands | 160 | 0 | 0 | 0 |
| 3 | North-west Antarctic Peninsula | 5,183 | 0 | 3,822 | 73.74 |
| 4 | Central South Antarctic Peninsula | 4,962 | 0 | 4,404 | 88.76 |
| 5 | Enderby Land | 2,188 | 0 | 1,918 | 87.66 |
| 6 | Dronning Maud Land | 5,523 | 153 | 5,353 | 96.93 |
| 7 | East Antarctica | 1,109 | 0 | 417 | 37.58 |
| 8 | North Victoria Land | 9,431 | 0 | 8,144 | 86.36 |
| 9 | South Victoria Land | 10,038 | 0 | 4,474 | 44.57 |
| 10 | Transantarctic Mountains | 18,480 | 47 | 14,414 | 78.00 |
| 11 | Ellsworth Mountains | 2,859 | 0 | 2,309 | 80.75 |
| 12 | Marie Byrd Land | 1,128 | 0 | 838 | 74.35 |
| 13 | Adélie Land | 179 | 0 | 176 | 98.59 |
| 14 | Ellsworth Land | 217 | 0 | 176 | 81.05 |
| 15 | South Antarctic Peninsula | 2,875 | 0 | 2,757 | 95.91 |
| 16 | Prince Charles Mountains | 5,992 | 83 | 5,678 | 94.76 |
| Total | ACBRs | 71,537 | 283 | 55,426 | 77.48 |
| | Ice-free areas (†) | 30,848 | 67.47 | 20,794 | 67.41 |
| | All land areas (in. ice-shelves) | 13,650,241 | 4,332,500 | 13,598,148 | 99.62 |

Sizes of Inviolate Antarctic Wilderness and Negligibly Impacted Antarctic Wilderness areas across Antarctica, and within each of the ice-free Antarctic Conservation Biogeographic Regions (ACBRs[28]), modelled at a 25-km$^2$ resolution. Inviolate and Negligibly Impacted Antarctic Wilderness areas are large (≥10,000-km$^2$), contiguous areas of unvisited or negligibly impacted sites (that is, unvisited and infrequently visited sites, weighted by proportion of ice-free area per site), respectively. Because of resolution and rounding errors, total ACBR areas differ slightly (by <2 km$^2$) from those published in Terauds and Lee[28]. †Total ice-free area estimates derived from the spatial data for exposed rock of Burton-Johnson et al.[75] for Antarctica.

**Extended Data Table 4 | Biodiversity representation in wilderness areas**

| Antarctic regions | IBA area ($km^2$) | Number of IBAs represented | ASPA area ($km^2$) | Number of biodiversity records |
|---|---|---|---|---|
| Negligibly Impacted Wilderness areas | 109 | 78 | 153 | 1,472 |
| Inviolate Wilderness areas | 0 | 0 | 0 | 0 |
| Non-wilderness areas | 558 | 157 | 460 | 21,859 |
| Total | 205,163 | 220 | 1,577 | 26,779 |
| Total terrestrial area | 667 | 202 | 613 | 23,331 |

Areas of Antarctic IBAs and biodiversity-relevant ASPAs and numbers of biodiversity records from the Antarctic Terrestrial Biodiversity Database represented within Antarctica's Negligibly Impacted Antarctic Wilderness, Inviolate Antarctic Wilderness and the non-wilderness areas excluded from the Negligibly Impacted Antarctic Wilderness. Total IBA and ASPA areas include marine and terrestrial areas.

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Last updated by author(s): Apr 22, 2020

# Reporting Summary

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## Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

| n/a | Confirmed | |
|---|---|---|
| ☐ | ☒ | The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement |
| ☐ | ☒ | A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly |
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| ☐ | ☒ | A description of all covariates tested |
| ☐ | ☒ | A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons |
| ☐ | ☒ | A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals) |
| ☒ | ☐ | For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted<br>*Give P values as exact values whenever suitable.* |
| ☒ | ☐ | For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings |
| ☒ | ☐ | For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes |
| ☒ | ☐ | Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated |

*Our web collection on statistics for biologists contains articles on many of the points above.*

## Software and code

Policy information about availability of computer code

| | |
|---|---|
| Data collection | No computer code was used to obtain the data |
| Data analysis | All analyses were conducted in R (v.3.4) and ArcGIS (v.10.6). The R code is available at http://doi.org/10.26180/5c32bf1b041ea |

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors/reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

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All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

The wilderness areas and historical human activity data used for the analyses and figures are freely availably through Monash Figshare (doi: 10.26180/5c32bf1b041ea). The other spatial data, including high-resolution shapefiles of the Antarctic coastline, human infrastructure footprint and Antarctic Conservation Biogeographic Regions, are available from their creators [18,28,53,68].

# Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

# Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

| | |
|---|---|
| Study description | We compiled ~2.7 million historical human activity records for Antarctica to assess the extent of Antarctic wilderness areas and whether they capture the continent's important biodiversity features. We projected the human activity coordinates on to a 25 km^2 grid of Antarctica, and used the number of independent records per cell, weighted by the proportion of ice-free area per cell and the proportion of ice-free area in the eight adjacent cells, to quantify the cumulative impact of human visitation to sites across the continent. Ice-free areas and areas with high ice-free area connectivity were weighted as more likely to have been impacted by past activity than glaciated areas because ice-free areas are home to most of the continent's biodiversity and are slow to recover from disturbance. We defined a threshold impact score to delineate between impacted and negligibly-impacted or pristine areas. We defined large, contiguous areas of negligibly-impacted or pristine sites as Antarctic wilderness areas. We also used the human activity dataset to identify large, contiguous areas with no historical visitation records, which we considered to be putatively inviolate. These areas were identified as an Inviolate Antarctic Wilderness. In addition, we used data on the human infrastructure footprint of the continent and the peak population of Antarctic stations to define wilderness areas using definitions developed elsewhere. To determine whether Antarctica's wilderness areas capture major features of biodiversity value, spatial layers of Antarctica's ice-free Antarctic Conservation Biogeographic Regions (ACBRs), 220 Important Bird Areas (IBAs), biodiversity and Antarctic Specially Protected Areas (ASPAs) were overlaid onto the wilderness areas excluding biological sampling activity data and the overlap area and proportions calculated. |
| Research sample | The research sample is of ground-based human activity of all kinds, including scientific sampling sites, traverses, infrastructure and tourism. The data excludes aerial surveys, remote-sensed data and data from social networking and public image-hosting services (e.g. Twitter, Flickr, Facebook). The data covers the whole of the Antarctic continent and its offshore islands. Our area of interest for an assessment of wilderness of the Antarctic continent, is Antarctica. After consideration of the literature on wilderness, we used human activity to help define those areas that could be considered wilderness in Antarctica. The Important Bird Area, Antarctic Biogeographic Regions, biodiversity, ice-free areas, tourism and human footprint data were all taken from published sources. Specifically: The Important Bird Areas data are comprehensive from the original source (provided by Birdlife International), the Antarctic Conservation Biogeographic Regions were downloaded from Terauds & Lee's (2016 Diversity & Distributions) paper, the biodiversity data were from an online database from Terauds & Lee's (2016 Diversity & Distributions) paper, the ice-free area layers came from the Scientific Committee for Antarctic Research's Antarctic Digital Database, the tourism data from the 2017-2018 season were obtained from the International Association of Antarctic Tour Operators data portal (www.iaato.org) and the human infrastructure footprint from Brooks' et al. (2019 Nature Sustainability) paper. |
| Sampling strategy | Sample size was not pre-determined because the scope of human activity data was not known even within an order of magnitude when the project commenced. The sample size reflects the data that were accessible and could be obtained from all sources we are aware of over the ~5 year period of collection. At close to ~2.7 million human activity records, of which ~ 2 million are unique, and which cover all known areas of human activity (e.g. from the Council of Managers of National Antarctic Programs Station Catalogue) the authors considered this to be the most comprehensive sampling of human activity achievable. Data from other sources was used as presented. |
| Data collection | The collation of this data took place between 2014 and 2018 and was undertaken by the authors (excluding SLC and KB) led by RIL. Data were collected from online sources (databases of scientific activity or collections or localities of work), published books, scientific articles, and a few personal communications. The metadata file provides a full record of the data sources. |
| Timing and spatial scale | The database of historical human activity covers the whole Antarctic continent and its maritime (Antarctic Peninsula) islands (ca. 13.6 million km^2) and represents records from 1819 to 2018 at a 25 km^2 resolution. |
| Data exclusions | The entire ~2.7 million records were used for the analysis of Negligibly Impacted Antarctic Wilderness Areas and Inviolate Antarctic Wilderness areas. |
| Reproducibility | Because our study is mensural, experimental repeatability is not at issue here. |
| Randomization | The study is a mensural one, not experimental, hence randomization was not undertaken. |
| Blinding | Blinding was not applicable to this study. |

Did the study involve field work? ☐ Yes ☒ No

# Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

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| n/a | Involved in the study |
|---|---|
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| ☒ | ☐ Eukaryotic cell lines |
| ☒ | ☐ Palaeontology |
| ☒ | ☐ Animals and other organisms |
| ☒ | ☐ Human research participants |
| ☒ | ☐ Clinical data |

## Methods

| n/a | Involved in the study |
|---|---|
| ☒ | ☐ ChIP-seq |
| ☒ | ☐ Flow cytometry |
| ☒ | ☐ MRI-based neuroimaging |