Antarctic Science 21 (3), 229–236 (2009) © Antarctic Science Ltd 2009 Printed in the UK doi:10.1017/S0954102009001795

Soil trampling in an Antarctic Specially Protected Area: tools to assess levels of human impact

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Abstract: Research in extremely delicate environments must be sensitive to the need to minimize impacts caused simply through the presence of research personnel. This study investigates the effectiveness of current advice relating to travel on foot over Antarctic vegetation-free soils. These are based on the concentration of impacts through the creation of properly signed and identified paths. In order to address these impacts, we quantified three factors - resistance to compression, bulk density and free-living terrestrial arthropod abundance - in areas of human activity over five summer field seasons at the Byers Peninsula (Livingston Island, South Shetland Islands). Studies included instances of both experimentally controlled use and natural non-controlled situations. The data demonstrate that a minimum human presence is sufficient to alter both physical and biological characteristics of Byers Peninsula soils, although at the lowest levels of human activity this difference was not significant in comparison with adjacent undisturbed control areas. On the other hand, a limited resilience of physical properties was observed in Antarctic soils, thus it is crucial not to exceed the soil's natural recovery capability.

Received 7 August 2008, accepted 11 November 2008

Key words: Antarctica, ASPA, environmental monitoring, recovery capacity, soil degradation, trampling impact

Introduction

Antarctic terrestrial ecosystems are widely recognized as being fragile in the face of human disturbance. With the exception of the ornithogenic soils, Antarctic soils are typically of low organic content, poorly consolidated and unstable, while the limited plant communities that develop on them are predominantly composed of cryptogams (bryophytes, lichens, algae and cyanobacteria), which are vulnerable to physical damage and disturbance. The fragility of Antarctic ecosystems has been recognized within the Antarctic Treaty by designating protected areas. Since 1991 three classes of protected areas have been used, Antarctic Specially Protected Area (ASPA), Antarctic Specially Managed Area (ASMA) and Historic Sites and Monuments (HSM). ASPAs were created to "*protect outstanding environmental, scientific, historic, aesthetic or wilderness values, any combination of those values, or ongoing or planned scientific research*" (Article 3.1., Annex V: Protected Area System, Protocol on Environmental Protection to the Antarctic Treaty 1991). These areas are intended *inter alia* to be kept largely free from human interference, in order that future comparisons may be possible with localities that have been affected by human activities. Access to these areas is possible under permits that can only be issued by the appropriate national authorities. In applying for a permit a clear scientific justification needs to be given and researchers applying for access must present plans to minimize their impact on these ecosystems, where appropriate backed by a suitable environmental monitoring programme.

One of the most delicate component of these environments is the soil surface, which is an essential habitat for terrestrial microfauna and flora. Approximately 0.34% of the Antarctic continent is ice-free (Fox & Cooper 1994), and land surfaces are easily disturbed by human activities (Campbell *et al.* 1993). In some dry areas soils are typically overlain by a 'desert pavement', a thin layer of gravel and coarse sand formed by the winnowing out of fine material by wind over a long period of time until a measured of stability is achieved (Campbell *et al.* 1998). Disturbance to this desert pavement will slow the rate of recovery of the soil surface after impacts as all soil processes operate very slowly in the Antarctic environment (Beyer & Bölter 2002). Low temperatures, the general absence of vegetation and the limited soil biota underlie this low resilience (Campbell & Claridge 1987).

The Scientific Committee on Antarctic Research (SCAR) is a non-governmental organization whose functions include the initiation, development and coordination of high quality international scientific research in Antarctica. SCAR and the Council of Managers of National Antarctic Programs (COMNAP) have made numerous recommendations on environment management to Antarctic Treaty Parties, many of which have been incorporated into Antarctic Treaty instruments, including the minimization of environmental disturbance during approved operations within ASPAs (NSF/COMNAP/SCAR 2005). In relation to disturbance by human movement, ASPA Management Plans usually provide a single guideline: that pedestrian traffic should be kept to the minimum consistent with the objectives of any permitted activities and every reasonable effort should be made to minimize trampling effects. More specifically, walking traffic is advised wherever possible to follow bedrock or larger rocks, to prevent damage to often moist or waterlogged soils and vegetation, and to use and mark suitably any existing paths in order to prevent new and unnecessary damage. These guidelines are based on the 'precautionary principle' and the informal field experience and advice of scientific staff. However, to date, there are no quantitative studies to confirm the exact nature and extent of impacts caused by human activity on soils free of ice and vegetation. To address this we conducted a series of studies to assess whether the current recommendations, based on the concentration of researchers along established tracks, is the most appropriate approach for minimizing the impacts on Antarctic soils.

We focused on three variables in order to characterize impacts on the soils: bulk density, resistance to compression and free-living terrestrial arthropod abundance. This selection was based primarily on previous monitoring on (Convey *et al.* 1996, Brady 2001, Jorajuria 2004, Soil Survey Staff 2006, Benayas *et al.* 2007). Quantifying these three variables integrates important physical and biological features of soils in a simple and practicable manner, using standard methodologies and without generating further significant disturbances to the study area. Bulk density and resistance to compression are two variables that describe physical properties of soils. Both are closely related to other fundamental soil properties such as texture, porosity, organic matter content, aeration and infiltration and percolation of water (Soil Survey Staff 2006). Soil fauna are integral to the breakdown of organic matter in soils, levels of which are low in Byers Peninsula soils, typically between 1 and 1.5% (Navas *et al.* 2006). Most Antarctic terrestrial arthropods and smaller soil invertebrates are thought to have detritivorous and/or microbivorous diets although few detailed autecological studies have been completed (Convey 1996, Hogg *et al.* 2006), and the majority of energy flow in these ecosystems takes place through the decomposition cycle (Davis 1981). Therefore their central role in the cycling of nutrients suggests that they may be potentially excellent bioindicators of change processes. The primary aims of this study were to determine the relationships between the three variables and different intensities of human impact through trampling, and to use this information to propose appropriate thresholds to minimize accumulating damage over time.

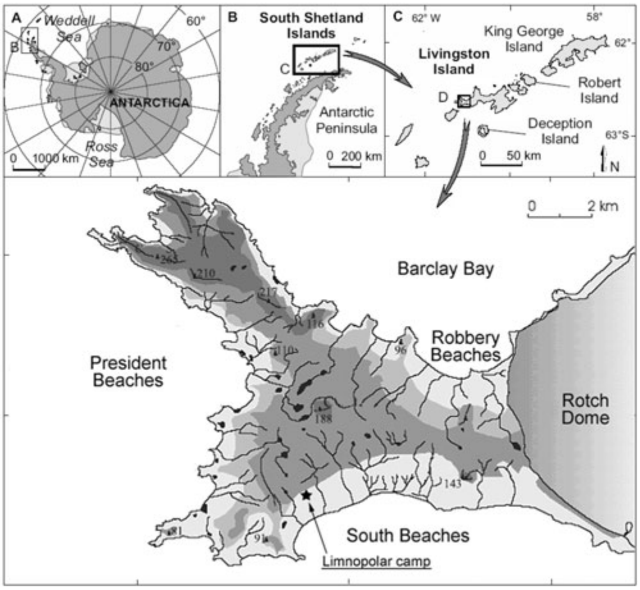

Fig. 1. Byers Peninsula and LIMNOPOLAR camp location in the South Shetland Islands, Maritime Antarctica.

Material and methods

Study area

The study took place in ASPA No 126, Byers Peninsula, Livingston Island (ATCM XXV, Measure 1, 2002). This is the largest ice-free area in the South Shetland Islands, maritime Antarctic, being approximately 60 km^2 in extent (Richard *et al.* 1994). Much of its area remains snow covered for at least nine months every year, with soils directly exposed during the short Antarctic summer. During the summer, the active soil layer at lower altitudes is 25–30 cm deep, and soils are frequently saturated with meltwater (Serrano 2002, 2003). At local scale, soil patterns are complex, relating to slope, substratum and other abiotic factors. These poorly drained soils are strongly influenced by solifluction and cryoturbation (Blume *et al.* 2002). Over the last 50 years, scientific research has been the principal human activity at Byers Peninsula, although in the context of global human activity the level of this remains very low (Bonner & Lewis Smith 1985). Research activities are typically based around temporary camps. These are most commonly situated in the first distinct geoecological belt sorrounding the Peninsula, which consists of open tundra on Holocene raised beaches and platforms (Hall & Johnston 1995, Serrano 2001, 2002). This is exemplified by the LIMNOPOLAR temporary base camp, which is situated at South Beaches (Fig. 1). The camp has formed a base for research in the area since the 2000/01 summer. Throughout this period a detailed record has been kept of LIMNOPOLAR researcher movements, allowing assessment of the level of disturbance experienced by different areas and the level of impact in consequence of this.

Methods

Samples were obtained at three different distances (0, 1 and 3 m) from the centre of existing paths created by researchers, with three replicates obtained at each position. Paths were sign-posted, and the personnel working at the Byers camp briefed, in order to prevent the dispersion of users from the centre of paths. This protocol permits a comparison of paths with greater transit pressure (0 m) with less impacted areas (1 m) and non-impacted areas (3 m, used as controls, with theoretically no trampling effects). Researchers followed the instructions, giving reasonable discrimination between these three points. The relatively close proximity of the three sampling locations is intended to minimize any influences of small scale geomorphological variations. Five samples of resistance to compression were obtained at each point, using only the median as the data value.

In the 2002/03 summer pilot studies were carried out in order to assess the sampling methods, determine natural environmental patterns, estimate error variability and identify the sampling effort required for resistance to compression and bulk density studies (Tejedo *et al.* 2005). In the 2003/04 summer, an experimental zone was established close to the field camp in an area of pristine dry ground. Four lines of 2 m length were created in this area in order to then expose them one day to a known frequency of trampling impact: 0 (control, not used), 100, 300 and 600 foot transits. The three physical and biological variables were measured both in this experimental area and along the network of paths created in the vicinity of the field camp. During the 2005/06 and 2006/07 summer campaigns, new experimental areas were created to test a higher level of use. In parallel with these experiments, new resistance to compression data were obtained to analyse the replicability of the previous results. In the 2003/04 summer season, just after snow retreat, first soil recovery data were obtained using resistance to compression. In this field season, the measure of resistance to compression was also used to compare the impact of researchers with that due to southern elephant seals (*Mirounga leonina*, Linn.) on the beaches of Byers Peninsula. In 2005/06, 2006/07 and 2007/08 summer seasons the measurements were repeated to determine the recovery of the impacted areas.

For the measurement of the bulk density, surface soil cores were extracted with a metal cylinder (4.2 cm depth, 5.7 cm diameter). These cores were labelled, sealed and stored for a maximum of two months in plastic bags at 4ºC until further analysis. In the laboratory, water content was measured after the samples were dried for 12 hours at 105ºC (Brady 2001). Bulk density (g cm^{-3}) was calculated as the relation between soil dry mass and the volume occupied by particles and pores (Blake & Hartge 1986, Soil Survey Staff 2006). Resistance to compression (kg cm^{-2}) was measured with a tubular penetrometer (Jorajuria 2004). Free-living terrestrial arthropods were obtained from soil samples including the top 8 cm of soil, equating to *c.* 500 cm^3. As most Antarctic terrestrial arthropods taxa are limited to the upper 3–5 cm of moss and/or soil profiles (Tilbrook 1967) the 8 cm cores are considered to be appropiate to obtain most soil fauna. Each sample was broken up by hand onto a wire mesh using Berlese funnel traps and a 40 w lamp placed 19 cm over the loose sample material for 48 h, and arthropods preserved in 70% ethanol after extraction (cf. Convey *et al.* 1996). Preserved arthropods were returned to Spain, where faunal counts and identifications were made to genus level. Previous investigations completed on the Byers Peninsula have recorded five groups and 23 species of free-living terrestrial arthropods in this area (Usher & Edwards 1986, Richard *et al.* 1994, Block & Starý 1996, Convey *et al.* 1996), and these were used for reference. Within the maritime Antarctic, the South Shetland Islands are thought to harbour one of the greatest diversities of soil invertebrates (Hogg & Stevens 2002) and, within South Shetland Islands, the diversity of free-living terrestrial arthropod on the Byers Peninsula is the greatest documented (Convey *et al.* 1996).

Results and discussion

Experimental impacts

Previous data has provided empirical evidence that even low human activity in polar regions may cause disturbance to the surface layer of soils (Tejedo *et al.* 2005). Nevertheless, we did not found statistical evidence that a very low level of foot traffic can generate significant differences in the selected measures relative to pristine nearby areas. Working on McMurdo Dry Valley areas, Campbell *et al.* (1993) documented that after as few as 20 foot transits there is a distinct decrease in the number of surface stones along the line of the track and an increase in color contrast between the track and the undisturbed surface alongside. These authors noted that changes can become apparent even after one single transit. Various authors have highlighted the long lifetime of indicators of physical disturbance such as footprints in soil and bryophyte vegetation (Smith *et al.* 1995). Our own casual observations suggest that visual evidence of footprints impressed on dry surfaces can disappear during the course of a single summer, while those on damp soils can remain visible for years (Quesada *et al.* unpublished data, Byers Peninsula; Convey & Hodgson unpublished data, Dufek Massif ASPA management plan).

Our experimental studies indicated that substantial alterations in the soil surface were evident even at the

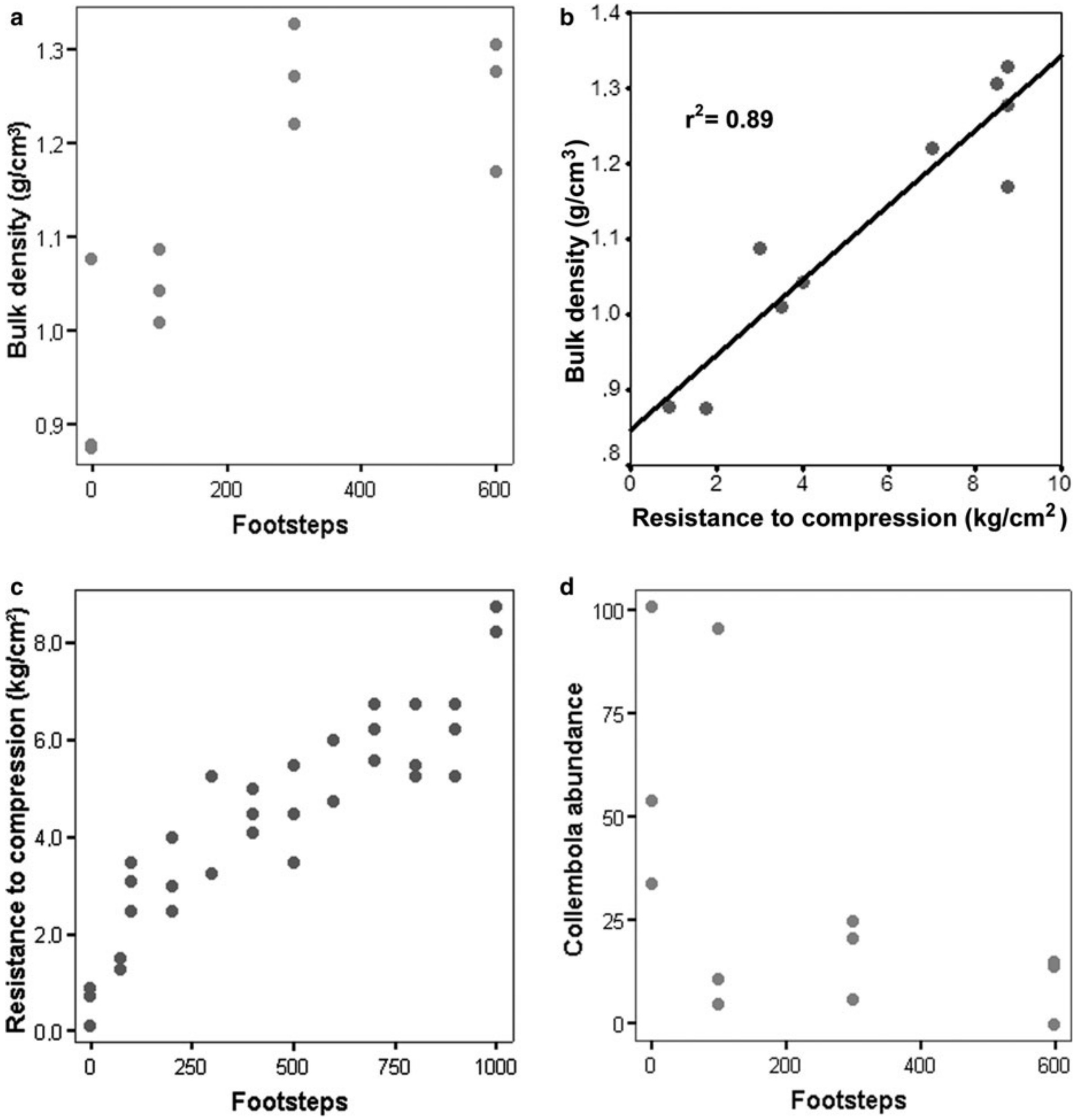

Fig. 2. Validating tools to assess the human impact under experimental conditions. **a.** Bulk density in 2003/04 summer season. **b.** Bulk density and resistance to compression in 2003/04 summer season. **c.** Resistance to compression in 2005/06 summer season. **d.** Collembola abundance in 2003/04 summer season.

lowest frequency of foot transit (Fig. 2a–d). Bulk density (Fig. 2a) increased significantly when use level was higher than 300 footsteps (ANOVA $P \leq 0.002$, $n = 12$), although there was not a significant difference (t-test $P \leq 0.218$, $n_0 = n_{100} = 3$) between control (non-impacted) ground and the lowest intensity of impact assayed (100 footstep), which we consider similar to a classification of occasional use. Comparable data were obtained with respect to resistance to compression. The high correlation between bulk density (y_i) and resistance to compression (c_i) was sufficient to justify data collection in subsequent sampling seasons being restricted to measurement of resistance to compression. The adjusted linear relation shown in Fig. 2b follows the equation

$$\hat{y}_i = 0.0496\, c_i + 0.8472, \text{ with } r^2 = 0.89.$$

This has many practical adventages, being easily measurable *in situ*, requiring minimum equipment and being a non-destructive sampling technique.

Having selected resistance to compression as an appropriate proxy of physical disturbances to the upper

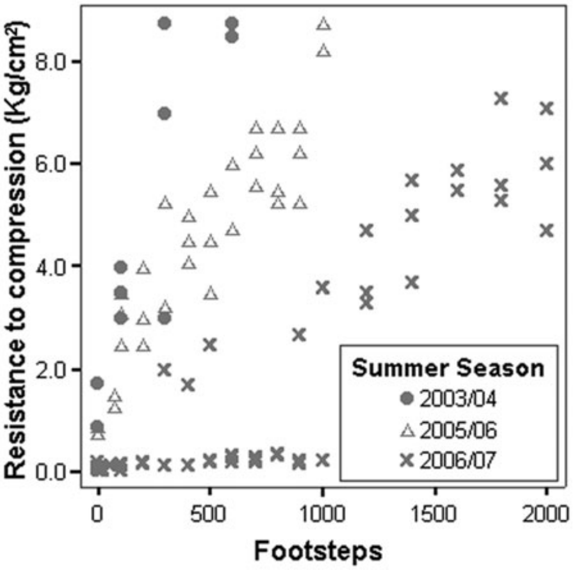

Fig. 3. Resistance to compression measured in different experimental areas during three summer campaigns.

layers of the soil surface, a second and more detailed experimental study was possible in the 2005/06 summer season, with a greater range of footstep impact frequencies and including measurement of researcher body mass. This more detailed experiment (Fig. 2c) demonstrated that the measurement of resistance to compression (i.e. soil compaction) was more sensitive to footstep frequency than to researcher body mass (data not shown). In this experiment, even the lowest experimental impact (100 steps) generated a significant detectable effect. Increasing walking impact under these experimental conditions identified an impact threshold at 800 transits, at that point the soil compaction reached the maximum value measurable by the penetrometer used. In order to examine the generality of these experimental findings, we obtained comparable data from a range of other sites and sampling seasons within the Byers Peninsula (Fig. 3). Although the absolute values of resistance to compression at different sites were not identical, similar trends were evident, indicating that this method for evaluating the trampling impact on soils in Antarctica may be generally applicable.

Two higher groups of free-living terrestrial arthropods taxa were recorded, springtails (Collembola) and mites (Acari) (Richard *et al.* 1994). The former represent over 99.5% of the 4209 individuals collected, thus our analyses focused on this group. Two genera of collembola were present, *Cryptopygus* (94.9%) and *Friesea* (4.6%), and the numbers of both were combined for analyses. Impacts of foot traffic on Collembola abundance are shown in Fig. 2d, with larger impacts being correlated with a decrease in numbers of Collembola. The arthropods were not lost from the soil even at the highest levels of experimental impact, but their abundance was substantially reduced (by 85%), with this

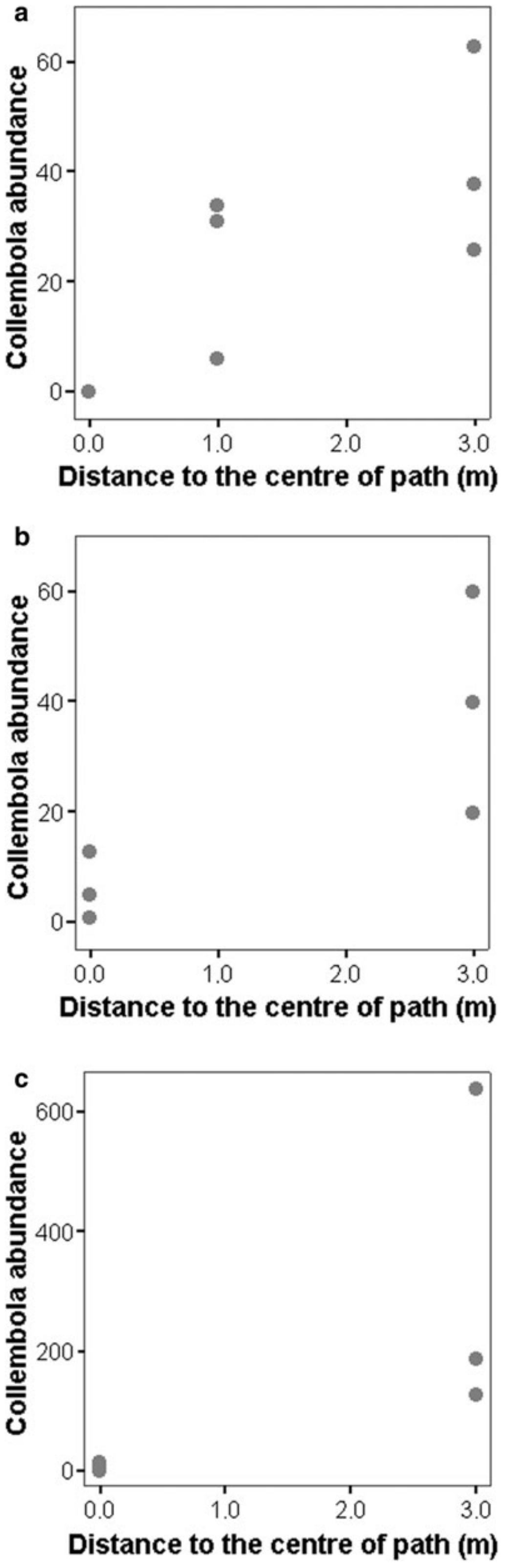

Fig. 4. Springtails (*Collembola*) abundance registered in tracks used by researchers in 2003/04 summer campaign: **a.** camp path, **b.** river path, and **c.** entrance path. Paths were selected from results showed in Tejedo *et al.* 2005.

reduction not being explained by the typical variability due to patchy distribution of Antarctic soil invertebrates (Usher & Edwards 1986). Our data clearly demonstrate that the activities of researchers in such habitats can generate an immediate impact on the soil surface fauna, consistent with the compression of soils described above. In addition to reducing the three-dimensional complexity of the soil habitat used by these invertebrates, compression is likely to reduce water availability in soils, known to be a fundamentally important control on Antarctic invertebrate distribution (Tilbrook 1967, Kennedy 1993, Block & Starý 1996). Water availability has been suggested to underlie the typically clustered distribution of Collembola in different habitats of the Byers Peninsula (Richard *et al.* 1994). As a consequence of this clustering or aggregating behaviour, the utility of such abundance measurements in studies of human trampling impact is more limited, in particular being most appropriate in comparisons of spatially adjacent areas with otherwise comparable environmental conditions. However, as the native soil arthropod fauna of both the maritime and continental Antarctic regions is taxonomically limited and consists of Collembola and Acari (Hogg & Stevens 2002), this tool could be simply adapted to allow application across the majority of Antarctic ice-free areas.

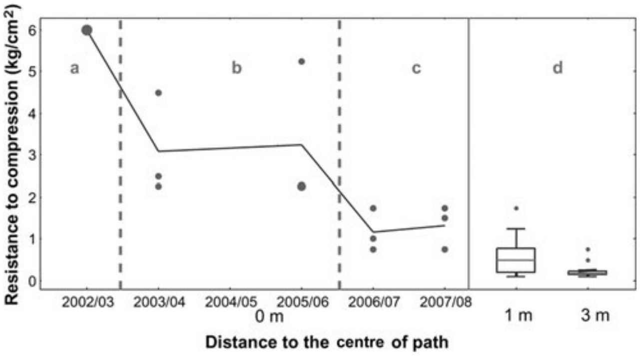

Fig. 5. Recovery capacity measured in the main base camp path along six summer seasons. For the centre of the path (0 m) the annual evolution is presented. **a.** Data from 2002/03 summer season were recorded after two campaigns of intensive use of the path. The rest of data were recorded just after snow retreat, **b.** in 2003/04 and 2005/06 before the track was again used by the researchers, and **c.** in 2006/07 and 2007/08 after the access to the track was not permitted (it was fenced to analyse natural soil recovery capacity). **d.** All the collected data at 1 m and 3 m distance to the centre of the path are summarized in two box-plots.

Assessment of limnopolar expedition impact

Using the experimental data as a baseline, we then assessed evidence for impacts associated with human movement around the Byers Peninsula. Features of paths created by researchers around the camp (Fig. 4a–c) were coincident with the results obtained in experimental areas (Figs 2 & 3). This observation has important ramifications, as it overrides the typically large complexity of maritime Antarctica terrestrial habitats, even at the scale of a few square metres or centimetres (Beyer & Bölter 2002), and validates the methodology proposed for monitoring the environmental impact of the researchers' trampling. Nevertheless, some differences between experimental areas and true tracks were apparent. Thus, the greatest bulk density values at the experimental site (Fig. 2b), were less than those found in normal Byers paths (1.80 g cm^{-3}). The specific location of this area of maximal compaction was recorded on the principal path of the base camp, which was also the only true track where springtails appear to have completely disappeared (Fig. 4a).

Elephant seals create small networks of paths at South Beaches of the Byers Peninsula that connect the coast with different resting areas in the first geoecological belt. One track made by a female seal (450–550 kg) was chosen to compare with the impact of researchers on soils. The data obtained demonstrated that the movement of elephant seals creates a small increase in the soil's resistance to compression, comparable with that of a use level of less than 100 footsteps, and a reduction of around 50% in Collembola abundance in the centre of the track, again a similar consequence to that of sporadic human use. These observations can be used to support an assumption that a controlled level of research activity can be tolerated by Antarctic soils, for which significant degradation problems are not apparent in vegetation-free areas close to the centres of elephant seal activity.

An estimate of the recovery capacity of soils was also obtained through the measurement of resistance to compression. Data were obtained from both experimental areas and paths close to the base camp, with a focus on the main camp path. Results for this track are shown in Fig. 5, which is divided in four sections. The data show some evidence of recovery from compaction, with resistance to compression tending to decrease over time, particularly once a track was closed in 2006/07. However, the means of the resistance to compression at 0 and 1 m during the 2007/08 summer season were not significantly different (t-test $P = 0.067$, $n_0 = 3$, $n_1 = 15$), and remained significantly different to that at 3 m (t-test $P \ll 0.0001$, $n_0 = 3$, $n_3 = 15$). It is likely that more time will be necessary to allow complete recovery. Our data show that areas subjected to high human trampling pressure have a lower recovery than those occasionally used. The cycle of saturation and drainage of soil, and cryoturbation through freeze-thaw activity, will have a central influence in the regeneration of soil structure. These processes generate physical changes in the upper centimetres of compacted soil that decrease resistance to compression towards the original (non-impacted) values, allowing considerable recovery from trampling effects where use levels are not too high. To take advantage of the recovery abilities of Antarctic soils does implicitly require the active use of systematic monitoring in order to avoid impacts exceeding their recovery capacity, allowing travel routes to be closed and alternatives routes created when impact variables approach acceptable limits favouring recovery.

Conclusions

The efficacy of methodologies to analyse the impact of researchers on Antarctic soils by trampling has been demonstrated by this study. Future developments of these methodologies should, however, involve expansion to include other variables such as soil characteristics; water content, temperature and snow cover duration.

We propose that the resistance to compression (i.e. compaction) is an appropriate and effective parameter to measure degradation due to trampling of the superficial layers of the soil. Additionally, biological data related to key processes (breakdown of organic material and the cycling of nutrients) can provide a further level of detail of impacts. Springtails, especially the genus *Cryptopygus*, are a primary target organism for such studies on the Byers Peninsula, through their large abundances, ability to tolerate at least to some extent high use levels, and measurable response to trampling intensity, although data interpretation can be complicated by their typically aggregated distribution in the field.

Our data demonstrate both that whilst a minimum human presence is sufficient to generate measurable changes in the physical characteristics of Byers Peninsula soils, a higher level of use is required to lead to substantial changes. This leads us to recommend a refinement of current practice relating to patterns of human movement around areas where disruption of soil ecosystems is a possibility. A 'Dispersion' strategy is advisable at those vegetation-free areas that experience sporadic use (around 100 foot transits or less per season), while a 'concentration' strategy based on the creation of properly signed paths is more appropriate in 'sacrificial areas' such as within the camp area and principal traffic routes. Strict control of areas visited by Antarctic expeditions is necessary in order to prevent future disturbance, since the unusually low diversity of Antarctic soil biota could be highly disrupted by the loss or decline of even a single species that is sensitive to environmental change.

Acknowledgements

This is a contribution of the LIMNOPOLAR project, and also contributes to the BAS BIOFLAME and SCAR EBA research programmes. It was supported by the Spanish Government (REN2000-0435ANT, REN2002-11617-E, CGL2004-20451-E and CGL2005/06549/02/01-ANT). Logistical support was provided by the UTM (Marine Technology Unit, CSIC) and the Spanish Navy. We thank all the members of the LIMNOPOLAR team for data collection, particularly to Antonio Camacho, Carlos Rochera and David Velázquez, and Javier Arcones (IE University student) for collaboration in the identification work.

References

Benayas, J., Tejedo, P., García, D. & Muñoz, M. 2007. Perspectivas actuales y retos futuros en la gestión de las actividades de Uso Público en la Naturaleza. *In* Boada, M. & Benayas, J., *eds. Naturaleza y uso público: movilidad, impactos y propuestas*. Barcelona: Fundación Abertis, 37–48.

Beyer, L. & Bölter, M. 2002. *Geoecology of Antarctic ice-free coastal landscapes*. Berlin: Springer, 463 pp.

Blake, G.R. & Hartge, K.H. 1986. Bulk density. *In* Klute, A., *ed. Methods of soil analysis. Part 1: Physical and mineralogical methods*, 2nd ed. Madison, WI: Soil Science Society of America, 363–376.

Block, W. & Starý, J. 1996. Oribatid mites (Acari: Oribatida) of the maritime Antarctic and Antarctic Peninsula. *Journal of Natural History*, **30**, 1059–1067.

Blume, H.P., Khun, D. & Bölter, M. 2002. Soils and landscapes. *In* Beyer, L. & Bölter, M., *eds. Geoecology of Antarctic ice free coastal landscapes*. Berlin: Springer, 91–114.

Bonner, W. & Lewis Smith, R.I. 1985. SSSI No 6: Byers Peninsula, Livingston Island, South Shetland Islands. *In* Bonner, W.N. & Lewis Smith, R.I., *eds. Conservation areas in the Antarctic*. Cambridge: SCAR, 147–156.

Brady, N. 2001. *The nature and properties of soils*, 13th ed. Upper Saddle River, NJ: Prentice Hall, 960 pp.

Campbell, I.B. & Claridge, G.G.C. 1987. *Antarctica: soils, weathering processes and environment*. Amsterdam: Elsevier Science Publishers, 406 pp.

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., Campbell, D.I. & Balks, M.R. 1998. The soil environment. *Antarctic Research Series*, **72**, 297–322.

Convey, P. 1996. The influence of environmental characteristics on life history attributes of Antarctic terrestrial biota. *Biological Reviews*, **71**, 191–225.

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.

Davis, R.C. 1981. Structure and function of two Antarctic terrestrial moss communities. *Ecological Monographs*, **5**, 125–143.

Fox, A.J. & Cooper, P.R. 1994. Measured properties of the Antarctic Ice Sheet derived from the SCAR digital database. *Polar Record*, **30**, 201–204.

Hall, C.M. & Johnston, M.E., *eds*. 1995. *Polar tourism: tourism in the Arctic and Antarctic regions*. Chichester: John Wiley, 346 pp.

Hogg, I.D. & Stevens, M.I. 2002. Soil fauna of Antarctic coastal landscapes. *In* Beyer, L. & Bölter, M., *eds. Geoecology of Antarctic ice-free coastal landscapes*. Berlin: Springer, 265–282.

Hogg, I.D., Cary, C., Convey, P., Newsham, K.K., O'donnell, A.G., Adams, B.J., Aislabie, J., Frati, F., Stevens, M.I. & Wall, D.H. 2006. Biotic interactions in Antarctic terrestrial ecosystems: are they a factor? *Soil Biology and Biochemistry*, **38**, 3035–3040.

Jorajuria, D. 2004. La resistencia a la penetración como parámetro mecánico del suelo. *In* Filgueira, R. & Micucci, F., *eds. Metodologías físicas para la evaluación del suelo: penetrometría e infiltrometría*. EDULP, 43–53.

Kennedy, A.D. 1993. Water as a limiting factor in the Antarctic terrestrial environment: a biogeographical synthesis. *Arctic and Alpine Research*, **25**, 308–315.

Navas, A., López-Martínez, J., Casas, J., Machín, J., Durán, J.J, Serrano, E., Cuchi, J.A. & Mink, S. 2006. Características de los suelos sobre diferentes sustratos en las Islas Shetland del Sur. El caso de la Isla Livingston. *Libro de resúmenes del VII Simposio Español de Estudios Polares. Granada, 18-20 de septiembre*, 226–228.

NSF/COMNAP/SCAR. 2005. *Practical biological indicators of human impacts in Antarctica*. Bryan, College Station, Texas, 16–18 March 2005. Workshop Report, vol. **1**, 24 pp.

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.

Serrano, E. 2001. Protected areas and territorial politicy in South Shetland Islands (Antarctica). *AGE Bulletin*, **31**, 5–21.

Serrano, E. 2002. Ice, mountains, sea and fauna: tourism in South Shetland Islands (maritime Antarctic). *Revue de Géographie Alpine*, **1**, 9–24.

Serrano, E. 2003. Natural landscape and geoecological belts on ice free areas of the maritime Antarctica (South Shetland Island). *AGE Bulletin*, **35**, 5–32.

Soil Survey Staff. 2006. *Keys to soil taxonomy*, 10th ed. Washington, DC: USDA-Natural Resources Conservation Service, 332 pp.

Smith, R.C., Baker, K.S., Fraser, W.R., Hoffman, E.E., Karl, D.M., Klinck, J.M., Quetin, L.B., Prézelin, B.B., Ross, R.M., Trivelpiece, W.Z. & Vernet, M. 1995. The Palmer LTR: a long-term ecological research program at palmer Station, Antarctica. *Oceanography*, **8**, 77–86.

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.

Tilbrook, P.J. 1967. Arthropod ecology in the maritime Antarctic. *Antarctic Research Series*, **10**, 331–356.

Usher, M.B. & Edwards, M. 1986. The selection of conservation areas in Antarctica: an example using the arthropod fauna of Antarctic islands. *Environmental Conservation*, **13**, 115–122.