RESEARCH/REVIEW ARTICLE

Trampling on maritime Antarctica: can soil ecosystems be effectively protected through existing codes of conduct?

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Abstract

Soil trampling is one of the most obvious direct negative human impacts in Antarctica. Through a range of experiments and field studies based on quantitative physical (soil penetration resistance) and biological (collembolan abundance) indicators, we evaluate the current codes of conduct relating to the protection of Antarctic soils from the consequences of pedestrian impacts. These guidelines include using, where available, established paths that cross vegetation-free soils. However, the effectiveness of this strategy is highly dependent on context. Limited intensity use—below 100 foot passes per year—produces small changes at the soil surface that can recover relatively rapidly, suggesting that the dispersal of activity across wider corridors may be the most appropriate option. However, for paths with a higher use level and those located in steep-sloped sites, it is desirable to define a single track, following stony or bouldery surfaces wherever possible, to keep the disturbed area to a minimum. It is clear that both environmental conditions and expected use levels must be taken into account in determining when and where it is more appropriate to concentrate or disperse human activities. Even though they may have performed satisfactorily to date, the increasing pressure in terms of numbers of visits for certain sites may make it necessary to revise existing codes of conduct.

Antarctica is a vast continent with an area around 14 000 000 km^2, but its terrestrial life is limited to only 0.34% of this area, including exposed nunataks, cliffs, and seasonally snow- and ice-free ground (Convey 2010), having a combined area of only ca. 44 000 km^2 (Convey et al. 2009). Terrestrial habitats can be considered as isolated "islands" separated by ice or ocean (Bergstrom & Chown 1999). Soils exposed during the austral summer are characterized by limited depth, low organic matter content, low biomass and primary production, limited availability of nutrients such as nitrogen and phosphate as well the entire range of trace elements, low water content approaching aridity in many cases, and slow decomposition rates (Thomas et al. 2008). These features make many Antarctic soils readily vulnerable to disturbance by human activities (Campbell et al. 1993). Unconsolidated soils with sandy pebble-gravel textures are very vulnerable to damage by pedestrian traffic. Foot tracks can be formed in these soils in a very short time and may remain visible for many years after the event (Campbell & Claridge 1987). In the Victoria Land Dry Valleys, Campbell et al. (1998) reported that tracks formed in sandy gravel soils after as few as 20 pedestrian transits remained visible up to 30 years later. The high fragility of the surface pavement and the absence of significant natural rehabilitation processes in this area underlie this long-lasting disturbance. Hodgson et al. (2010) similarly observed the continued presence of footprints in the Davis Valley, Pensacola Mountains, from a single visit over 50 years ago. Meanwhile, soils

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with a high surface boulder cover and/or a large particle-size fraction are the least sensitive (Campbell et al. 1998). Paths on these surfaces are less obvious, especially in the absence of clear slopes or areas of finer grained soil or mud. Regardless of soil type, it is recognized that ground surface damage through trampling by national operator staff and tourists visiting the region is one of the most obvious direct negative impacts of human presence in the Antarctic (Cessford & Dingwall 1998; Tin et al. 2009). In recent years, there has been an increase in the extent of activities (the "operational footprint") of both scientists and visitors across Antarctica, and an associated expansion and diversification of human activities (Stewart et al. 2005). As a result, the interest in and attention paid to human impacts on the Antarctic environment is growing (Tin et al. 2009).

Numerous studies identify trampling as a human impact on Antarctic terrestrial ecosystems (e.g., Chen & Blume 1997; Kriwoken & Roots 2000), but quantitative studies (e.g., Tejedo et al. 2009) are still scarce. The consequences of pedestrian traffic vary according to the nature of the soils and vegetation being considered. In terms of soil structure and surface properties, trampling produces an increase in track width, penetration resistance and bulk density (Campbell et al. 1998; Tejedo et al. 2005; Tejedo et al. 2009), micro-relief changes and visual impacts (Campbell et al. 1998; O'Neill et al. 2010), albedo alterations (Campbell et al. 1994), and modifications in nutrient cycles including reduced soil CO_2 flux in some cases (Ayres et al. 2008). Several impacts on soil biota have also been identified, the most obvious being reduction in vegetation cover and loss of vegetal biomass around paths (de Leeuw 1994; Pertierra et al. 2013). Ayres et al. (2008) observed reductions of up to 52 and 76%, respectively, in densities of two species of nematode, *Scottnema lindsayae* and *Eudorylaimus* sp., between paths with heavy pedestrian traffic and nearby undisturbed reference areas. Tejedo et al. (2009) detected a clear decrease in Collembola abundance with increased pedestrian traffic, and Greenslade et al. (2012) similarly noted large reductions in soil collembolan densities in areas on Deception Island subject to a high level of visitation relative to neighbouring undisturbed areas. Finally, some authors have proposed the possibility of non-indigenous species establishment as a direct result of the foot traffic associated with human presence, although there is still little evidence about the relative importance of this mechanism (Frenot et al. 2005). Given this background, protection of Antarctic soil ecosystems is a priority, as it provides habitat for fauna and flora which are regionally important and, in some cases, include endemic representatives.

The political context of Antarctic governance provides an important framework in efforts to develop mechanisms to protect soils in this region. Hughes & Convey (2010) highlight that Antarctica is unique in being "governed" through an international treaty, which currently has 50 signatory nations. This agreement, the Antarctic Treaty, places existing national territorial claims in abeyance, allows unrestricted movement cross the continent, and specifies that signatory nations should have a peaceful, scientific presence in the region. The Protocol on Environmental Protection to the Antarctic Treaty, also known as the Madrid Protocol, which came into force in 1998, provides the main regulatory framework relating to environmental protection that is applied to all human activities involving Treaty Parties in Antarctica. Article 3.2.b.iii of the Madrid Protocol states that activities in the Antarctic Treaty area should be planned and conducted so as to avoid significant changes in the terrestrial environment. However, the Madrid Protocol does not include specific measures to minimize trampling effects. The mechanism by which the Madrid Protocol identifies risks to the environment is through the use of environmental impact assessments, which are described in Annex I and should be applied to all activities undertaken in Antarctica, whether governmental, private or commercial. The Madrid Protocol also includes a series of related recommendations. Recommendation XXVIII-1, entitled "Guidance for visitors to the Antarctic," was adopted in 1994 by the Antarctic Treaty Consultative Parties and includes a series of practical and simple measures and items of advice to ensure that all visitors to Antarctica, both scientists and others, comply with the provisions of the Antarctic Treaty and the Madrid Protocol. The Secretariat of the Antarctic Treaty (SAT) has made the guidelines available in the form of "General guidelines for visitors to the Antarctic" (http://www.ats.aq/documents/recatt/att483_e.pdf). However, soils are not specifically mentioned, with explicit reference only being made to the prohibition of collecting geological items as souvenirs, including rocks and fossils. The International Association of Antarctica Tour Operators (IAATO), which includes most of the operators in this trade sector, applies a version of this recommendation as a code of conduct for their clients during their visits to Antarctica.

Apart from these general legal instruments, there are a number of specific codes of conduct developed by different organizations to ensure the proper protection and conservation of Antarctic ecosystems. The SAT has developed a collection of "Site guidelines for visitors" to provide specific instructions on the conduct of activities at the most heavily visited Antarctic sites (available at

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www.ats.aq/e/ats_other_siteguidelines.htm). This includes practical guidance for tour operators and guides on how they should conduct visits at those sites, taking into account the environmental values and sensitivities particular to each site. Some measures for controlling the effects of trampling are mentioned, including the demarcation of closed areas to protect vulnerable features or fragile surfaces and the establishment of walking routes to avoid vegetation trampling. The Scientific Committee on Antarctic Research (SCAR) has developed the "Environmental code of conduct for terrestrial scientific field research in Antarctica" (SCAR 2009), a document approved at the 30th SCAR Delegates Meeting in 2008 and by the Council of Managers of National Antarctic Programs. This code of conduct provides recommendations on the undertaking of scientific field activities while protecting the Antarctic environment for future generations, complementing the relevant sections of the Madrid Protocol and providing guidance for all researchers conducting scientific research on land, lakes and ice. Although non-binding, all countries with permanent and summer scientific stations are encouraged to include this code of conduct within their operational procedures. These guidelines are underlain by the precautionary principle and based on the field experience of members of relevant organizations. With reference to trampling through pedestrian traffic, two measures are proposed: (1) to stay on established trails when available, and (2) to avoid walking on areas that are especially vulnerable to disturbance. However, importantly, as yet few field data are available to provide robust and objective support for these measures.

This article evaluates the recommendations relating to path use proposed in various codes of conduct. Paths have become established in many Antarctic locations, usually in an *ad hoc* fashion, to access certain areas including tourist sites, coastal vertebrate colonies, water supplies, warehouses and research sites. Around research stations in particular, SCAR's "Environmental code of conduct for terrestrial scientific field research in Antarctica" recommends that people follow marked routes. These permanent facilities often occupy large areas that are effectively "sacrificial areas" due to the high level of use that they are exposed to. However, it is not clear that current recommendations are appropriate in the case of paths located in the vicinity of temporary field camps, or in sampling areas or tourist visitation sites which are subjected to more limited use. To address this issue, we carried out a range of experimental trampling studies in several locations of the maritime Antarctic remote from the influence of research stations. Additionally, we analysed the physical recovery capacity of soil to assess the time required for recovery of impacted surfaces. Our data contribute to improving management strategies for this type of human impact.

Methods

Study areas

This research was conducted in three Antarctic locations, all situated in the South Shetland Islands: Byers Peninsula, Livingston Island (62°34′S, 61°13′W); Barrientos Island (62°24′S, 59°47′W); and Whalers Bay, Deception Island (62°59′S, 60°34′W) (Fig. 1). Some basic soil characteristics for the study sites are summarized in Table 1. Byers Peninsula comprises an area of about 60 km^2 at the western end of Livingston Island. Most of this peninsula remains snow-free during the austral summer. Including over 110 lakes and ponds as well as numerous seasonal streams, this important site hosts one of the most complex and diverse limnetic systems in the maritime Antarctic (Toro et al. 2007). Terrestrial biodiversity is also relatively high (Richard et al. 1994; Sancho et al. 1999). The annual average temperature ranges from −1.5 to −3°C (Toro et al. 2007). Precipitation is high, about 700–1000 mm per year, occurring mostly as rain in summer (Bañón 2001). In 2002, Byers Peninsula was designated as Antarctic Special Protected

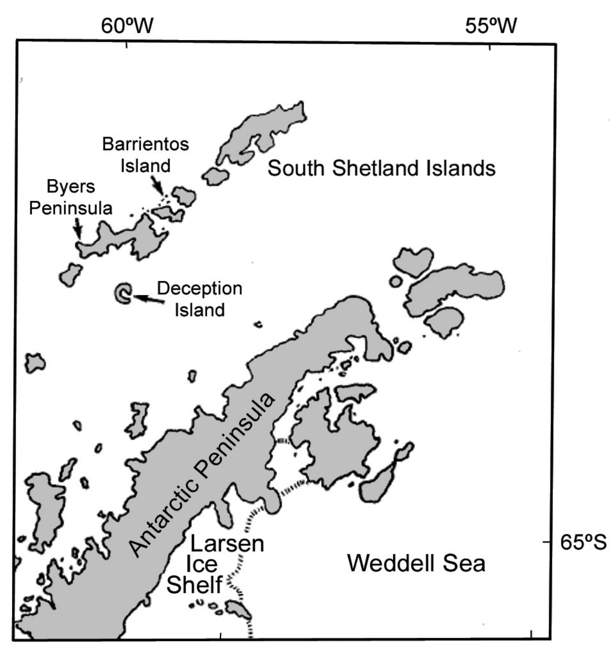

Fig. 1 Map showing the northern Antarctic Peninsula and offshore islands. The locations of Byers Peninsula, Barrientos Island and Deception Island are indicated.

Table 1 Some chemical characteristics of the soils present in the study areas.

Location	Site description	pH	Organic matter (%)	Electrical conductivity (dS/m)	Carbon: nitrogen ratio	Carbon (%)	Nitrogen (%)	Texture
Byers Peninsula[a]	Soil with patches of cushion-forming mosses and lichen	6.1	1.6	0.07	12.2	1.84	0.15	Sandy
Barrientos Island[b]	Bare ground caused by a tourist path crossing a moss meadow	5.6	3.1	0.04	7.2	2.15	0.30	Loamy
Whalers Bay[b]	Low fluvial terraces close to the beach	7.5	0.2	0.04	2.7	0.11	0.04	Very coarse sandy soil

[a]Data from Pertierra et al. (2013).
[b]Data from Samsundar (2011).

Area No. 126, although it has come under different protection regimes since 1966. Human presence has therefore been limited in recent years to scientific activity, with most researchers occupying temporary camps in the vicinity of South Beaches. Most other parts of the peninsula have remained free from regular human influence, providing an excellent opportunity to develop experimental studies on almost pristine soils.

Barrientos Island is situated at the north entrance to English Strait, between Robert and Greenwich islands. It is relatively small, only 1.5 km wide at most. The island's north coast comprises cliffs that reach a height of 70 m, sloping gently towards the south coast. Although there are no site-specific data, the climate is assumed to be closely similar to neighbouring Greenwich Island, which hosts the Ecuadorian Pedro Vicente Maldonado Station. The average temperature during the austral summer at the latter station ranges between -2 and $+2$°C, with about 600 mm of rainfall per year. Barrientos Island is a popular tourist destination, usually amongst the top 20 Antarctic visitor sites (IAATO 2011), and has received around 6300 visitors per season in the last five years. Most tourist visits concentrate on coastal wildlife colonies, with roughly 11% of visitors exploring the whole island (IAATO 2011). Amongst its main attractions for visitors is the presence of very extensive moss carpets, numerous lichens, geomorphological features, and breeding colonies of seabirds and mammals. These features and its popularity led to its inclusion in the first set of "Site guidelines for visitors" developed by the SAT. Relating to the movement of visitors around this island and their effects on soils and associated communities, these guidelines recommend: (1) that visitors avoid walking on any vegetation, and (2) that visitors respect the island's proposed zoning (Fig. 2), which establishes two free-roaming areas at the western and eastern ends of the island where they can walk and explore under supervision. The guide includes several closed areas created to protect the extensive moss carpets located in the central part of the island, the main breeding sites used by southern giant petrels (*Macronectes giganteus*) and one area used to monitor chinstrap penguins (*Pygoscelis antarcticus*). Connecting the two free-roaming areas is a path which runs over the rocks along the shoreline at the island's eastern end and along a narrow gravel stream bed through the vegetation. This path is further specified for use by closely guided groups of no more than 10 visitors. Only one group should follow the stream bed at a time, taking extreme care not to trample the edges of the vegetation (SAT 2006).

Receiving an average of 15 300 visitors per season in the last five years, Whalers Bay is the most popular visitor site on Deception Island, and one of the most visited sites in the Antarctic (Lynch et al. 2010; IAATO 2011). It includes a small harbour where the remains of the abandoned British "Base B" and the Norwegian Hektor Whaling Station can be visited. The latter is the most significant whaling remains in the Antarctic. The location also includes various geological features of volcanic origin (Smellie 2002), including a lahar (mud slide) which formed as a result of an eruption in 1969 that caused the

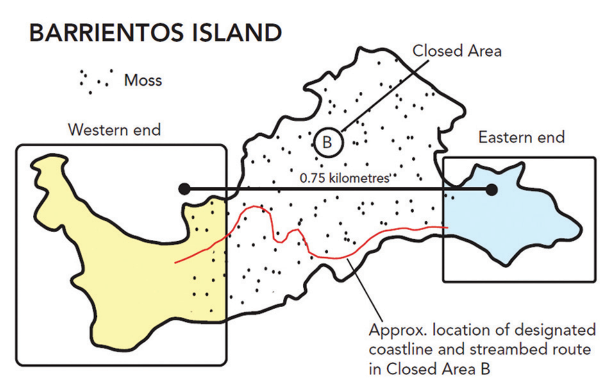

Fig. 2 Schematic diagram of the zoning of Barrientos Island. There are two free-roaming areas in both ends of the island. A designated route crosses Closed Area B, which occupies the central part of the island. Source: Secretariat of the Antarctic Treaty (SAT 2006).

abandonment of the British and Chilean stations on the island. The climate of Deception Island is again maritime polar, with an annual average temperature of $-3°C$ and about 500 mm of precipitation per year. Deception Island was adopted as an Antarctic Specially Managed Area at the 28th Antarctic Treaty Consultative Meeting in 2005. The Deception Island management package (Deception Island Management Group 2005) contains a "Code of conduct for visitors to Deception Island", which was used as the basis to develop the various island's visitor site guides. Currently, there are site guidelines for the four more visited locations on Deception Island: Whalers Bay, Baily Head, Telefon Bay and Pendulum Cove. These guidelines are similar to those proposed for Barrientos Island, including the designation of free-roaming and closed areas. Several sites of current geothermal activity and with exceptional associated vegetation communities collectively form Antarctic Specially Protected Area No. 140.

Physical and biological impacts on established paths

In our analyses of trampling impacts, only the first 10 cm of the soil profile was considered as this is the layer most likely to be disturbed by pedestrian traffic (LaPage 1967). The two parameters used for monitoring trampling effects were soil penetration resistance (a proxy for soil compaction) and springtail abundance. Both are closely related to important ground surface properties, including soil texture, porosity, organic matter content, aeration and infiltration rate (Soil Survey Staff 2006). Because both parameters are strongly influenced by soil water content, experiments were only carried out when the circumstances were appropriate, i.e., when the ground surface was well drained. Together, these data provide the first robust quantification of the consequences of concentrated human movement along established trails in terms of physical and biological changes. The value of these parameters in assessing human impact has been confirmed by several studies, as summarized by Tejedo and co-authors (Tejedo et al. 2005; Tejedo et al. 2009).

Penetration resistance was obtained using a manual precision penetrometer ST-308 (Eurosite, Ancona, Italy). This instrument records the force (kg/cm^2) necessary to introduce a marker into the ground to a certain depth. The instrument's measuring range was 0 to 6 kg/cm^2. When the upper measurement limit was exceeded, an arbitrary value of 7 kg/cm^2 was assigned for graphical representations and calculations. Springtails were obtained from samples of approximately 500 cm^3 taken from the top 0–10 cm of the soil profile. These samples were collected using a plastic cylinder of known volume. Each core was broken up by hand onto a wire mesh of (1 mm mesh) and was exposed for 48 h to a 40 W light placed 20 cm above the sample, following the method used by Convey et al. (1996). To avoid drying out, active arthropods migrate to the lower layers of the sample and fall through the mesh. Specimens pass through a funnel into a jar containing 80% ethanol. Preserved springtails were returned to Spain, where they were counted and identified to species level by optical microscopy.

Studies were conducted along: (1) an experimental length of path specifically created in a previously undisturbed area on Byers Peninsula; (2) part of the trail net created by scientists since the 2001–02 summer season in the vicinity of the temporary camp located at South Beaches, Byers Peninsula; and (3) lengths of different tourist paths on Barrientos Island and at Whalers Bay that experience intensive use by Antarctic standards. All protocols were based on well-established methods typically used in recreation ecology and applied in the analysis of soil disturbance and trampling consequences (e.g., Marion & Leung 2001; Farrell & Marion 2002; Cole 2004; Marion & Olive 2006; Marion et al. 2006; and references therein).

The Byers Peninsula experimental path length was created in the 2003–04 season in a flat, pristine area. In January, after the melting of winter snow, four transects of 2 m length and 60 cm width were created. Each one was subjected over a single day to a different use level: 0 (control), 100, 300 and 600 pedestrian transits by a researcher weighing about 88 kg. Soil penetration resistance was recorded at three points for each trampling intensity, and with five replicate measurements taken at each point. Three cores were taken to determine the abundance of springtails under each experimental level of pedestrian traffic.

During the same field season, soil penetration resistance and springtail abundance were recorded on three paths used by researchers in the area of the temporary camp located at South Beaches. Here, two sampling areas were established: the centre of the path (considered the most impacted area); and a strip 3 m away from the path (used as control area). In each area, three points separated by 1 m were selected as sampling points. Again, five replicates per point were obtained for penetration resistance, with a single core for the extraction of Collembola obtained at each point.

For analyses on Barrientos Island, a stretch of 225 m on an unofficial trail was selected. The route proposed in the island's "Visitor site guide" was not used for this purpose as it runs mostly over rocks and a stream bed, limiting the possibility of applying the selected parameters.

After an initial visual inspection used to measure the length of this studied path, soil penetration resistance was measured every 5 m, both in the centre of the path (zone of maximum impact) and 50 cm to either side (used as control areas). We recorded 138 points, 46 per zone, taking five replicates per point. Most of the measurements in the outer control areas actually lay within the path boundary, which was over 100 cm wide (about two-thirds of all data collected). This sampling regime was considered the best option because the path crosses the extensive moss carpets located in the central part of the island, and most of the substratum outside the path boundary was not comparable to that located within it. The maximum slope and path width were also recorded every 5 m, using a hypsometer (Suunto, Vantaa, Finland) and a measuring tape. Cores for the extraction of springtails were taken every 40 m, in the centre of the path and 50 cm on either side, totalling 18 samples.

Two complementary studies were developed on Barrientos Island and Deception Island to assess the influence of slope and soil surface texture on soil penetration resistance. On Barrientos Island, a sloping stretch of 30 m was selected from the officially recommended path that runs over a loamy soil (Samsundar 2011). Soil penetration resistance was recorded at the centre of the path every metre, with five replicates per point.

On Deception Island, the 700 m trail to Neptune's Window was chosen to be compared with the 225 m stretch of tourist path analysed (described above) on Barrientos Island. The width, slope and penetration resistance (five replicates) were recorded every 10 m along this trail, also using a control area defined 50 cm from the centre of the path. This path runs over very coarse volcanic sand soil.

Physical resilience

To quantify the physical resilience of Antarctic soils, three experiments were conducted. The first was undertaken on Byers Peninsula and involved medium-term (three years) research on an experimental path in which the changes in the soil penetration resistance were analysed over time. In the 2006–07 summer season, five stretches of 2 m length were demarcated in a vegetation-free soil in order to expose them to a known number of pedestrian transits by a researcher weighing ca. 100 kg: 0 (not used), 250, 500, 1000 and 2000 transits. This experiment was carried out one day after snow retreat from the demarcated areas. Soil penetration resistance was measured for each use level (five replicates) in this season and again in the 2009–10 summer.

The most impacted stretch from the paths created by scientists at South Beaches, Byers Peninsula, was selected for use in a further experiment of five years' duration. In 2002–03, soil penetration resistance was measured at 0 and 3 m from the centre of the path (most impacted area and control zone, respectively). At each distance, three points separated by 1 m were measured. The data collection was repeated in the 2007–08 season, when five replicates per point were undertaken. From 2002–03 to 2005–06, the path experienced normal use, while it was closed during 2006–07 and 2007–08 to test the recovery of the ground surface.

Finally, the recovery capacity of tourist paths was evaluated on Barrientos Island. Most of this path was covered by snow and ice when it was visited in 2010–11 season, and we therefore assumed that soils remained basically unaltered from the previous tourist season. In the available ice-free stretch (110 m), penetration resistance data were taken every 10 m both in the centre of the path and 50 cm to either side to compare them with those obtained in 2008–09 season. Thirty-three points were recorded, 11 per zone, with five replicates per point.

Statistics

The Mann-Whitney non-parametric test was applied to compare groups. The median of the five recorded replicates of penetration resistance at each sampling location was used for statistical analyses as this measure of central tendency is more robust than the arithmetic mean and is less affected by the extreme values that are frequently encountered in soils because of natural heterogeneity at the micro-scale.

Results

The data obtained on Byers Peninsula in the 2002–03 summer season allowed the construction of impact-response curves for the two monitored parameters. These data, which are included in Tejedo et al. (2009), show how the impact developed with increasing trampling pressure. There was a clear increase in penetration resistance with increasing pedestrian transits. Before the impact, the penetration resistance was around 1 kg/cm^2 on average, whereas it was close to 5 kg/cm^2 after 600 transits. Our results fit well to a linear model ($y = 0.0068x + 0.9747$, $r^2 = 0.7948$, $P < 0.001$), although a polynomial equation explains a slightly higher proportion of the variability, up to 83% ($y = 0.000009x^2 + 0.0125x + 0.6136$, $r^2 = 0.8364$, $P < 0.001$). Data corresponding to 300 pedestrian transits showed some variability, which could be due to differences at the

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micro-relief level. The data suggest that even a low use level, around 100 pedestrian transits, significantly increased soil penetration resistance (Mann-Whitney test, $P=0.050$).

In the study developed for the second monitored parameter, two collembolan species were sampled: *Cryptopygus antarcticus* and *Friesea woychiechowskii*. The majority of springtail specimens obtained were *C. antarcticus* (90.6%) and, as a result, the data indicated that only *C. antarcticus* was significantly affected by the trampling impact. In the non-impacted zone, 180 *C. antarcticus* individuals were obtained in total (including the three replicates), 106 in the stretch subjected to 100 pedestrian transits, 44 in the stretch subjected to 300 footsteps, and 16 at the maximum level of trampling (600 transits). *F. woychiechowskii* did not show the same trend, yielding a total of 9, 6, 8 and 13 individuals, respectively, in each stretch. Springtails did not disappear completely even at the highest trampling level applied, although their number was reduced markedly (by 84.7%, relative to the initial value). The most abrupt change in their abundance occurred at 300 pedestrian transits. The data are not fitted well by any simple mathematical model, although a reduction in collembolan abundance is observed when use increases ($y=0.0002x^2-0.2198x+60.879$, $r^2=0.3876$).

Soil penetration resistance was measured across a network of paths which were created by the researchers on Byers Peninsula and in a tourist path on Barrientos Island (Fig. 3a). In both cases, there were higher levels of compaction in the centre of the track than in control areas (Mann-Whitney test, $P<0.001$ for both paths). Physical degradation of the tourist route surface on Barrientos Island was significantly higher (Mann-Whitney test, $P=0.003$); in many cases the upper limit of detection of the penetrometer was exceeded. Total abundances of Collembola (Fig. 3b) were also significantly different between the most impacted zones and control areas in both cases (Mann-Whitney test, $P<0.001$ in each case). On the Barrientos Island path, only 29 specimens were found in all samples ($n=6$) from the centre of the path, while a total of 822 individual springtails (all *C. antarcticus*) were obtained in the 12 samples from control areas.

The influence on the penetration resistance of some key physical characteristics of soils affected by trampling is illustrated in Figure 4. The slope (Fig. 4a) has a clear influence on resistance, with the section of path crossing a gradient ($17.6\pm0.34°$) showing values significantly greater than the near-horizontal section ($4.87\pm0.61°$; Mann-Whitney test, $P<0.001$). Most of the values obtained from the former exceeded the upper detection limit of the penetrometer, whereas data variability was much greater for the latter. Regarding the dominant texture of the ground surface (Fig. 4b), soil penetration resistance in the loam soil was significantly higher than in the very coarse sand soil, both in the centre of the track (with an average of 5.25 vs. 1.48) and in the control area (0.71 vs. 0.05; Mann-Whitney test, $P<0.001$). Clear differences were also observed in the data variability, being much higher for the trail on the Barrientos Island. The variance for the centre of the path with a loamy texture (Barrientos Island) was 1.21, while this figure was 0.18 for the path with a very coarse sand texture (Deception Island). A similar trend was observed in the control areas, with variances of 0.71 and 0.05, respectively.

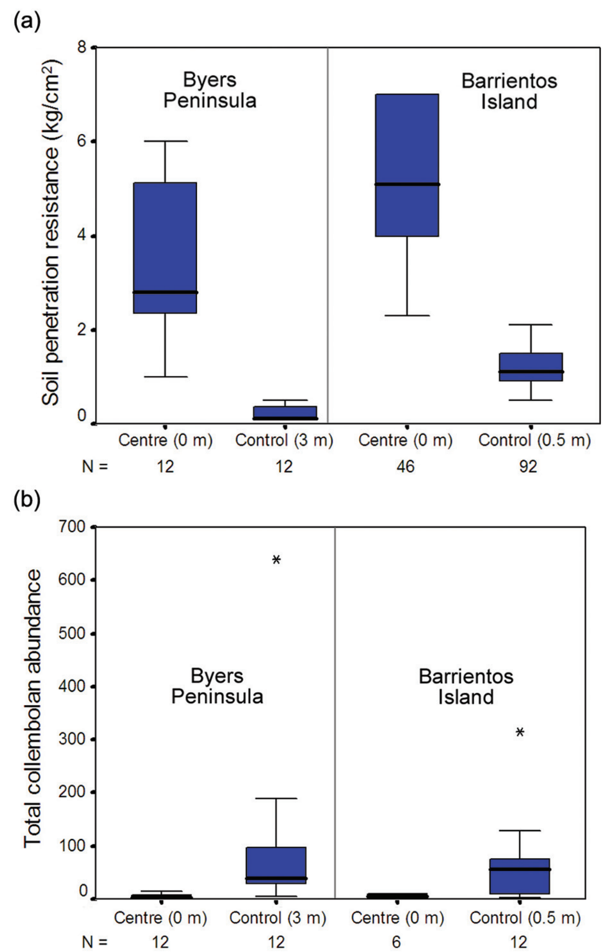

Fig. 3 (a) Soil penetration resistance and (b) total collembolan abundance were measured in Byers Peninsula in a group of trails created by scientists during their fieldwork and in a tourist trail located on Barrientos Island. In both cases, data were obtained in the most impacted zone (centre of the track) and in nearby areas used as control. In the box plots, the asterisks represent outliers.

The physical recovery capacity in the medium-term (two–three years) for maritime Antarctic soils is illustrated in Fig. 5. In all cases, there was an improvement over time in the properties of the soil surface layer. In the experimental path created in 2006–07 and revisited three years later, all the penetrometer values obtained in the latter season were very similar, around 1 kg/cm^2. In contrast, at heavily trampled areas (subjected to 2000 pedestrian transits), initial values reached 6 kg/cm^2. The penetration resistance in the control area was greater in 2009–10 than in the 2006–07 season (Fig. 5a). The path located in the research camp in Byers Peninsula showed a similar trend (see Fig. 6 in Tejedo et al. 2009). The centre of this track presented initially extreme values of penetration resistance, which substantially decreased after it had been closed for two years (Mann-Whitney test, $P = 0.037$). Finally, on Barrientos Island (Fig. 5b), the local environmental conditions suggested that the path had been little used in the 2010–11 season, providing an analogy to a recovery situation. Data obtained here reinforce this suggestion, with a lower resistance being obtained for the 2010–11 season both in the centre of the path and in the control areas (Mann-Whitney test, $P < 0.001$ in each case). In the most

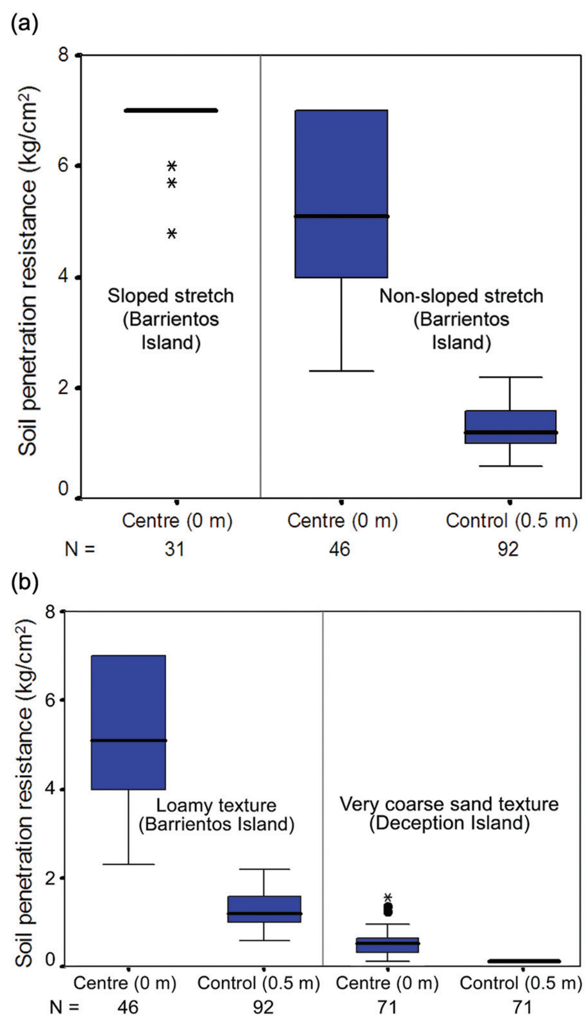

Fig. 4 Influence on the soil penetration resistance of the slope and the dominant texture of the ground surface. (a) This parameter was analysed in two stretches with different slopes from the network of tourist paths on Barrientos Island. The first presents a steep average slope while the other has a flat profile. (b) The flat stretch, which has a loamy texture, is compared with the tourist path leading to Neptune's Window, Deception Island. This trail is dominated by lapilli. The dots represent extreme data and the asterisks are outliers.

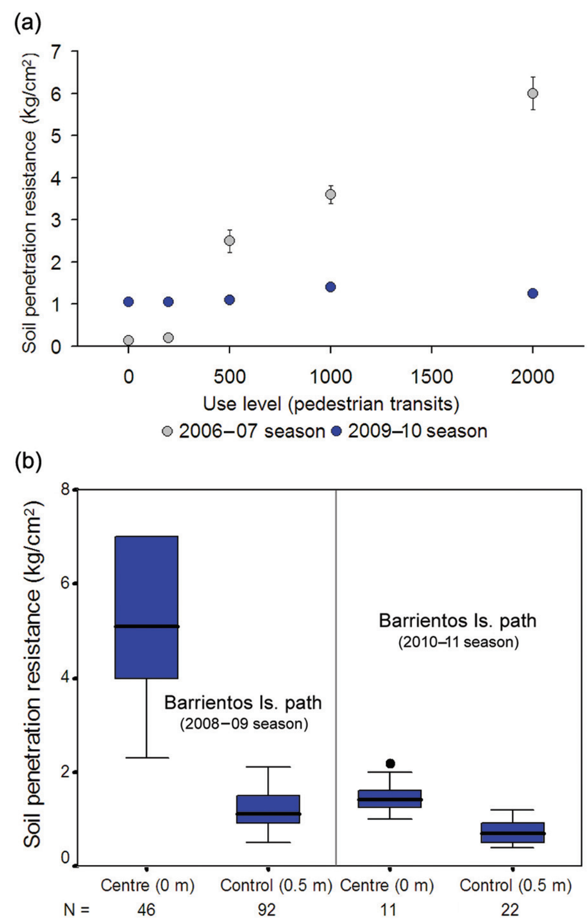

Fig. 5 Study of the ground surface physical recovery capacity using the soil penetration resistance. (a) An experimental stretch on Byers Peninsula was subjected to different trampling intensities in the 2006–07 season. Data were recorded again three years later. (b) Data from a non-official tourist path on Barrientos Island in two non-consecutive years. The left part of (b) shows data for the 2008–09 season along a 225 m stretch. On the right, data are shown for the 2010–11 season from a partial section of the previous stretch. Data were taken at the centre of the path and 50 cm on each side of this point (control areas). In the box plots, dots represent extreme data.

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Fig. 6 Waterlogged area on the designated track route on Barrientos Island. Pedestrians trying to avoid the mud widen the track.

impacted area, the penetration resistance decreased from an average of around 5 kg/cm^2 to 1.43 kg/cm^2.

Discussion

The relationship between trampling and physical and biological disturbance to maritime Antarctic soils has been partially analysed by Tejedo and co-authors (Tejedo et al. 2005; Tejedo et al. 2009), focussing on a limited set of experimental paths and trails created by scientists in the vicinity of a temporary camp on Byers Peninsula. In the present article, we compare the previous results with those obtained from tourist trails located on Barrientos Island and Deception Island in order to evaluate whether they can be generalized to soils subjected to a higher level of use. Our data indicate that maritime Antarctic soils can be altered by relatively low trampling intensity. The threshold at which very obvious damage occurred in an experimental path was very low, around 100–300 foot passes, depending on the parameter considered. As the intensity of trampling increased, compaction and total collembolan abundance were reduced. Our data suggest that human trampling pressure can generate an immediate impact on the abundance of soil fauna. This may be due to direct killing of specimens, to changes in the microhabitat that reduce the ecological viability of the Collembola, or a combination of both processes. Trampling alters the macroporosity and the structure of the upper few centimetres of the ground surface, reducing the water-holding capacity, permeability and water infiltration (Cole 2004). Abiotic features of Antarctic terrestrial habitats, particularly limited availability of liquid water, strongly influence collembolan abundance (Convey et al. 2003; Hayward et al. 2004). Therefore, significant changes in soil properties as a result of trampling above a certain threshold could reduce the viability of these organisms.

Impacts observed at the centre of paths are clearly higher than those recorded in adjacent control areas. This suggests that implementing a strategy of impact concentration through path creation may not be the most appropriate option in all cases. Rather than path creation, in areas subjected to very limited use a better strategy might be to define access corridors within which movement could be more dispersed without following a specific route. However, in areas subjected to higher use levels the concentration strategy would remain as the best option. Path creation also has benefits that can be important factors in cases where the use intensity is not the only variable to consider. For example, it could facilitate the monitoring of certain impacts by reducing the area under control measures, for instance, in detecting the presence of non-indigenous species. The concentration strategy allows the designation of routes which take into account the breeding activity of species sensitive to human presence and the safety of hikers, for instance, avoiding dangerous areas near cliffs. Partially as a result of these advantages, the use of pre-defined paths is a common recommendation in the "Site guidelines for visitors" promulgated by the SAT. But possibly the greatest advantage of these instruments is that they can permit both the concentration of impact through official paths and the dispersion of foot traffic in those areas less vulnerable to trampling, where free-roaming can be permitted. This mixed strategy has given so far good results in certain heavily visited tourist sites, such as Barrientos Island and Whalers Bay, and more generally is a strategy widely used in recreation ecology.

The international Leave No Trace programme, which was created to assist outdoor enthusiasts in reducing their impacts on the environment, proposes different strategies for camping and hiking, depending on whether visiting popular areas or pristine zones (Harmon 1997; www.LNT.org). The implementation of codes of conduct directly supported by scientific knowledge and activity zoning will normally be a less harmful alternative to manage the movement of scientists and tourists than other more intrusive measures, including the installation of permanent hiking facilities such as boardwalks or causeways. While such constructions may be appropriate in the immediate vicinity of research stations and have also been proposed for some specific high use intensity sub-Antarctic locations (McKee 2006), the Antarctic Treaty System community generally discourages their use at visitor sites because they can severely affect the aesthetic values of Antarctica (Bastmeijer 2007;

Tin et al. 2008), as well has having more local impacts such as obstructing faunal movement. It would be advantageous to include professional trail designers in processes selecting those routes that are more sustainable, such as alignments that seek to remain on rock or coarse substrates, avoid animal trails, respect vegetation, and to avoid steep gradients vulnerable to erosion or muddy soils that encourage trail widening.

Among the characteristics of soils affected by trampling that influence the degree of degradation, the most important factors appear to be slope, the dominant texture of the ground surface, and the presence of muddy areas. Our data suggest that steeper slopes can increase the compaction of soil caused by trampling, as reported in other environments (Leung & Marion 1996; Whinam & Chilcott 2003). Paths formed on a steep relief are more vulnerable to concentration of trampling than those running over a flatter terrain. For trails that cross steep-sloped sites it would be desirable to define a single track to keep the disturbed area to a minimum, following stony or bouldery surfaces wherever possible, and using aligned trails that transit slopes at an angle (e.g., 45 degrees from the fall line). Regarding the dominant texture of the ground surface, Campbell et al. (1998) concluded that soils dominated by large particles were less vulnerable to compaction, a finding consistent with our data obtained from Deception Island. In this island's environment, where soils are dominated by volcanic lapilli, a volcanic material ranging in size from 2 to 64 mm in diameter, foot traffic along defined fixed paths often causes permanent changes in ground surface colour and texture. Such alterations may be reduced or even avoided by dispersing the routes taken by pedestrians. The final factor, the presence of muddy areas, was highlighted by Gremmen et al. (2003), who observed that paths created in waterlogged areas often experienced flooding. This resulted in expansion of the track boundary and zone of disturbance as pedestrians tried to avoid the worst affected areas. Similar track expansion was observed during our research on Barrientos Island (Fig. 6). Where such increased degradation occurs, changes need to be made in path route designation.

As well as confirming the vulnerability of maritime Antarctic soils to trampling, the documentation of their recovery capacity is also important. The generally accepted assumption is that disturbance effects on Antarctic soils are very long-lasting, especially in continental environments such as the Victoria Land Dry Valleys and Transantarctic Mountains (Campbell & Claridge 1987; Ayres et al. 2008; Hodgson et al. 2010). However, our data suggest that some areas of maritime Antarctic soil that have suffered intermediate levels of use could possibly physically recover after a period of as little as two–three years without human presence. Separately, a three–five-year interval of time has been suggested for bryophyte and associated invertebrate communities to develop on previously bare soil (Convey 2003), although soil exposed for longer probably needs more time to reach a complete recovery of soil communities, and signs of damage (e.g., footprints, vehicle tracks) can remain visible in moss turf vegetation for many decades. The repeated freeze–thaw cycling typically experienced in many maritime Antarctic soils could assist recovery from soil surface layer impacts in a relatively short period of time. However, for those walking trails that support a large number of visitors each year, recovery will take longer.

Our data provide support to the proposition that the adoption of temporary closures in locations experiencing erosion, or in which vulnerable biotypes have been altered, will help their recovery. The limited use of the majority of Antarctic walking trails (below 5000 users per season according to annual IAATO statistics) would currently permit utilization of this option, which would not be appropriate in areas that receive larger numbers of visitors. Use of this management measure is not a novelty in Antarctica. Temporary closures are applied in certain breeding sites, such as Hannah Point (Livingston Island). Since the 2005–06 season, the "Visitor site guide" for this location has recommended avoiding visits between the beginning of the penguin breeding season and the end of the early phase of incubation (October to mid-January).

The current study has not investigated the effects of trampling on soil chemical variables, but data are now becoming available suggesting that trampling could reduce the amount of available nutrients in several Antarctic moss communities (Pertierra et al. 2013). A further potential impact associated with trampling is the proliferation of non-native species. Gremmen et al. (2003) highlighted that trampled areas on sub-Antarctic Marion Island (46°50′S, 37°50′E) seem to be more vulnerable to the establishment of non-native species than are vegetated undisturbed areas, and several authors consider that tracks provide routes for further human-assisted dispersal of non-native species already established on several sub-Antarctic islands (e.g., Scott & Kirkpatrick 1994; Frenot et al. 2005). However, the use of designated walking trails facilitates the identification of establishment of non-native vegetation in comparison with monitoring a network of informal (visitor-created) trails. Other key biological factors, such as soil functional gene expression and microbial community structure, were not assessed in this study and would be valuable to incorporate in future studies of this type.

It is clear that trampling can have a considerable impact on maritime Antarctic soils. However, these effects are typically localized and there are large differences in impacts between habitats (Monz et al. 2000; Gremmen et al. 2003). The existing codes of conduct have to date contributed to controlling the scale of many of the potential impacts generated by trampling. However, their recommendations require ongoing assessment and where necessary revision to ensure their continued effectiveness in the face of expected increases in the extent and intensity of human activities in future (Tin et al. 2009). In this study, we raise the possibility that the guidelines produced by the various interested or controlling organizations, such as SCAR and the SAT, could recommend different strategies depending on the local characteristics of each site, as already included in the SAT's non-binding site-specific guidelines. We suggest that some strategies proposed in SCAR's "Environmental code of conduct for terrestrial scientific field research in Antarctica" are appropriate to be applied without exception, such as the avoidance of walking in vulnerable areas. The fast degradation caused by trampling on certain vulnerable soils and plant communities has been clearly demonstrated (Campbell et al. 1993; de Leeuw 1994; Campbell et al. 1998; Gremmen et al. 2003; O'Neill et al. 2010). However, with reference to the creation and use of defined paths, consideration of different local variables may be appropriate in assessing if a strategy based on the concentration of pedestrians is the best option. Although our data indicate that the resilience and rate of recovery of maritime Antarctic soils may be higher than generally supposed, selecting the most appropriate management strategy will further help minimize physical and biological effects of trampling on the ground surface.

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References

Ayres E., Nkem J.N., Wall D.H., Adams B.J., Barret J.E., Broos E.J., Parsons A.N., Powers L.E. & Simmons B.L. 2008. Effects of human trampling on populations of soil fauna in the McMurdo Dry Valleys, Antarctica. *Conservation Biology 22*, 1544–1551.

Bañón M. 2001. *Observaciones meteorológicas en la Base Antártica Española Juan Carlos I. Monografía A-151. (Meteorological observations at the Spanish Antarctic Base Juan Carlos I. Monograph A-151.)* Madrid: National Institute of Meteorology.

Bastmeijer C.J. 2007. Special offer-7 days fly and drive Antarctica. The role of wilderness protection in deciding whether (semi)permanent tourist facilities in Antarctica should be prohibited. In A. Watson et al. (eds.): *Science and stewardship to protect and sustain wilderness values: Eighth World Wilderness Congress Symposium, September 30 – October 6, 2005, Anchorage, AK*. USDA Forest Service RMRS-P-49. Pp. 190–195. Fort Collins, CO: Rocky Mountain Research Station, Forest Service, US Department of Agriculture.

Bergstrom D.M. & Chown S.L. 1999. Life at the front: history, ecology and change on Southern Ocean islands. *Trends in Ecology and Evolution 14*, 472–476.

Campbell I.B., Balks M.R. & Claridge G.G.C. 1993. A simple visual technique for estimating the effect of fieldwork on the terrestrial environment in ice-free areas of Antarctica. *Polar Record 29*, 321–328.

Campbell I.B. & Claridge G.G.C. 1987. *Antarctica: soils, weathering processes and environment*. Elsevier: Amsterdam.

Campbell I.B., Claridge G.G.C. & Balks M.R. 1994. The effects of human activities on moisture content of soils and underlying permafrost from the McMurdo Sound region, Antarctica. *Antarctic Science 6*, 307–314.

Campbell I.B., Claridge G.G.C. & Balks M.R. 1998. Short and long-term impacts of human disturbance on snow-free surfaces in Antarctica. *Polar Record 34*, 15–24.

Cessford G. & Dingwall P.R. 1998. Research on shipborne tourism to the Ross Sea region and the New Zealand sub-Antarctic islands. *Polar Record 34*, 99–106.

Chen J. & Blume H.P. 1997. Impact of human activities on the terrestrial ecosystem of Antarctica: a review. *Polarforschung 65*, 83–92.

Cole D.N. 2004. Impacts of hiking and camping on soils and vegetation: a review. In R. Buckley (ed.): *Environmental impacts of ecotourism*. Pp. 41–60. CABI Publishing: Wallingford, UK.

Convey P. 2003. Maritime Antarctic climate change: signals from terrestrial biology. In E. Domack et al. (eds.): *Antarctic*

Peninsula climate variability: historical and palaeoenvironmental perspectives. Pp. 145–158. Washington, DC: American Geophysical Union.

Convey P. 2010. Terrestrial biodiversity in Antarctica—recent advances and future challenges. *Polar Science 4*, 135–147.

Convey P., Block W. & Peat H.J. 2003. Soil arthropods as indicators of water stress in Antarctic terrestrial habitats? *Global Change Biology 9*, 1718–1730.

Convey P., Greenslade P., Richard K.J. & Block W. 1996. The terrestrial arthropod fauna of the Byers Peninsula, Livingston Island, South Shetland Islands. *Polar Biology 16*, 257–259.

Convey P., Stevens M.I., Hodgson D.A., Smellie J.L., Hillenbrand C.-D., Barnes D.K.A., Clarke A., Pugh P.J.A., Linse K. & Cary S.C. 2009. Exploring biological constraints on the glacial history of Antarctica. *Quaternary Science Reviews 28*, 3035–3048.

Deception Island Management Group 2005. Deception Island management package. Accessed on the internet at http://www.deceptionisland.aq/package.php on 19 November 2012.

de Leeuw C. 1994. *Tourism in Antarctica and its impact on vegetation*. PhD thesis, Arctic Centre, University of Groningen.

Farrell T.A. & Marion J.L. 2002. Trail impacts and trail impact management related to ecotourism visitation at Torres del Paine National Park, Chile. *Leisure/Loisir: Journal of the Canadian Association for Leisure Studies 26*, 31–59.

Frenot Y., Chown S.L., Whinam J., Selkirk P.M., Convey P., Skotnicki M. & Bergstrom D.M. 2005. Biological invasions in the Antarctic: extent, impacts and implications. *Biological Reviews 80*, 45–72.

Greenslade P., Potapov M., Russel D. & Convey P. 2012. Global Collembola on Deception Island. *Journal of Insect Science 12*, Article 111.

Gremmen N.J.M., Smith V.R. & Van Tongeren O.F.R. 2003. Impact of trampling on the vegetation of subantarctic Marion Island. *Arctic, Antarctic, and Alpine Research 35*, 442–446.

Harmon W. 1997. *Leave no trace: minimum impact outdoor recreation*. Helena, MT: Falcon Publishing.

Hayward S.A.L., Worland M.R., Convey P. & Bale J.S. 2004. Habitat moisture availability and the local distribution of the Antarctic Collembola *Cryptopygus antarcticus* and *Friesea grisea*. *Soil Biology and Biochemistry 36*, 927–934.

Hodgson D., Convey P., Verleyen E., Vyverman W., McInnes S., Sands S., Fernández-Carazo R. & Wilmotte A. 2010. Observations on the limnology and biology of the Dufek Massif, Transantarctic Mountains 82° South. *Polar Science 4*, 197–214.

Hughes K.A. & Convey P. 2010. The protection of Antarctic terrestrial ecosystems from inter and intra-continental transfer of non-indigenous species by human activities: a review of current systems and practices. *Global Environmental Change 20*, 96–112.

IAATO (International Association of Antarctica Tour Operators) 2011. Tourism statistics. Accessed on the internet at http://iaato.org/tourism-statistics on 19 November 2012.

Kriwoken L.K. & Rootes D. 2000. Tourism on ice: environmental impact assessment of Antarctic tourism. *Impact Assessment and Project Appraisal 18*, 138–150.

LaPage W.F. 1967. *Some observations on campground trampling & ground cover response*. *Research Paper NE-68*. Upper Darby, PA: Northeastern Forest Experiment Station, Forest Service, US Department of Agriculture.

Leung Y. & Marion J.L. 1996. Trail degradation as influenced by environmental factors: a state-of-the-knowledge review. *Journal of Soil and Water Conservation 51*, 130–136.

Lynch H.J., Crosbie K., Fagan W.F. & Naveen R. 2010. Spatial patterns of tour ship traffic in the Antarctic Peninsula region. *Antarctic Science 22*, 123–130.

Marion J.L. & Leung Y.-F. 2001. Trail resource impacts and an examination of alternative assessment techniques. *Journal of Park and Recreation Administration 19*, 17–37.

Marion J.L., Leung Y.-F. & Nepal S. 2006. Monitoring trail conditions: new methodological considerations. *The George Wright Forum 2*, 36–49.

Marion J.L. & Olive N. 2006. *Assessing and understanding trail degradation: results from Big South Fork National River and Recreational Area*. Laurel, MD: Patuxent Wildlife Research Center, US Geological Survey.

McKee R. 2006. South Georgia Government Update 2006. Paper presented at the 17th Annual General IAATO Meeting, 24–30 April, Washington DC.

Monz C.A., Pokorny T., Freilich J., Kehoe S. & Ayers-Baumeister D. 2000. The consequences of trampling disturbance in two vegetation types at the Wyoming Nature Conservancy's Sweetwater River Project area. In D.N. Cole et al. (eds.): *Wilderness Science in a Time of Change Conference. Vol. 5. Wilderness ecosystems, threats, and management. USDA Forest Service RMRS-P-15.* Ogden, UT: Rocky Mountain Research Station, Forest Service, US Department of Agriculture.

O'Neill T.A., Balks M.R. & López-Martínez J. 2010. A provisional method for assessing the impact on, and recovery of, Antarctic desert pavements from human-induced disturbances. In R.J. Gilkes & N. Prakongkep (eds.): *Proceedings of the 19th World Congress of Soil Science: soil solutions for a changing world.* Brisbane, Australia, 1–6 August 2010. Published on DVD. International Union of Soil Sciences.

Pertierra L., Lara F., Tejedo P., Quesada A. & Benayas J. 2013. Rapid denudation processes in criptogamic communities from Maritime Antarctica subjected to human trampling. *Antarctic Science 25*, doi: 10.1017/S095410201200082X.

Richard K.J., Convey P. & Block W. 1994. The terrestrial arthropod fauna of the Byers Peninsula, Livingston Island, South Shetland Islands. *Polar Biology 14*, 371–379.

Samsundar J. 2011. *Análisis de la diversidad microbiana y su relación con las características físico–químicas en suelos del archipiélago Shetland del Sur (Antártida) con un diferente impacto antrópico. (Analysis of microbial diversity and its relationship with the physical–chemical characteristics of soils in the South Shetland Islands [Antarctica] with different levels of human impact.)* Master's thesis, Faculty of Biology, Universitat de València.

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Sancho L.G., Schulz F., Schroeter B. & Kappen L. 1999. Bryophyte and lichen flora of South Bay (Livingston Island, South Shetland Islands, Antarctica). *Nova Hedwigia 68*, 301–337.

SAT (Secretariat of the Antarctic Treaty) 2006. Barrientos Island (Aitcho Islands). Visitor site guide. Accessed on the internet at http://www.ats.aq/siteguidelines/documents/Barrientos_e.pdf on 19 November 2012.

SCAR (Scientific Committee on Antarctic Research) 2009. Environmental code of conduct for terrestrial scientific field research in Antarctica. Accessed on the internet at http://www.scar.org/researchgroups/lifescience/Code_of_Conduct_Jan09.pdf on 19 November 2012.

Scott J.J. & Kirkpatrick J.B. 1994. Effects of human trampling on the sub-Antarctic vegetation of Macquarie Island. *Polar Record 30*, 207–220.

Smellie J.L. 2002. The 1969 subglacial eruption on Deception Island (Antarctica): events and processes during an eruption beneath a thin glacier and implications for volcanic hazards. *Geological Society Special Publications 202*, 59–79.

Soil Survey Staff 2006. *Keys to soil taxonomy.* 10th edn. Washington, DC: Natural Resources Conservation Service, US Department of Agriculture.

Stewart E., Draper D. & Johnston M. 2005. A review of tourism research in the polar regions. *Arctic 58*, 383–394.

Tejedo P., Justel A., Benayas J., Rico E., Convey P. & Quesada A. 2009. Soil trampling in an Antarctic Specially Protected Area: tools to assess levels of human impact. *Antarctic Science 21*, 229–236.

Tejedo P., Justel A., Rico E., Benayas J. & Quesada A. 2005. Measuring impacts on soils by human activity in an Antarctic Special Protected Area. *Terra Antarctica Reports 12*, 57–62.

Thomas D.N., Fogg G.E., Convey P., Fritsen C.H., Gili J.M, Gradinger R., Laybourn-Parry J., Reid K. & Walton D.W.H. 2008. *The biology of polar regions* 2nd edn. Oxford: Oxford University Press.

Tin T., Fleming Z.L., Hughes K.A., Ainley D.G., Convey P., Moreno C.A., Pfeiffer S., Scott J. & Snape I. 2009. Impacts of local human activities on the Antarctic environment. *Antarctic Science 21*, 3–33.

Tin T., Hemmings A.D. & Roura R. 2008. Pressures on the wilderness values of the Antarctic Continent. *International Journal of Wilderness 14*, 7–12.

Toro M., Camacho A., Rochera C., Rico E., Bañón M., Fernández-Valiente E., Marco E., Justel A., Avendaño M.C., Ariosa Y., Vincent W.F. & Quesada A. 2007. Limnological characteristics of the freshwater ecosystems of Byers Peninsula, Livingston Island, in maritime Antarctica. *Polar Biology 30*, 635–649.

Whinam J. & Chilcott N. 2003. Impacts after four years of experimental trampling on alpine/subalpine environments in western Tasmania. *Journal of Environmental Management 67*, 339–351.