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ORIGINAL PAPER

Microarthropod communities of industrially disturbed or imported soils in the High Arctic; the abandoned coal mining town of Pyramiden, Svalbard

Stephen J. Coulson · Arne Fjellberg · Elena N. Melekhina · Anastasia A. Taskaeva · Natalia V. Lebedeva · Olga A. Belkina · Stanisław Seniczak · Anna Seniczak · Dariusz J. Gwiazdowicz

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Abstract The terrestrial environment of the High Arctic consists of a mosaic of habitat types, both natural and anthropogenic. At the abandoned coal mining town of Pyramiden, Svalbard, topsoil was imported from southern European Russia. This, and further industrial disturbance in the town, offers new opportunities for the native invertebrate fauna, but may also introduce alien, potentially invasive, species. Few studies have examined anthropogenic habitats in the High Arctic. But increasing activity, including industry and tourism, requires an understanding of the responses of the Arctic to such pressures. The microarthropod communities observed in the settlement were substantially different from the natural tundra. In the settlement, nine species of mesostigmatid mite occurred (three new records for Svalbard; *Dendrolaelaps foveolatus*) and two additional not identified to species (*Halolaelaps* sp., *Arctoseius* sp.), 26 species of Collembola (12 not seen in the natural tundra close to Pyramiden) and two new records (*Thalassaphorura debilis* and *Desoria*

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S. J. Coulson (✉)
Department of Arctic Biology, University Centre in Svalbard, P.O. Box 156, 9171 Longyearbyen, Svalbard, Norway
e-mail: steve.coulson@unis.no

A. Fjellberg
Mågerøveien 168, 3145 Tjøme, Norway

E. N. Melekhina · A. A. Taskaeva
Institute of Biology of Komi Scientific Centre of the Ural Branch of the Russian Academy of Sciences, Kommunisticheskaja, 28, 167000 Syktyvkar, Russia

N. V. Lebedeva
Institute of Arid Zones, Southern Scientific Centre, Russian Academy of Sciences and Azov Branch, Murmansk Marine Biological Institute, Kola Scientific Centre, Russian Academy of Sciences, Chekhova 41, 344006 Rostov-on-Don, Russia

tigrina), but only five Oribatida. This is set against 8, 20 and 24 species respectively for Mesostigmata, Oribatida and Collembola from natural tundra in the vicinity. The imported soils remain to be yet fully exploited by the native microarthropod fauna. Taxa disparities may result from differential mortality during collection and shipping of the soil, and subsequent colonisation. While none of the introduced species appear to be invasive, responses to climate change scenarios are difficult to project. Understanding of alien species and the timespans required for colonization by native faunas are of importance for remediation and reclamation projects in polar regions.

Keywords Oribatida · Gamasida · Soil biodiversity · Introduced · Microarthropod · Alien

Introduction

The tundra environment of the High Arctic is characteristically diverse, ranging from dry windblown ridges largely devoid of winter snow cover to snowbeds, wet moss banks and stream margins. This physical diversity is mirrored in the vegetation with sedge-moss mires, grass moss, low shrub, cushion plants/cryptograms and barren stony ridges with extremely low plant cover (Rønning 1979; Bliss and Matveyeva 1992; Cooper 2011) forming a patchy mosaic of diverse habitat types which can vary over a horizontal scale less than a metre (Jónsdóttir 2005; Coulson et al. 2014). This heterogeneity is reflected in the soil microarthropod fauna where relationships may be observed between vegetation cover (and humus form and quantity) and invertebrate species diversity (Seniczak and Plichta 1978, Coulson et al. 2003; Hodkinson et al. 2004). In a few locations, this natural habitat diversity is enhanced by human activities in settlements or at industrial sites often associated with mineral extraction (Coulson et al. 2013a, b). One such location is the abandoned Russian coal mining town of Pyramiden, Svalbard.

Reclamation and restoration of industrial sites, past and present, in the Arctic is of importance in obtaining and maintaining a pristine polar environment under ever increasing human pressure. To date, there are few examples of such reclamation activities from High Arctic latitudes but useful insights may be drawn from the beautification project of Pyramiden. In c. 1983, agricultural soil was imported to the coal mining town of Pyramiden in the High Arctic archipelago of Svalbard to supplement the thin, nutrient poor natural soils and enable the establishment of imported grasses as part of a "greening" initiative. The exact origin of these soils is, unfortunately, unknown but it is identified as a

O. A. Belkina
Laboratory of Flora and Vegetation, Polar-Alpine Botanical Garden and Institute, Kola Science Center of Russian Academy of Sciences, Fersman St. 18a, Apatity, Murmansk Province 184209, Russia

S. Seniczak
Department of Zoology, Kazimierz Wielki University, Ossolińskich 12, 85-092 Bydgoszcz, Poland

A. Seniczak
Department of Ecology, University of Technology and Life Sciences, Kordeckiego 20, 85-225 Bydgoszcz, Poland

D. J. Gwiazdowicz
Department of Forest Pathology, Poznan University of Life Sciences, Wojska Polskiego 71, 60-625 Poznan, Poland

chernozem type sourced from southern European Russia or the Ukraine. As seen at the operating Russian coal mine in Svalbard, Barentsburg, the import of these foreign soils to Svalbard may have introduced alien invertebrate species (Coulson et al. 2013a). Such non-indigenous species are considered amongst the greatest threats to Antarctic biodiversity (Hughes and Convey 2010) and the Scientific Committee on Antarctic Research (SCAR) recently highlighted introduced species to be a priority issue for Antarctic research for the next "20 years and beyond" due to the threat presented to native fauna and floras (Kennicutt et al. 2014). Nielsen and Wall (2013) suggest that the threat represented by such introductions to biodiversity in the Arctic may actually be larger than in the Antarctic precisely due to the greater biodiversity in the Arctic. But, while many species may be introduced, not all have the ability to establish and still fewer possesses characteristics that lead to invasive tendencies where individuals colonise, disperse, and reproduce at multiple sites (Blackburn et al. 2011). There is therefore a requirement to monitor such introductions.

Svalbard is often described as an undisturbed Arctic environment with regions set aside as ''reference areas for research'' under special protective legislation. The archipelago also has a comparatively well documented terrestrial invertebrate species inventory (Hodkinson 2013; Coulson et al. 2014). Nevertheless, invertebrate studies of anthropogenically disturbed locations here are lacking. In a period of rapid environmental change this omission is particularly disturbing. It is generally thought that the native flora and fauna of the Svalbard archipelago is the result of immigration since the retreat of the ice during the last 10,000 years (Eidesen et al. 2013; Coulson et al. 2014; but see Westergaard et al. 2011). The communities have therefore assembled somewhat recently and consist largely of Holarctic species but with particular taxa otherwise restricted to either the Palaearctic or Nearctic regions. The natural colonization of islands is an accidental process and depends on numerous factors (Jacot 1934). But in addition to natural processes human activities are often accelerating the establishment of new species. Such actions have resulted in the introduction of many alien invertebrate species in the southern polar regions, many of which have established successfully (Hughes et al. 2010; Greenslade and Convey 2012). But there are fewer known examples of introduced invertebrate species in the Arctic than in the Antarctic. In total, 180 species of alien plant (108) or terrestrial invertebrate (72) are known to have colonized the sub-Antarctic islands (Frenot et al. 2005), the majority originating from Europe and via human activities during the last 200 years. There is generally greater terrestrial connectivity in the Arctic compared to the Antarctic. Large expanses of continental land mass extending into the Arctic aid the dispersal of terrestrial flora and fauna. Moreover, there is a lack of equivalent isolating oceanic and weather systems such as the Antarctic Circumpolar Current which is driven by strong westerly winds and which hinders north–south dispersal of terrestrial invertebrate faunas, in the Arctic. Both have likely facilitated natural dispersal processes in this region compared to the Antarctic (Ávila-Jiménez and Coulson 2011; Eidesen et al. 2013; Coulson et al. 2014). Moreover, the low species richness and the absence of many functional groups might result in islands, such as in the maritime Antarctic or the island-like ice and snow free regions of Antarctica, being more susceptible to alien invasions (Frenot et al. 2005). Therefore, human activity in the far north is not thought to so far have resulted in large numbers of introductions of new species. Studies on the anthropogenic introduction of invertebrates to the Arctic are wanting but there is a potential threat. Ware et al. (2012) identified seeds from 53 plant species from shoes of visitors arriving at Svalbard international airport during summer 2008 with an average of 3.9 seeds per traveler. It would seem likely that invertebrates are also being introduced in a similar fashion. In a recent survey of anthropogenic soils in the mining town of Barentsburg in Svalbard 24 % (11 of 46) of soil invertebrate species identified to species level were considered to have been introduced, most likely along with imported soils brought for use in the greenhouse (Coulson et al. 2013a) including the collembolan *Deuteraphorura variabilis* (Coulson et al. 2013a). This is a common species in enriched ornithogenic soils along the coasts of the White Sea (Pomorski and Skarzynski 2001) and is suggested as potentially invasive in certain habitats, especially in the floristically rich and diverse ornithogenic habitats considered characteristic of the Svalbard archipelago (Jónsdóttir 2005).

Climate change projections indicate that the Arctic regions have experienced a very substantial Arctic warming since the mid-20th century and that they are likely to continue to warm more rapidly than the global mean (ACIA 2005; AMAP 2012; IPCC 2014). Such projections indicate mean temperature increases for this region of between 3 and 7 °C by 2100 over the 1986–2005 baseline and the Svalbard region has already experienced a long-term normal annual air temperature rise from −6.7 °C (period 1960–1991) to −4.6 °C (period 1981-2010) (Førland et al. 2011). Range shifts by currently thermally restricted native or introduced species are expected (Nielsen and Wall 2013) following this warming of the Arctic cryosphere and less specialized taxa, including invasive species from the south, are likely to become increasingly common (Vincent et al. 2011). Recently, a correlation has been demonstrated between elevated mean winter temperatures and sea bird tick (*Ixodes uriae*) infestation in Svalbard suggesting a response of the invertebrate fauna to the milder winters (Descamps 2013). Although current environmental conditions may be too extreme for many imported species to establish, projected climatic amelioration may in the future enable select alien species to establish and possibly become invasive or those already established to become invasive. Nonetheless it is clear that individual species will have idiosyncratic responses and that responses of single species are difficult to accurately predict.

There is, nonetheless, generally little information concerning the invertebrate communities in the settlements of Svalbard, especially in those created, or influenced, by human activity. There is hence a need to assess the fauna of such locations, evaluate possible alien species and the threat these species may pose to the native flora and fauna. We here aim to (i) describe the microarthropod fauna of the disturbed and imported soils in Pyramiden, (ii) compare this fauna with the natural and undisturbed tundra present in the region, (iii) identify introduced species and estimate potential threats to the native flora and fauna, (iv) determine if such disturbed soils are colonized by the native soil microarthropod fauna, and (v) evaluate potential recovery periods for disturbed soils to return to the natural situation.

Materials and methods

The principal islands of the Svalbard archipelago lie in the European Arctic between 74° and 81°N and 10° to 35°E (Fig. 1a) and have a total land area of 61,200 km^2 of which 60 % is under permanent snow and ice (Hisdal 1998). Two soil types were selected from within the abandoned coal mining town of Pyramiden in Billefjord (78°40N, 016°27E, Fig. 1b, Table S1): (i) *heavily disturbed* (designated as *hd* in the site letter code) consisting of trodden, previously built upon, or polluted ground, and (ii) *imported soils* (designated as *is*) referring to areas where chernozem soils were spread and which were formally protected as lawned areas. Chernozem is a black-coloured humus rich soil which is extremely fertile and capable of producing a high agricultural yield. A third substrate type was also sampled (designated as *nest*), that of the black-legged kittiwake (*Rissa tridactyla*) nest

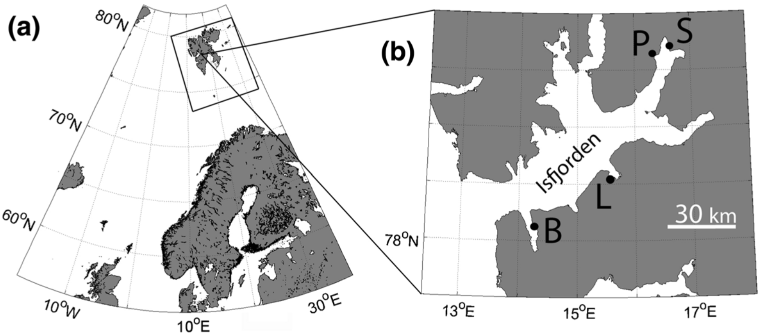


Fig. 1 **a** Location of Svalbard (*box*), and **b** the Isfjorden region of Svalbard indicating the locations of Pyramiden (P), Skottehytta (S), Longyearbyen (L) and Barentsburg (B)

detritus lying underneath the colony breeding on window ledges within the settlement. This substrate was selected due to the unusual characteristics of this habitat and the expected specialised coprophagic invertebrate fauna. *Natural undisturbed* sites (designated as *nu*), where little or no anthropogenic activity has occurred and the flora and fauna is considered to representative of the natural tundra for the region, were located on the immediate periphery of the town and in the vicinity of Skottehytta at the entrance to Ebbadalen in Petuniabukta (78°42 N, 016°36E; Fig. 1b) approximately seven kilometres from Pyramiden. Sampling at Skottehytta was undertaken at the same location as Seniczak et al. (2014).

Site descriptions

Pyramiden

At the start of the twentieth century several mineral mines were established in Svalbard by various nations. The now abandoned Russian coal mining town is located in Billefjord, north eastern end of Isfjord, and was founded by Sweden in 1910 before being bought by the Soviet Union in 1927 (Andreassen et al. 2010). The population of the town attained approximately 1000 and infrastructure included greenhouses, animal house, swimming pool and a cultural centre housing the library, gymnasium and theatre. The mine was finally closed and town abandoned in 1998. There is currently some limited tourism associated with the derelict town with small numbers of visitors arriving each day during the summer months as part of day cruises from Longyearbyen and snow mobile safaris to the settlement forming a popular winter activity. Recently a small hotel has established in the town.

The lawns of Pyramiden were laid out in c. 1983 using soil supplied by Murmansk company "Arctic Flowers" ("Tsvety Zapolyarya"). The soil was sourced from southern European Russia or the Ukraine (N. Shmatova, Trust Arktikugol, and N. Myski, chief editor of the journal "Russkii Vestnik Spitsbergena, pers. comm.). The exact quantity of imported soil to the settlement of Pyramiden is not known. However, we have identified a lawned area of c. 100,000 m^2 on aerial photograph images (© Norwegian Polar Institute) (Fig. 3). These lawns were seeded by cultivar grass grown for the northern conditions and were periodically fertilized with manure from the cowshed. The inhabitants of Pyramiden were forbidden to walk on the lawns but livestock was occasionally grazed here and cut grass was used as fresh forage for the 20–25 cows in the settlement. Although the exact location of the source of the imported soils is unknown, we indicate the invertebrate species observed in this study which are known to occur in the broad chernozem soil region in southern European Russia and the Ukraine and which may reasonably be expected to have been in the soils when collected for shipping to Svalbard.

The vegetation in Pyramiden (Table S1, supplementary electronic material) has been heavily influenced by not only mining activities but also the accidental and deliberate introduction of plants. Belkina et al. (2013) identified 14 distinct habitats based on floral communities and this flora includes at least three alien species; *Barbarea vulgaris* subsp. *vulgaris, Stellaria graminea* and *Tripleurospermum inodorum* (Liška and Soldán 2004). The natural vegetation of the Pyramiden region may be assumed to be similar to the undisturbed tundra at Skottehytta/Ebbadalen; *Dryas* heath.

Skottehytta

Skottehytta refers to a small cabin on the east side of Petuniabukta (Fig. 1b) at the entrance to a valley, Ebbadalen. Since 1984 the Institute of Geoecology and Geoinformation of Adam Mickiewicz University in Poznan, Poland, have had a summer field camp at this hut and which has recently been expanded with a container laboratory. The environment of Ebbadalen is considered to be largely undisturbed by human activities. The flora is defined as typical middle-Arctic tundra zone B (Jónsdóttir 2005) "tundra heath" with dwarf shrub vegetation including *Dryas octopetala*.

Images of sampling locations are provided in Figs. S1, S2 and S3, supplementary electronic material.

Climate

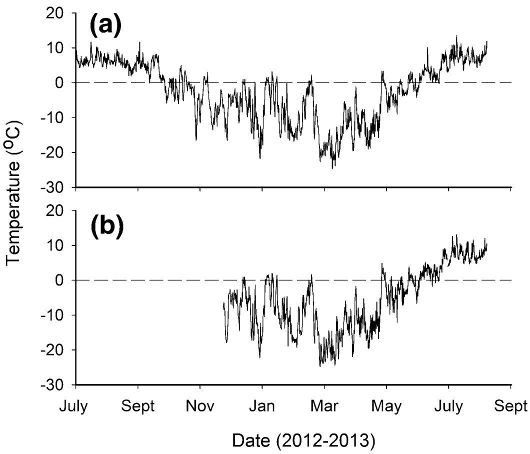
Daily mean air temperatures are only available for Pyramiden from November 2012. Nevertheless, comparison of recent air temperatures at Pyramiden and Svalbard airport, Longyearbyen (www.eKlima.no) reveal only small differences between the locations (Fig. 2). Therefore, long term air temperature records from Longyearbyen are used to describe the climate in the northern Billifjord region. The long-term annual mean air temperature is −4.6 °C (1981–2010) (Førland et al. 2011) and while summer air temperatures reach a mean of +5.2 °C, the mean for the three coldest months is −11.7 °C (Førland et al. 2011). The midnight sun lasts 126 days from 20 April until 23 August. Conversely, the duration of the polar night is 81 days, from 11 November to 30 January.

Sampling

The sampling locations (Table 1; Fig. 3) were chosen to be representative of the different soil habitat types present in the town; including *heavily disturbed* (*hd*) (sites: *hd*-**A**, *hd*-**B**, *hd*-**C**, *hd*-**D**, *hd*-**E**), *imported soil* (*is*) (sites: *is*-**F** and *is*-**G**), and *natural undisturbed* soils (*nu*) (site: *nu*-**I**) (Site images are provided in supplementary electronic material Figs. S1, S2 and S3). Nest detritus on the concrete path beneath a black-legged kittiwake colony breeding on window ledges on an abandoned building (site: *nest*-**H**) was also sampled.

Five soil samples each with dimensions 10*10 cm by 5 cm deep were taken from sites *hd*-**A** to *is*-**G** (Fig. 3) in Pyramiden on July 16. 2012. A further five samples of black-legged kittiwake nest detritus of approximately the same volume as the soil samples were collected at the same time from site *nest*-**H**. In 2013 an undisturbed *D. octopetala*/*Cassiope tetragona*

Fig. 2 Air temperatures in Longyearbyen (**a**) and Pyramiden (**b**). 0 °C reference line included. Data for Pyramiden only available from November 2012 (Norwegian Meteorological Institute; www.eKlima.no)



tundra heath was identified on the north west boundary of the settlement and designated site *un*-**I**. Five 10*10*5 cm soil samples removed as for the 2012 samples. Samples from the undisturbed site were obtained on 28 June 2013 when a further ten 10*10*5 cm soil samples were collected from the undisturbed *D. octopetala*/*C. tetragona* tundra heath adjacent to Skottehytta; site *un*-**Z**. Data for the oribatid and mesostigmatid mite community at the *natural undisturbed* site *un*-**Z** (Skottehytta) are taken from Seniczak et al. (2014).

Invertebrate extraction and identification

The soil samples were immediately returned to the University Centre in Svalbard (UNIS), Longyearbyen, Svalbard, maintained at c. +7 °C and placed into Tullgren soil extractors (Tullgren 1918) (Burkard Scientific Ltd., Uxbridge, U.K.) within 24 h of sampling. The microarthropod fauna was extracted under 40 W light bulbs into 96 % alcohol for five days until the soil was completely dry.

The mesostigmatid mites were mounted on permanent (Hoyer's medium) and semi-permanent (lactic acid) slides and identified according to Gwiazdowicz and Coulson (2010), Gwiazdowicz et al. (2011a, 2011b), Kolodochka and Gwiazdowicz (2014) and Teodorowicz et al. (2014). The Collembola and mites were identified to species by morphological taxonomic characters (Collembola: Dunger 1994, Fjellberg 1998, 2007; Potapov 2001; Thibaud et al. 2004; Mites: Gilyarov and Krivolutsky 1975; Colloff 1993; Norton and Behan-Pelletier 2009). Classification of families of Oribatida mite is according to Norton and Behan-Pelletier (2009) and Schatz et al. (2011). Identified material is deposited at Institute of Biology of Komi Scientific Centre of the Ural Branch of the Russian Academy of Sciences, Kommunisticheskaja, 28, RU-167000, Syktyvkar, Russia (Collembola and Oribatida), Poznan University of Life Sciences, Department of Forest Protection, Wojska Polskiego 71, PL-60-625 Poznan, Poland (Mesostigmata), Arne Fjellberg Entomological Research, Mågerøveien 168, NO-3145 Tjøme, Norway (Collembola), and Department of Arctic Biology, University Centre in Svalbard, P.O. Box 156, NO-9171 Longyearbyen, Svalbard, Norway (Collembola, Mesostigmata and Oribatida).

Statistics

Cluster analysis (Unweighted Pair Group Method with Arithmetic Mean, UPGMA employing Bray-Curtis similarity index) in PAST v. 3.1 (Hammer et al. 2001) was employed to identify species community composition similarities between sampling sites using species presence/absence data.

Results

Acari

Nine species of mesostigmatid mites were recorded (Table S2 supplementary electronic material). The *undisturbed natural* soils had the greatest diversity with eight species, but seven occurred in the *imported soils*. The most common species were *Antennoseius oudemansi*, *Arctoseius multidentatus, Arctoseius haarlovi* and *Proctolaelaps parvanalis*. Three taxa were recorded in Svalbard for the first time; *Dendrolaelaps foveolatus* from *heavily disturbed* soil (*hd*-**B**), *Arctoseius* sp. from the *imported soil* at site *is*-**F** and *Halolaelaps* sp. from special habitat of the black-legged kittiwake nest debris (*nest*-***H***).

Table 1 Sampling site locations and brief descriptions

Site	Location	Site description	Disturbance level/type
hd-A	78°39.178 16°19.827	Open grassland close to helicopter base. Ecotone between habitat types *Deschampsia alpina*-dominated wetlands and anthropogenic *Poa alpigena*-dominated meadows and grasslands	Heavy disturbance
hd-B	78°39.164 16°19.663	Wood chips/sawdust. Ornithogenic and anthropogenic *Cochlearia groenlandica*-dominated meadows (ornithogenic and anthropogenic common scurvy grass meadows)	Heavy disturbance
hd-C	78°39.157 16 19.646	Thin dry soils close to animal house. Anthropogenic *Poa alpigena*-dominated meadows and grasslands ("anthropogenic meadow-grass grasslands")	Heavy disturbance
hd-D	78°39.194 16°19.423	Thin dry soils close to animal house. Anthropogenic *Poa alpigena* and *Poa pratensis* dominated meadows and grasslands ("anthropogenic meadow-grass grasslands")	Heavy disturbance
hd-E	78°39.133 16°20.953	Salt marsh close to fuel storage tanks. *Puccinellia phryganodes*-dominated marshes (creeping saltmarsh grass-marshes)	Heavy disturbance
is-F	78°39.277 16°18.907	Grassland between housing blocks adjacent to town centre. Anthropogenic *Poa alpigena*-dominated meadows and grasslands (anthropogenic meadow-grass grasslands)	Imported soil
is-G	78°39.272 16°19.827	Grassland close to location of greenhouse now removed. Anthropogenic *Poa alpigena*-dominated meadows and grasslands (anthropogenic meadow-grass grasslands)	Imported soil
un-H	78°39.342 16°19.595	Material from black legged kittiwake (*Rissa tridactyla*) nests; dry plant debris and kittiwake faeces under accommodation building in town centre	Undisturbed Natural
un-I	78°39.305 16°18.280	East facing shallow slope on the outskirts of the north west of the settlement. No evidence of disturbance or imported soils	Undisturbed natural
un-Z	78°42.120 16°36.420	Typical middle Arctic tundra zone. No evidence of disturbance or imported soils	Undisturbed natural

See supplementary electronic material for site images and complete flora

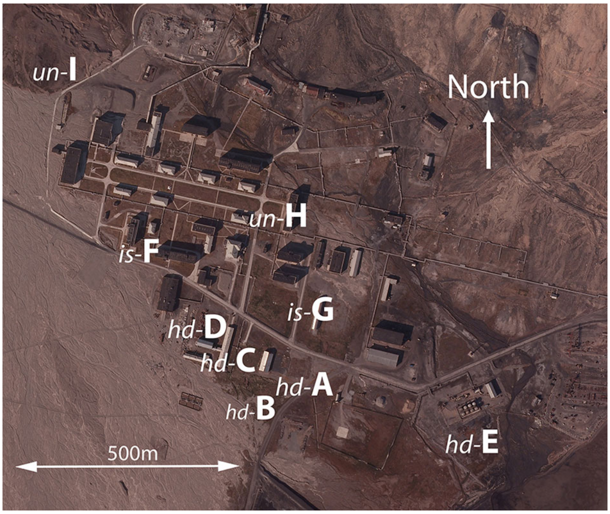


Fig. 3 Aerial photograph of Pyramiden (©Norwegian Polar Institute) showing the locations of the sampling sites around the settlement. Images of each site are provided in Figs. S1, S2 and S3 in the supplementary electronic material

Five species were common with Pyramiden soils and the two natural sites, *un*-**I** and *un*-**Z**; *A. oudemansi*, *A. haarlovi, A. multidentatus*, *P. parvanalis* and *Z. solenites*.

Only two species of oribatid mite were extracted from the imported soils (*is*-**F**, *is*-**G**, Table S2) both at extremely low densities; *Tectocepheus velatus* and *Liochthonius laetepictus*. Oribatid diversity was only marginally greater in the *heavily disturbed* soils on the perimeter of the settlement where a total of five species were observed; *Diapterobates notatus*, *Liochthonius sellnicki, Camisia horrida,* as well as *T. velatus* and *L. laetepictus*. The latter species, *L. laetepictus*, was occasionally very rich in juveniles. For example, at *heavily disturbed* site *hd*-**B**, juveniles dominated comprising 97 % of individuals extracted. At site *is*-**F**, where soil was imported, the density of *L. laetepictus* was lower and this species was absent at the natural sites. In contrast to the paucity of the Oribatida at the disturbed sites, 12 species of Oribatida were observed at the undisturbed tundra site *un*-**I** and 16 at site *un*-**Z**, resulting in a combined species diversity of 20 for the two *undisturbed natural* sites (Table S2). *Ceratozetes spitsbergensis* was observed at both *natural undisturbed* sites but was absent from *heavily disturbed* or *imported soil* sites.

Collembola

Twenty six species of Collembola were collected from the *heavily disturbed* and *imported soils* sites in Pyramiden, two of which are new records for Svalbard; *Thalassaphorura debilis* and *Desoria tigrina* (Table S3 supplementary electronic material), with a further two only previously known from anthropogenic soils in Barentsburg; *Hypogastrura assimilis* and *Deuteraphorura variablis*. This compares to 18 species at the *natural undisturbed* site in Pyramiden (*un*-**I**) and 19 at Skottehytta (*un*-**Z**). Although the species composition at these two undisturbed sites is slightly different, 14 species were shared between sites (Table S3). In Pyramiden, *Anurida polaris* was the only collembolan observed in the black-legged kittiwake debris at *nest*-**H** although it was also present at the *undisturbed natural* site *un*-**Z**. The

Collembola community of the *heavily disturbed* and *imported soil* sites included 12 species not seen at either of the two *undisturbed natural* sites.

Soil microarthropod communities

Cluster analysis revealed strong relationships between the species communities and soil types (Fig. 4) with samples taken from the three soil types examined - *heavily disturbed*, *imported soil* and *natural undisturbed*—each displaying a clear tendency to group together indicating distinct community compositions of the three soil types.

Amongst the *heavily disturbed* soil locations site *hd*-**E** forms an outlier (Fig. 4a–d). Site *hd*-**E** lies on the coastal margin of the settlement below the oil storage facility (Fig. 3) and is influenced by pollution from this installation. This site has no species of Mesostigmata in

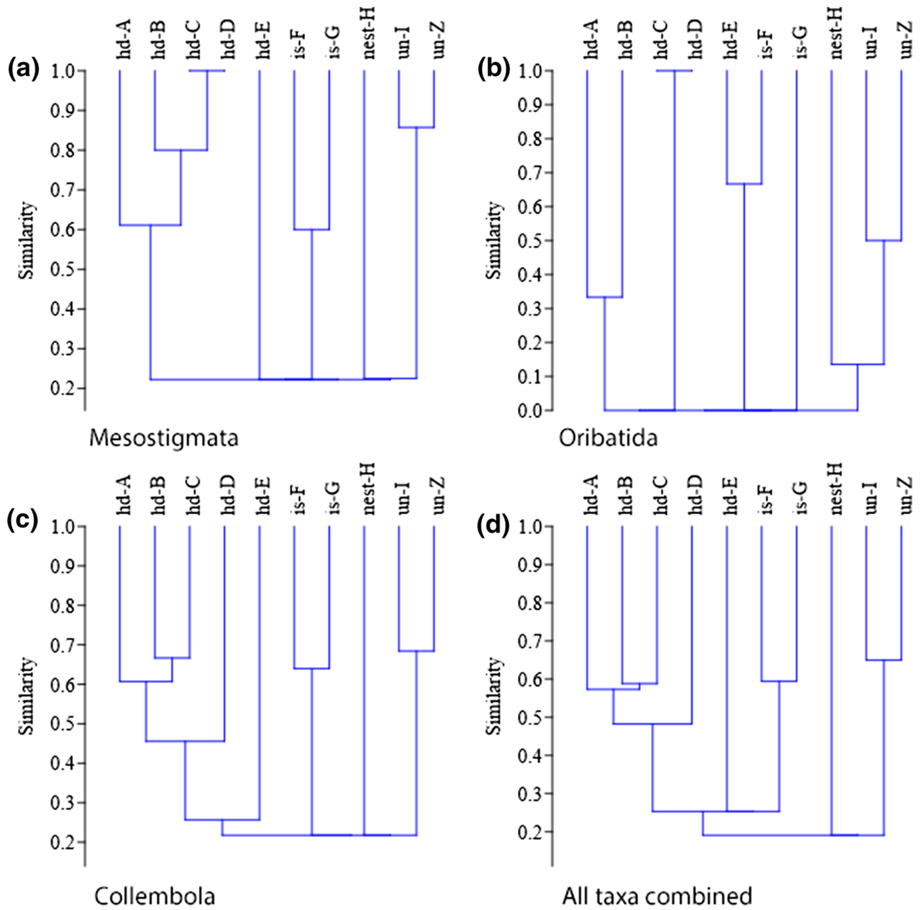


Fig. 4 Cluster analysis (UPGMA) presenting the soil microarthropod community relationships between the soil types; **a** Mesostigmata, **b** Oribatida, **c** Collembola, **d** Acari and Collembola combined. Soil types: i) *heavily disturbed* (designated as *hd* in the site letter code) consisting of trodden, damaged, previously built upon or polluted; *imported soils* (designated as *is*) referring to areas where chenozem soils were spread and which were formally protected as lawned areas; and *natural undisturbed* (designated as *nu*). See supplementary electronic material for more detailed explanation of the sites and full community descriptions

common with the other *heavily disturbed* (*hd*) sites (Table S2; Fig. 4a). The *imported soil* (*is*) locations also tend to cluster together but for the Oribatida (Fig. 4b) site *is*-**F** is more closely related to the *heavily disturbed* site *hd*-**E** due to sharing *L. laetepictus* (Table S2). The *natural undisturbed* site (*nu*) from the fringe of Pyramiden - site *un*-**I** - clusters closely with the *natural undisturbed* Skottehytta (*un*-**Z**) location for all three taxa (Fig. 4a–c). The black-legged kittiwake nest detritus (*nest-H*) does not cluster with any of the other three soil types with extremely low species diversity and one unique species, *Halolaelaps* sp. not observed from the other locations in this study (Table S2). When all taxa are considered together (Fig. 4d), the *heavily disturbed* and *imported soils* are seen to be more related to each other than to the *undisturbed natural* locations.

Discussion

Even after over 30 years since the importation of the soils, and some 16 years since the town was abandoned (Andreassen et al. 2010), there remain clear distinctions between the micro-arthropod communities from Pyramiden, both from the *heavily disturbed* and *imported soil*, and the native naturally occurring tundra communities from the *undisturbed natural* sites. The most striking difference between the invertebrate communities is the almost total lack of oribatid mites in the imported soils. Despite the often complete vegetation cover of the imported soil, only two species of Oribatida were observed at the *imported soil* and just five from the *heavily disturbed* sites. Four, *D. notatus*, *T. velatus*, *C. horrida* and *L. sellnicki*, were also present at the *undisturbed natural* sites *un*-**I**, and *un*-**Z** (Skottehytta), and are generally widespread in Svalbard (Bayartogtokh et al. 2011; Coulson and Refseth 2004). The fifth species, *L. laetepictus* (Brachychthoniidae), was only found in the soil of the settlement, but in some samples from sites on the periphery of the settlement it was rather abundant and very rich in juvenile stages. Such age structure indicates that this species develops here. *Liochthonius laetepictus* is a Palaearctic species and has previously been recorded from Svalbard but it is rather uncommon (Bayartogtokh et al. 2011). A closely related species, *L. sellnicki*, is more common. This species was highly abundant in all microhabitats at Vestpynten (close to Longyearbyen, Adventfjord) (moss and grasses, *C. tetragona* and *Salix polaris*), and in moss and open ground habitats at Skottehytta (site *un*-**Z**) (Seniczak et al. 2014). The recorded species of Oribatida in the *undisturbed natural* sites are all common in Svalbard and occur in various habitats (Bayartogtokh et al. 2011). Further, the majority of species are widespread throughout the Arctic (Danks 1981; Behan-Pelletier 1997; Melekhina 2011; Melekhina and Zinovjeva 2012). Not only was the diversity of the Oribatida in the disturbed soil lower than the natural sites but the density of these mites in the disturbed soils in the town was also far lower than in the natural tundra at either *un*-**I** or *un*-**Z** (Skottehytta).

The majority of the Mesostigmata observed in the settlement are recorded from the natural tundra at Skottehytta and other localities within Svalbard (Ávila-Jiménez et al. 2011) and form common elements of the soil invertebrate fauna. But *D. foveolatus* is recorded in Svalbard for the first time. *Dendrolaelaps foveolatus* occurs widely in diverse microhabitats including soil from cultivated fields and meadows, compost, manure, forest litter and rotting bark (Hirschmann and Wiśniewski 1982; Karg 1993) from central Europe, for example Austria, Finland, Germany, Lithuania, Poland, the Ukraine. In Pyramiden this species was present in a similar habitat, a mound of sawdust and shavings mixed with tree bark (site *hd*-**B**). The genus *Halolaelaps,* collected from the nest detritus and observed for the first time in Svalbard, is coprophagic and characteristic of excrement (Błaszak et al.

2001). The lack of previous records of this genus from Svalbard may reflect the general paucity of studies from this substrate type (Pilskog et al. 2014).

The species composition of the collembolan community from the *heavily disturbed* or *imported soil* sites in Pyramiden are very different from the *undisturbed natural* tundra close to the settlement (site *un*-**I**) or at Scottehytta (site *un*-**Z**). The Pyramiden community includes the probably introduced species *H. assimilis, D. variabilis* and *D. tigrina*. The record of *T. debilis* is probably the first verified from Svalbard. However, it is very close to the common Svalbard species *T. duplopunctata* and may have been previously overlooked. It is unlikely that this species is a human introduction and it is recorded from other littoral habitats in the Palaearctic (Fjellberg 1998), but the possibility of introduction cannot be excluded. *Desoria tigrina* is a first record in Svalbard and is numerous at heavily disturbed site *hd*-**C** and present at some other Pyramiden locations but absent from the *natural undisturbed* sites. It is an anthropophilous species, often abundant in cultivated fields (Ponge 1993) and closely related to *D. grisea* reported from Barentsburg (Coulson et al. 2013a). These *Desoria* belong to a group not yet fully clarified taxonomically and the Pyramiden specimens may be a new species currently being described and which has been seen from the Murmansk region and from Greenland. Twenty six species of Collembola occurred in the *heavily disturbed* or *imported soil* of which 13 species were shared between Pyramiden and Barentsburg (Coulson et al. 2013b). Four new records to Svalbard were identified in the imported soils from Barentsburg (Coulson et al. 2013a) but only two of these were also observed in Pyramiden; *H. assimilis* and *D. variablis.* With *D. tigrina*, only seen so far in Pyramiden, five records new to Svalbard have been recorded from the imported or disturbed soils in Pyramiden and Barentsburg together from a total diversity of 31 species; i.e. 16 % of the Collembola species in these soils are likely imports. With the inclusion of *T. debilis* the proportion of new records from these soils rises to almost 20 % clearly demonstrating a significant component of introduced species in the Collembola communities of this habitat.

A second feature of the collembolan communities, and matching the absence of oribatids, is an almost total absence of *Folsomia quadrioculata* in the Pyramiden soils (only two specimens at *heavily disturbed* site *hd*-**A** and one specimen at *heavily disturbed* site *hd*-**B**) despite being common at both *natural undisturbed* sites. This ubiquitous species is often present at extremely high densities in a variety of habitats in Svalbard and densities between 40,000 to 60,000 m^2 are not unusual (Sømme and Birkemoe 1999). The almost total absence within Pyramiden was hence entirely unexpected. *Folsomia quadrioculata* is sensitive to different forms of disturbance such as metals, industry, and radioactive pollution (Geissen et al. 1997; Kuznetsova and Potapov 1997; Taskaeva 2011) which may explain its almost non-existence in the Pyramiden soils. In addition, there is also an absence of *Hypogastrura tullbergi*, *Parisotoma notabilis* and an almost complete absence of *Lepidocyrtus lignorum* (only one specimen in single sample) in the *heavily disturbed* soils. All these species are common at the *natural undisturbed* sites besides in many habitats elsewhere in Svalbard (Coulson and Refseth 2004; Coulson 2007 and references therein). The absence of *P. notabilis* is particularly surprising since it is common at both the *natural undisturbed* sites, tolerant to various anthropogenic pressures, and even prefers moderately disturbed biotopes (Moore and Luxton 1988; Stebaeva and Andrievsky 1997; Dunger et al. 2004). The single observation of *A. polaris* in the nest detritus may represent lack of sampling effort at other locations in, or close to, Pyramiden but may also be related to the nest material itself. This species may have been imported to the black-legged kittiwake nests along with nesting material, often moss, and which may be collected at a considerable distance from the breeding colony (Pilskog et al. 2014).

We hypothesized that there would be introduced species associated with the imported soils. Two of the three new taxa records identified to species [*D. foveolatus* (Mesostigmata) and *D. tigrina* (Collembola)] are known to occur in the region where the soils were collected; southern European Russia and the Ukraine. The third, *T. debilis,* is known from littoral habitats in the Palaearctic (Fjellberg 1998) and is not considered to be a human introduction in Pyramiden. The two additional species [*H. assimilis* and *D. variablis* (Collembola)] observed in Pyramiden, and only previously recorded in Svalbard from the imported soils in Barentsburg (Coulson et al. 2013a), are also present in southern European Russia and the Ukraine. Hence, the four species of soil microarthropod considered to be introduced—one mesostigmatid mite and three Collembola—and only known in Svalbard from sites related to this imported chernozem soil, also have a distributions overlapping with the source region for the imported soils. This is highly suggestive that these species were introduced to Svalbard with the imported chernozem soils. It should be noted that with the limited sampling possible within the settlement, partly due to the strict environmental protection of the archipelago (Svalbard Environmental Protection Act 2001), the complete α-diversity will likely not have been captured in this study and additional introduced species may wait to be identified from Pyramiden.

As many of the species identified from the *heavily disturbed* or *imported soil* sites are known from diverse locations within the archipelago (Coulson 2007; Coulson and Refseth 2004; Coulson et al. 2014) it is difficult to fully appraise the extent of importation of individuals of species already recorded from Svalbard. Of the 32 species recorded from Pyramiden and also previously known from Svalbard, 16 (50 %) are known from the regions where the chernozem soils were collected from indicating that many con-specifics may have been imported along with the new species records. We here are unable to assess the possible importation of con-specifics and the introduction of new genetic material to Svalbard. This requires a molecular approach.

None of the five new species records for Svalbard observed here appear to be currently invasive since they have not yet been recorded outside of Pyramiden. However, the collembolan *D. variablis*, recorded here but also previously from Barentsburg (Coulson et al. 2013a), is potentially invasive of high nutrient habitats such as the ornithogenic habitats characteristic for Svalbard (Jónsdóttir 2005). Moreover, Svalbard, and the Arctic in general, are undergoing rapid environmental change and it is difficult to project precisely the response of introduced species in future climate scenarios (Nielsen and Wall 2013); especially in post-industrial sites with potential cocktails of pollutants present (Holmstrup et al. 2007; FSHEM (Federal Service for Hydrometeorology and Environmental Monitoring) 2009; Menezes-Oliveira et al. 2014).

It is therefore clear that the soil invertebrate fauna of Pyramiden is distinct from the natural situation. This fauna is also distinct from the anthropogenically modified soils near Barentsburg where eight species of oribatid mite were recorded (Coulson et al. 2013b). The communities of oribatid mites in Pyramiden are poor in species, but the density of *L. laetepictus* can be relatively abundant at certain localities, mainly due to the high numbers of juveniles. It is unclear why so few oribatid mites, both individuals and species, were present in the Pyramiden soils but we can hypothesize that one cause may be residual soil pollution associated with the recent industrial activity. Pollution levels in the settlement are often high (FSHEM 2009; Pedersen 2011); for example, polychlorinated biphenyl (PCB) levels in the soils around the buildings in Pyramiden are 3695 ng/kg (Pedersen 2011). It is well appreciated that many groups of soil invertebrates are sensitive to such pollutants (Cortet et al. 1999). But, it is unclear why pollution *per se* would explain the lack of Oribatida but the presence of Collembola and Mesostigmata. Similarly, pollutant levels at the imported soil site in Barentsburg are high (FSHEM 2009) yet the oribatid community is relatively rich. While Collembola are recognized to be often pollution resistant or tolerant (Fountain and Hopkin 2005; Kuznetsova 2009), oribatid mites also appear tolerant of heavy metal pollution at other abandoned mining sites (Caruso et al. 2009; Skubała and Zaleski 2012). It is more likely that this difference is related to source, and transport, of the imported soil. Topsoil was imported into Pyramiden to help "green" the settlement in c. 1983. While no documented records of this have been found, the soil is a chernozem from southern European Russia or the Ukraine (N. Shmatova, Trust Arktikugol, and N. Myski, chief editor of the journal "Russkii Vestnik Spitsbergena, pers. comm.) as was imported for the greenhouses in Barentsburg (Coulson et al. 2013a). Chernozem is a black-coloured humus rich soil which is extremely fertile and capable of producing a high agricultural yield. The number of introduced plant species is small compared to Barentsburg and only three introduced species were found in Pyramiden by Liška and Soldán (2004) compared to 44 taxa in Barentsburg. However, while areas of Pyramiden are largely a monoculture of *Poa alpigena* (Belkina et al. 2013), it seems unlikely that the novel soil invertebrate species assemblage is directly a result of the vegetation as there is often only an imprecise relationship between the flora and the soil invertebrate species (Coulson et al. 2003; St John et al. 2006a), that grassland monocultures at lower latitudes often retain substantial oribatid mite diversity (St John et al. 2006b), that the Collembola community was as diverse as other natural locations in Svalbard, and, not least, that the oribatid mite species present in Svalbard are often generalist taxa with wide habitat and geographical ranges in the Holarctic or Palaearctic regions (Bayartogtokh et al. 2011; Coulson et al. 2014). Environmental disturbance is appreciated to filter species and particular taxa may decline in densities while others are able to exploit the new conditions (Siepel 1996). This may be what we observe in Pyramiden. The presence of several species of Collembola here not observed in Svalbard outside of the settlements implies that certain taxa were able to survive the journey to Svalbard with the imported soils and since have thrived in the new environment. However, the slower moving Oribatida, which are dependent on soil cavities, pore spaces and galleyways (Gilyarov 1965; Krivolutsky et al. 1995; Hansen 2000), may not have survived the mixing and mechanical stresses encountered during the collection, shipping and spreading of the soils. The oribatid community of the imported soils, and to some extent the heavily disturbed soils, is hence dependent on the colonization of native species from the surrounding tundra; a process that may be sluggish at High Arctic latitudes with low temperatures and short snow free summer seasons. Recolonisation by the invertebrate fauna of prepared soils on industrial wasteland can, however, be rapid. Hutson (1980) records Acari and Collembola "rose to a high level" within 2 years. Yet recolonization processes in the Arctic appear to be more gradual. Slow invertebrate community assembly processes have been observed previously in Svalbard (Hodkinson et al. 2004) and other periglacial regions (Hågvar et al. 2009) when during the colonization of post-glacial substrates the Collembola appeared earlier than the oribatid mites. Similar slow colonization of the Oribatida compared to Mesostigmata and Collembola has been observed previously at polluted or industrial reclamation sites (St John et al. 2002; Stebaeva and Andrievsky 1997; Wanner and Dunger 2002). Melekhina (2007, 2012) described three stages of the invertebrate colonization of cleaned oil polluted soils; stage (i) simple communities dominated by predators (mainly Mesostigmata), stage (ii) Collembola began to appear, and stage (iii) appearance of the Oribatida. This final stage could take decades to occur, for example, the colonization of stone quarry heaps which required 30 years to resemble the natural undisturbed system

(Riabinin and Pan'kov 2009). Such slow colonization rates may result from several causes, for instance, low soil organic matter (Scheu and Schulz 1996), extreme microclimatic conditions (Karg 1967), poor soil structure (Hansen 2000), the low reproductive rate of Oribatida [lifecycles of 5 years in the High Arctic (Søvik et al. 2003)], and the slow, often passive, dispersal of Oribatida (Lehmitz et al. 2011, 2012). All these factors are exacerbated in High Arctic latitudes where temperatures are low and the ground may only be unfrozen for three months of the year (Coulson et al. 1995) resulting in gradual community assembly processes (Hodkinson et al. 2003, 2004). Moreover, the importance of earthworms in the formation and structuring of the humus layer has been observed in reclamation projects elsewhere (Frouz et al. 2009). The general absence of lumbricid earthworms in Svalbard (Coulson et al. 2014), and the slow accumulation of a humus layer, will further delay the creation of a suitable microhabitats for the soil dwelling oribatids. The hypothesis of differential taxa survival during shipping of the soils is further supported by previous studies of the imported soils at the active Russian settlement in Svalbard; Barentsburg, Here, Coulson et al. (2013a), recorded several species of Mesostigmata and Collembola new to Svalbard and thought have been introduced with soils imported from southern European Russia/Ukraine for the greenhouse, yet no new species of Oribatida were recorded.

The focus of this discussion has been the soil fauna of imported soils and potential introductions with these soils. However, it is clear that other human activities can also introduce alien species. Movement of people associated with, for example, tourism or science, is one such route. The number of passengers arriving at Svalbard airport has increased sharply in recent years from 50,000 in 1997 to circa 130,000 in 2013 (Governor of Svalbard 2013). Similarly the number of tourist on expedition ships with multiple landings has risen from 3,500 in 2001 to 10,500 in 2013 with the number of locations visited going up from 145 to 220 over the same period. Ware et al. (2012) demonstrated that travelers have the potential to introduce many alien species of plants, and hence by inference potentially invertebrates as well, and that field scientists with uncleaned boots were amongst the worst "offenders" with a mean of 5.7 seeds per individual compared to an overall mean of 3.9. With the increased number of landings it is also clear that there is a risk that alien species established in the settlements may be transported to other locations around the archipelago and pose a threat to native communities, for example those forming the characteristic communities beneath birdcliffs. Steps are being taken to limit the threat of marine invertebrate introductions, for example via ballast water dumping (Ware et al. 2014) and the Svalbard Environmental Protection Act 2002 prevents the deliberate importation of alien species but there is yet limited attention on preventing accidental introductions to the terrestrial environment.

In conclusion, we report the soil microarthropod community of an abandoned industrial town in the High Arctic at which a greening programme was undertaken using imported soil from continental Europe. The almost complete lack of oribatid mites in the soils within the settlement is difficult to explain but may be a result of high mortality during transportation of the shipped soils and subsequent slow colonization by the native Oribatida. But an interaction with local pollution cannot be discounted. After circa 30 years, the microarthropod communities of the disturbed soils remain dissimilar from the undisturbed natural tundra and several species of introduced invertebrates are present. The ratio of species richness and abundance of Collembola, Mesostigmata and Oribatida indicate that the soil invertebrate community in the settlement is immature and still developing. Natural colonisation of anthropogenic environments by the resident Arctic soil fauna may take surprisingly long periods. Remediation measures for industrially disturbed sites in the

Arctic will require extended recovery periods to be effective, especially for the colonization of the effected terrain by the resident soil fauna. In this study none of the introduced species have become invasive, although this is not to say that they will not become invasive in the future. Although the introduced species observed here do not appear to have an immediate high invasive potential, responses to future climate scenarios are difficult to project. It is also clear that there are specific points of entry for imported species. In Svalbard these are currently mainly the two ports of Longyearbyen and Barentsburg and at the former port of Pyramiden. But, spread of imported species from these locations to other regions of Svalbard is likely via movement of people, including researchers and tourists. Biosecurity measures may need to be considered to prevent colonization of potentially fragile habitats by invasive species and where recovery periods may be lengthy. Long term monitoring of the situation is required to determine the colonization rate of the resident soil fauna to the imported soils but also potential invasiveness and spread of the introduced species. Taxa specific responses to disturbance, and the protracted response period, should be taken into account when considering remediation projects in Arctic regions. However, this is complicated by uncertain responses of the soil fauna, and the introduced species in particular, to climate change scenarios, especially in polluted soils. Human introduction of alien invertebrates to Arctic regions and the required remediation of disturbed terrain is likely to increase in the future. Such examples as Pyramiden provide useful illustrations of the challenges ahead.

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