Terrestrial Antarctic ecosystems in the changing world: An overview

Katarzyna J. CHWEDORZEWSKA

Zakład Biologii Antarktyki, Polska Akademia Nauk , Ustrzycka 10/12, 02-141 Warszawa, Poland
<kchwedorzewska@go2.pl>

Abstract: Although the Antarctic has avoided the worst effects of alien species, its future seems endangered due to increasing natural and man-made pressures. Rapid changes in three major environmental variables have occurred in the Antarctic region during the last decades. In the short term terrestrial biota are likely to benefit from reduced environmental stresses, but in the long run the colonization of the region by lower latitude species with greater competitive ability will become increasingly important and can lead to large-scale changes in biological composition and trophic complexity in some existing Antarctic terrestrial ecosystems. Moreover, the recent dynamic climate changes combined with human activities in the Antarctic region might modify the status of several alien species which have hitherto been considered transient or persistent and could, therefore, become naturalized and threaten the native communities on a larger scale than today, or influence the status of naturalized species.

Key words: Antarctica, alien species, human impact.

Specificity of Antarctic conditions and its implications

Isolation and the glaciation of Antarctica are strongly associated with the evolution of Antarctic organisms (Clarke *et al.* 2005) and are the main reasons why its terrestrial ecosystems are relatively simple, with poorly developed trophic structure and are poor in species as compared to lower latitudes (Bokhorst *et al.* 2007). This isolation means that there is currently little or even no influence on natural communities from colonization by alien competitors (Wasley 2004).

Over the last 30 million years many groups of organisms became extinct in the Antarctic as a result of increasingly extreme climate (Clarke *et al.* 2004). Thus the diversity of Antarctic flora is exceptionally low (Bergstrom and Lewis Smith 1990). This region differs from all other continents by the rarity of vascular plants. No species reach the continental region south of 69°S. As a consequence of polar severe conditions, the vegetation of the Antarctic consists almost entirely of cryptogams with lichens predominating in drier, more exposed sites (Olech 2004) and bryophytes prominent in the more sheltered and humid habitats (Longton 1966; Lindsay 1971; Ochyra 1998). Outside the maritime zone the vegetation is primarily limited to

a few rocky outcrops along the coast, the dry valleys and nunataks. Antarctic organisms are exposed to extreme conditions with very low temperatures, desiccating winds, intermittent water supply, a highly seasonal light regime, continuous light in midsummer, elevated ultraviolet-B radiation levels and very short growing season. In some places terrestrial organisms can be exposed to daily temperature fluctuations of 20–40°C and annual temperature fluctuations as high as 40–80°C and are therefore highly eurythermal (Convey 1996). Many of Antarctic continent areas are considered polar deserts, because the precipitation is less than 100 mm/year and is almost always delivered as snow. Exacerbating the extremely dry conditions are the subzero summer temperatures which lock most water away, significantly limiting plant growth and productivity (Hansom and Gordon 1998). Antarctic terrestrial organisms have biochemical and physiological adaptations that allow them to withstand prolonged periods of both freezing and desiccation. For example plant and fungi metabolism is quickly established when water becomes available, with lichens having greater recovery potential than others (Olech 2000; Wasley *et al.* 2006). Associated with desiccation stress is the impact of wind, which acts both as a stressor and a disturbance, as well as abrasion factor (Berjak 1979). Also the autochthonous resources of biogenic substance available for Antarctic communities are minimal (Olech 2002). The low level of energy available in summer and long periods of enforced winter inactivity directly constrain the development rates that can be achieved, carrying the corollary of extended development times and the necessity of repeated overwintering before maturity can be reached (Bergstrom *et al.* 2006). Very characteristic features of Antarctic organisms are high stress tolerance, wide ecological amplitude, lack of competitive ability or investment in dispersal strategies, reduced reproductive investment and output, and extended lifespans and life cycles (Convey 1996; 1997; 2000). It is the possession of considerable flexibility in many physiological and life history characteristics, rather than any specific single adaptation, that has been the key element in the response of many Antarctic terrestrial biota to environmental variation (Convey 1996).

Climatic changes and their influence on the Antarctic flora

Plant communities of Antarctic environments are limited purely by the extreme conditions rather than biotic interactions and are expected to be very sensitive to changes in climate or consequential processes (Frenot *et al.* 2005). Most of climate change in coastal Antarctic is causing an increased temperature, extended length of "growing season", precipitation, ice melt, extinction of ice-free habitat, availability of soil moisture, release or input of nutrients into the ecosystem, frequency and changes in the direction of severe weather events (Lewis Smith 2001). Global temperatures increased by about 0.6°C during the 20th century (Houghton *et al.* 2001). However, the picture is more complex in the regional scale. Since austral polar regions have been relatively undisturbed, small climatic shifts may have a significant

impact on biological habitats, much greater than one of similar scale in a less extreme environment at lower latitudes (Convey and Lewis Smith 2006). Currently, some parts of Antarctica belong to the fastest warming regions of our planet. Over the last 50 years documented temperature changes along the Antarctic Peninsula reach on average about 2°C (Convey 2006). By contrast, there is one report of regional cooling in the Dry Valleys (Doran *et al.* 2002). The warming trends are not constant throughout the year, with higher increases during winter than during the summer. The limited direct effect on summer conditions, shortening of the winter period, as well as earlier spring thaws and later autumn freezing may extend the active season for terrestrial biota. By contrast, in some places (South Orkney Is) warming occurred mostly in summer (Lewis Smith 1991). There were also documented changes in patterns of cyclonic activity around the Antarctic, along with changes in the intensity of precipitation. The availability of liquid water may be even more important than temperature for the biological activity in Antarctic terrestrial habitats. Even minor differences in moisture availability may result in significant changes in the composition of plant communities (Kennedy 1993). Increases in precipitation have been documented in the maritime Antarctic (Turner *et al.* 1997), there is also an increasing likelihood that summer precipitation will fall as rain rather than snow, and hence be immediately available to terrestrial ecosystems. While increasing the input of water to terrestrial ecosystems, earlier or increased melt may also exhaust reserves of ice or snow before the end of the summer, hence locally increase water stress (Davey *et al.* 1992). The potential consequences of the annual formation of the Antarctic ozone hole lead to greater penetration of UV-B radiation during the austral spring. For Antarctic plants, most studies have found little effect on photosynthesis, but growth was affected by exposure to UV-B radiation especially in two species of vascular plants. In both thicker leaves, reduced branching and fewer leaves per shoot were observed with increased exposure (Day *et al.* 2001; Ruhland and Day 2000; Xiong and Day 2001). UV radiation altered also the pigment composition (Robinson *et al.* 2005). The consequences of climate changing throughout the maritime Antarctic include also the increase in favourable conditions for colonization, community development, reproduction and dispersal, frequent stimuli for the development of buried propagules, increased rate of development of the buried soil propagule bank, potential for the establishment of species new to region, increased reproduction success, increased local propagule dispersal, enhancing the survival of some species and possibly favouring new colonists, as well as possible reduction in resilience of modified communities to brief periods of reversed climate trend (Lewis Smith 2001). Botanical responses to recent climate amelioration are already visible in the maritime Antarctic and sub-Antarctic in the form of growth of local population density and distribution of the vascular plant species and changes in their reproductive patterns, with a greater incidence of successful sexual reproduction and increased seed output (Fowbert and Lewis Smith 1994; Grobe *et al.* 1997) may have a further impact through their ability to remain dormant in soil propagule banks (McGraw and

Day 1997). Rapid population increases have also been observed among bryophytes and microbiota in the maritime Antarctic (Lewis Smith 2001; Green *et al.* 1999). Sexual reproduction in mosses also leads to the production of highly dispersible spores, possibly providing opportunities not available to the range of asexual propagules also produced, which will alter the pattern of colonization (Convey and Lewis Smith 1993). However, colonization by alien species and consequential change in the patterns and importance of competition will in itself be one of the major outcomes of climate change for Antarctic terrestrial ecosystems (Convey 2006).

Human impact

Human activity in the Antarctic region has only taken place for the last 200 years. This region shows no evidence of ever having supported indigenous human populations. Excessive commercial exploitation took place in the sub-Antarctic during the late 18th and 19th centuries, initially through sealing and, subsequently, whaling industries, followed by exploitation beyond the Polar Front (Frenot *et al.* 2005).

Early exploration and seal hunters. — The first systematic search for a southern continent started in 1700 when Edmond Halley crossed the Polar Front. During the 1700's, the French became active, and discovered Bouvet I. and Kergulen I. From 1773 to 1775 Cook made three crossings of the Polar Front and in February 1775 completed the first circumnavigation of Antarctica (Wise 1973).

During his expeditions Cook noted in his log large numbers of animals he observed in the high latitudes (Gurney 1997) and before long, hunters headed south. A new phase in Antarctic exploration and exploitation began in 1819, when William Smith had discovered South Shetlands. During the 1820–21 summer season there were between 55 and 60 sealing vessels working in the South Shetlands. Perhaps a quarter of a million seals were eliminated within three months. Voyages of many sealers looking for new hunting grounds were underwritten by a whaling company "Enderby Brothers", whose owners were eager to have their captains make new geographical discoveries. During only two decades which had passed since the discovery of the South Shetlands nearly all commercially valuable seals had been extirpated (Wise 1973).

The whale slaughter. — During the early part of the nineteenth century, whalers ventured further south. Late 19th century Norway's whaling expeditions to the Antarctic were not successful, but by the early twentieth century whaling technology had improved. The industry was re-established in the Antarctic in 1904, when the first shore station was built at Grytviken on South Georgia I. (Tønnessen and Johnsen 1982; Kittel 2004). In 1906, the first factory ship was sent to the South Shetlands. By 1912 there were six shore stations, 21 factory ships, and 62 catchers in Antarctica. In 1923 the British government, alarmed by the diminishing number of whales, established the Discovery Committee. Members of the committee, us-

ing a ship named *Discovery*, began their work on South Georgia in early 1925. Thus, they began the first major scientific study in Antarctica. In 1937, nine countries agreed to minimum size restrictions of hunted whales. Nonetheless, during the 1937–1938 season, over 46,000 whales were killed (Wise 1973).

Heroic age. — Scientific research started to be emphasized during the "Heroic age" of exploration of the early 20th Century. This is the period of Antarctic exploration from the Fifth International Geographical Conference in 1895 to the end of Shackleton's Antarctic exploits. The final major expedition of "the heroic era" began when Ernest Shackleton left England in the ship *Endurance* (Wise 1973).

Scientific research activities. — The region has attracted scientists since the late nineteenth century. According to Antarctic Treaty obligatory data in the 2008/09 seasons, at 111 stations, refuges and field camps in Antarctica there were 4460 (1094 in winter) personnel (www.comnap.aq). Only a few stations have been built on the continental ice sheet, most of them are situated in coastal regions (Bölter and Stonehouse 2002). The largest numbers were deployed at the stations in the Scotia Arc and Antarctic Peninsula sector and the single McMurdo Station in the Ross Sea sector. National transport programs used over 60 ships each year. Many of the national programs are run by European and Asian countries, and the USA. Large numbers of ships inevitably travel from the Northern Hemisphere, with some working consecutive Antarctic/Arctic summers to take advantage of ice-strengthened or ice-breaking capabilities (Enzenbacher 1994).

Domestic animals. — There are numerous records of domestic animals and their foodstuff being imported to Antarctic stations, but mainly to the sub-Antarctic islands. Ponies, pigs, sheep, hens and occasionally cows were kept as a food source at the whaling stations, and at some research stations until as late as the nineteen sixties. The cattle and sheep were fed on dry alfalfa and the poultry on maize, and ponies were fed on hay (Lewis Smith 1996).

Tourists. — In 1956 the Chileans started tourist flights over the Antarctic continent. This was soon followed by cruises to the South Shetland Is (1957) (Stonehouse 1994). There has since been an initially erratic but later rapid increase in tourism, especially in the last decade. In 2006/2007 58 tourists ships took 37 000 tourists (plus over 22 000 crew and staff) (www.iaato.org). It can be expected that both commercial tourists and private adventurers will have similarly high levels of travel mobility to expeditioners. Practically all tourists are ship-based transistents, living on their ship, requiring no infrastructure ashore, and staying for only a few days in the area, mainly in the four summer months (Stonehouse 1999). Tourists congregate in the small coastal areas rather than in land ice (Bölter and Stonehouse 2002). The majority departs by small ships from Ushuaia, or Punta Arenas, and participates in multi-site tours. The sequence of sites visited over a short time period is often from warmer, higher biodiversity areas to cooler, lower biodiversity

areas. Furthermore, Antarctic tourist expeditions commonly visit other high-latitude regions within six months before departing for Antarctica (www.iaato.org). Most tourists are from Europe, North America and Japan. The standard pattern of visits during the 1980s and 1990s was simply to land on beaches and observe immediately accessible wildlife, but the options now include extensive walks, kayaking and even a marathon (www.marathontour.com). Currently, over 28 000 ship-based tourists visit the Antarctic each year, making use of over 150 landing sites. While some locations receive only a few visits per decade, the most popular may be visited even three times weekly throughout a summer season (even 430 landing per site) (Ciaputa and Salwicka 1997; www.iaato.org).

Colonization

Low species richness and the absence of many functional groups might make polar islands, and the island-like exposed land of Antarctica, more susceptible to alien invasion (Bergstrom and Chown 1999). Successful transport across the Polar Front and establishment in the Antarctic is an infrequent event, but long-distance dispersal and subsequent establishment appear to be more problematic than survival alone. Some groups of organisms are better adapted to dispersal and this determines the frequency with which they arrive at new habitats, but not their ability to establish there. Other organisms have limited mobility but have established and survived in various refugia on account of their ability to withstand a series of selective pressures. Establishment involves the initiation of a long-term viable and reproducing population and differs from simple survival, as it requires the resources and habitat to permit reproduction, development and completion of the life cycle. Consequently very limited number of species will be able to deliver all the biochemical processes required for colonization and persistence (Hughes *et al.* 2006). Stochastic arrival of a key species with essential capability of establishment at a site may itself alter the environmental conditions and permit establishment of other species. A wide range of biotic groups appear well-adapted in respect to the first of these requirements, having developed a range of stress-resistant propagules, which allow the possibility of survival during extended dispersal events (Convey 1996). Alien species are those that are considered to occur outside their normal or natural range as a result of human activity, or as self-introductions from a site of known human introduction (Frenot *et al.* 2005). The majority of alien species met at sub-Antarctic islands are transient or persistent and are unable to spread into the native vegetation. With the exception of a few highly invasive species these alien plants have a restricted impact on the ecosystems. However, the current changes in the climate conditions might modify the status of several alien species. Climate change could also influence the status of species that apparently have a small impact and could increase their competitive abilities making them dominant in the communities (Frenot *et al.* 2001).

Potential source of introduction

Whole organisms or their propagules can be transported in air, water current, associated with migratory birds and mammals, or in water, attached to flotsam (logs, kelp rafts) or by humans (Hughes 2006). There is some evidence of continuous immigration of sporomorphia from South America (Lewis Smith 1984; 1991; 1993). Exotic pollen and spores of bryophyte and lichen species have been detected on the continent (Linskens *et al* 1993; Kappen and Straka 1988; Marshall and Convey 1997). It suggests also that there is no or very rare passive introduction by wind drifts, birds or other vectors. However, these vectors may play a role in the dispersal of alien species inland (Chown and Avenant 1992). There is no evidence of seeds or vegetative fragments being transported into the austral polar regions by adhering to birds (Lewis Smith 1984). It is probably because all native migratory birds visiting these areas spend at least short periods on the sea. Transoceanic dispersal of propagules across the Southern Ocean by other natural agencies such as seals or tree trunks, or even flotation is highly unlikely (Lewis Smith 1996). There is no direct evidence of waterborne transfer of propagules into austral polar regions. Dispersal on the water surface is likely to be important within locations on the local scale (Hughes *et al.* 2006). Wind is probably the dominant natural agent of biological transport both into and within these regions for many biological groups. West Wind Drift around the Antarctic limits the direct transfer of biological material in the North-South direction. However, some propagules from the continents in the Southern Hemisphere may still reach the Antarctic continent and offshore archipelagos (Hughes *et al.* 2006). Marshall (1996) showed that air mass moving around the continent can be associated with dramatic influxes of airborne biological material into South Orkney Is from South America and estimated that suitable weather patterns occurred on average once every 18 months, although the same phenomenon in a less intensive form can appear more often. But the majority of biological material present in Antarctic air is likely to be of local rather than intercontinental origin (Marshall and Convey 1997). On the other hand, katabatic winds flowing from glaciers may inhibit local aerobiological transfer of propagules towards inland sites. The majority of the introduced alien species in the austral polar regions are considered human-dependent immigrants. A range of alien organisms can be accidentally transported and ultimately introduced by expeditioners, their associated equipment and cargo. Fresh fruit and vegetables are also a source of seeds, invertebrates and are often infected by fungi (Chwedorzewska *et al.* 2008). Another potential source of contamination are the means of transport including helicopters and all kind of boats used on re-supply expeditions for ship to shore transfer. Personal outdoor equipment and equipment cases, outdoor clothing and items (particularly pockets, seams, cuffs, boots and the hooks of Velcro® fasteners) held many propagules (Whinam *et al.* 2005). The increase in the propagule pressure is linked to direct human activities (building activity, waste deposits, number of expedition members, frequency of ship landing).

Statute of sub-Antarctic alien flora

Sub-Antarctic islands were discovered at the end of the eighteenth century and the introduction of alien species started with human arrival (Walton 1975). In the sub-Antarctic human activity influence strongly the diversity of plant communities, for example cattle have contributed to substantial changes in low altitudinal areas (trampling, soil erosion, decreasing in the water resources, and change in the organic matter dynamics, and imported livestock food), (Frenot *et al.* 2001). Frenot *et al.* (2005) recorded 108 alien vascular plant species in the sub-Antarctic. They belong mainly to cosmopolitan families including Poaceae (39), Asteraceae (20), Brassicaceae (8) and Juncaceae (7) and have not only survived but also spread and successfully competed. Poor family diversity and the low contribution of some families which are extensively developed elsewhere in the world constitute a real disharmony of the native flora and many alien species come from families non-represented or poorly represented in the native flora of sub-Antarctic (Frenot *et al.* 1999; 2001; Gremmen and Lewis Smith 1999). The recent colonization of vascular plants in the sub-Antarctic makes the first stepping stones for new colonisers, as the climate is less harsh than along the Antarctic Peninsula and the main landmass (Bokhorst *et al.* 2007).

Alien species in the Antarctic

All plant species introduced to the sub-Antarctic are common in temperate regions of the northern hemisphere, belong to the European flora and usually show a large ecological range (Frenot *et al.* 2005). This is partly because human colonization in the Antarctic was largely from the Old World (Headland 1989), and may also be a consequence of loading cargo from some of the New World's disturbed areas, such as farms, ports, holding areas in cities, where both the abundance and diversity of European invasive species is high (Slabber and Chown 2002). In comparison with sub-Antarctic Islands Antarctica shows much less successful alien introduction. Although the Antarctic has escaped the worst effects of alien species, its future seems endangered due to the increasing natural and man-made pressures (Whinam *et al.* 2005). The consequences of uncontrolled experimental and accidental introductions of organisms, and of importing unsterilized soil and other materials into the Antarctic, pose a potentially serious threat to the ecologically sensitive, near-pristine terrestrial systems comprising a very low species diversity (Lewis Smith 1996). Several stations maintained decorative and culinary plants in the greenhouses, often discarding the remains and imported soil nearby rather than sterilizing or incinerating the material (Hill 1967). There were some experiments of introduction of alien plants to the Antarctic. In 1944 nine species of vascular plants (three forbs, one germinoid, three dwarf shrubs and two ferns) were planted on the Goudier I., Port Lockroy, using imported peaty soil from Falkland Is. Four

species survived the ensuing winter and showed sings of new growth, although only two were found as healthy during their second summer. No records are available after January 1946, until January 1950, at which time none of imported plants was to be found. But probably the peat soil contained uncertain provenance dormant seeds, which germinated even at 1950, or the plants may have grown from seed imported during this expedition. In summer 1946 on this soil the seedling of cabbage were successfully grown (Holdgate 1964). An earlier attempt at such an introduction to the South Orkney Is (Laurie I.) was in 1904. 22 phanerogams, which prospered and produced seeds at polar region of North Hemisphere, were sown. However, none of the seeds germinated (Brown 1912; Lewis Smith 1996). The second documented attempt was made to grow sea kale *Crambe maritime* at Cape Geology (Victoria Land). A seed was sown in 1912, germinated, but survived only a week (Taylor 1913). A more casual attempt of sowing of "grass seed" and oats on the Argentine I. in 1935 (during the British Graham Land Expedition 1934–37) resulted in germination, but did not lead to the establishment of any species (Holdgate 1964). In 1962–63 Rudolph (1966) grew without success a number of seeds of several flowering species in natural soil at Cape Hallett, Victoria Land, that grew well at laboratory in the same soil. The following summer the experiment was repeated, and only two species germinated: *Poa pratensis* and *Diapensia lapponica*. Only *P. pratensis* grew very slowly and never developed beyond the two-leaf stage. In 1967 Edwards and Greene (1973) transplanted adult plants from the Falkland Is to South Georgia and Signy I. At Signy I. 11 species survived for 2,5 years, but there was a substantial reduction in their vegetation and reproductive performance suggesting that none of them was likely to become naturalized. All introduced material was destroyed at the end of the experiment. The most successful species in terms of reproductive capacity was *Poa annua,* which produced many inflorescences in each of the three summers. Similar experiment was carried out between 1967 and 1973, when 23 native and alien vascular species from South Georgia were transplanted in local soil and vermiculite on Signy I. Many of the transplanted species survived at the most sheltered site and eight species flowered after at least one winter; also the seed germination was observed during two summers, but seedlings establishment was generally low. In this experiment the most successful in flowering was *Poa alpinum*. When the experiment was completed in 1973 all plants were removed and incinerated (Edwards 1979). In 1960 Japanese expeditioners also grew *Salix reinii* Fr. and *S. pauciflora* Koidz. from Japan, with all native soil removed and later *Empetrum nigrum* at the same site. Both species survived one winter and the second summer, but failed to survive the following winter (Hoshiai 1970). Furthermore, extraordinary facts were discovered during the three austral summers between 1995 and 1998. Several new shoots of *Salix,* probably surviving from same site were found (Kanda 2002). Although substantial vascular flora is present on sub-Antarctic Is (Moore and Sladen 1965), only *Poa annua* and *Poa pratensis* are recorded as accidentally introduced into the Antarctic

biota (Greene and Greene 1963), the record of *Stellaria media* included by Greene and Greene (1963) having subsequently been proved false by Holdgate (1964). Both grasses have been recorded on Deception I. *P. pratensis* was first collected in 1944, while *P. annua* was not seen until 1953, when it was collected in Whalers Bay (Skottsberg 1954). *P. annua* in this locality was then observed for at least three summers and two winters. The grass flowered and also scattered seedlings appeared (Longton 1966). The population was destroyed during a volcanic eruption in November 1967 (Collins 1969). In 1960–61 tufts of *P. pratensis* were found at Cierva Cove, Huges Bay, Danco Coast, near Capitan Cobett station. Plants were growing in soil imported from Ushuaia. The soil was brought with six small trees of *Nothofagus pumilio* (Poepp. et Endl.) Kass and *N. antarctica* (Forst. F.) Derst. in the summer of 1954–55. The trees did not survived. In 1960–61 around the dead trees Corte found the dead remains of an unidentifiable leguminous plant and fern, as well as the living *P. pratensis* with young inflorences (Corte 1961). No further information about this grass was reported until the summer of 1990–91 when *P. pratensis* was growing at the southern part of the original plots. The grass had immature inflorences, but the colony did not spread beyond the original plot (Lewis Smith 1996). It was the first published account of the successful establishment of alien phanerogamic plants on the Antarctic mainland. In 1995 a single tuft of *Poa* cf. *trivialis* L. was found in a rock fissure about 5 m of refuge situated 20 km far from Syowa Station (Kanda *et al.* 2002).

On King George I. *Poa annua* L. spreads and inhabits areas in the vicinity of the Polish Antarctic *Arctowski* Station. The species was initially recorded in the austral summer of 1985/86 in front of the entrance of the main building (in holes of the metal grid used to clean shoes) (Olech 1996). Since the first record of this species in 1985/86, the populations of *P. annua* have increased markedly in density and abundance within the original areas. They expanded into new areas until the summer of 1989/90 when only one locality was noted. In 1991/92 a sudden increase in the number of localities and rapid spread of the grass were observed. In the following growing season the population of *P. annua* increased gradually. At the *Arctowski* station *P. annua* colonised places strongly altered by human activities, where the soil structure was destroyed e.g. by earthworks or caterpillars, preferring sites sheltered from the wind (Olech 1996). *P. annua* was noted for the first time in natural communities in summer 2005/2006 (Olech unpubl. data). In summer 2006/2007 the number of individuals in the natural communities as well as the total number of localities increased (Olech unpubl. data). *P. annua,* however, became invasive on some of the sub-Antarctic Is, spreading into native communities and displacing native species. At South Georgia (McIntosh and Walton 2000) and at the *Arctowski* station it seems to be rather persistent than invasive, and has restricted its distribution in the colonization area (Chwedorzewska 2008; Olech unpubl. data). For several alien species Antarctic and sub-Antarctic conditions may be close to their physiological limits (Davies and Melbourne 1999). It is note-

worthy that plant species introduced from original site even in imported soil did not persist longer than a couple of winter periods. There were also a couple of records of introduction of mosses in the maritime Antarctic, like for example *Funaria hygrometrica* Hedw. on Deception I., Adelaide I. or on Wilkes Land in East Antarctic (Ochyra *et al.* 2008). Our knowledge about symbiotic fungi and other microorganisms, which are essential for plants, but cannot exist in the Antarctic, is limited (Kappen and Schroeter 2002).

References

BERGSTROM D. and CHOWN S.L. 1999. Life at the front: history, ecology and change on South Ocean islands. *Trends in Ecology and Evolution* 14: 472–477.

BERGSTROM D.M., HODGSON D.A. and CONVEY P. 2006. The physical setting of the Antarctic. *In*: D.M. Bergstrom, P. Convey and A.H.L. Huiskes (eds) *Trends in Antarctic Terrestrial and Limnetic Ecosystems: Antarctica as a Global Indicator* .Springer, Dordrecht: 15–29.

BERGSTROM D.M. and LEWIS SMITH V.R. 1990. Alien vascular flora of Marion and Prince Edward Is: new species, present distribution and status. *Antarctic Science* 2: 301–308.

BERJAK P. 1979. The Marion I. flora – leaf structure in *Poa cookie* (F. Hook). *Proceedings of the Electron Microscopy Society of South Africa* 9: 67–68.

BOKHORST S., HUISKES A., CONVEY P. and AERTS R. 2007. The effect of environmental change on vascular plant and cryptogam communities from the Falkland Is and the Maritime Antarctic. *BMC Ecology* DOI: 10.1186/1472-6785-7-15.

BÖLTER M. and STONEHOUSE B. 2002. Uses, Preservation, and Protection of Antarctic Coastal Regions. *In*: L. Beyer and M. Bölter (eds) Geoecology of Antarctic Ice-free coastal landscapes. *Ecological Studies* 154: 393–407.

BROWN R.N.R. 1912. The problems of Antarctic plant life. Report on the Scientific Results of the SY "Scotia" during the years 1902, 1903, and 1904. *Botany* 3: 3–21.

CIAPUTA P. and SALWICKA K. 1997. Tourism at Antarctic *Arctowski* Station 1991–1997: policies for better management. *Polish Polar Research* 18: 227–239.

CHWEDORZEWSKA K.J. 2008. *Poa annua* L. in Antarctic – searching for the source of introduction. *Polar Biology* 31: 263–268.

CHWEDORZEWSKA K., OLECH M. and KORCZAK M. 2008. Obcy w Antarktyce. *In*: A. Kowalska, A. Latocha, M. Marszałek and J. Pereyma (eds) *Środowisko przyrodnicze obszarów polarnych*. Wydział Nauk o Ziemi i Kształtowania Środowiska Uniwersytetu Wrocławskiego, Wrocław: 197–201. (in Polish)

CHOWN S.L. and AVENANT N. 1992. Status of *Plutella xylostella* at Marion I. six years after its colonization. *South African Journal of Antarctic Research* 22: 37–40.

CLARKE A., BARNES D.K.A. and HODGSON D.A. 2005. How isolated is Antarctica? *Trends in Ecology and Evolution* 20: 1–3.

CLARKE M.S., CLARKE A., COCKELL C.S., CONVEY P., DETRICH H.W., FRASER K.P.P., JOHNSTON I.A., METHE B.A., MURRAY A.E., PECK L.S., RÖMISCH K. and ROGERS A.D. 2004. Antarctic genomics. *Comparative and Functional Genomics* 5: 230–238.

COLLINS N.J. 1969. The effects of volcanic activity on the vegetation of Deception I. *British Antarctic Survey Bulletin* 21: 79–94.

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

CONVEY P. 1997. How are the life history strategies of Antarctic terrestrial invertebrates influenced by extreme environmental conditions? *Journal of Thermal Biology* 22: 429–440.

CONVEY P. 2000. How does cold constrain life cycles of terrestrial plants and animals? *Cryo-Letters* 21: 73–82.

CONVEY P. 2006. Antarctic climate change and its influences on terrestrial ecosystems *In*: D.M. Bergstrom, P. Convey and A.H.L. Huiskes (eds) *Trends in Antarctic Terrestrial and Limnetic Ecosystems: Antarctica as a Global Indicator*. Springer, Dordrecht: 253–272.

CONVEY P. and LEWIS SMITH R.I.L. 1993 Investment in sexual reproduction by Antarctic mosses. *Oikos* 68: 293–302.

CONVEY P. and LEWIS SMITH R.I.L. 2006. Responses of terrestrial Antarctic ecosystems to climate change. *Plant Ecology* 182: 1–10.

CONVEY P., CHOWN S.L., WASLEY J. and BERGSTROM D. 2006. Life history traits. *In*: D.M. Bergstrom, P. Convey, and A.H.L. Huiskes (eds) *Trends in Antarctic Terrestrial and Limnetic Ecosystems: Antarctica as a Global Indicator*. Springer, Dordrecht: 101–127.

CORTE A. 1961. La Primera Fanerógama Adventicia Hallada en el Continente Antártico. *Contribución del Instituto Antártico Argentino* 62: 14 p.

DAVIES K.F. and MELBOURNE B.A. 1999. Statistical models on invertebrate distribution on Macquarie I.: a tool to assess climate change and local human impacts. *Polar Biology* 21: 103–121.

DAVEY M.C., PICKUP J. and BLOCK W. 1992. Temperature variation and its biological significance in fellfield habitats on maritime Antarctic islands. *Antarctic Science* 4: 383–388.

DAY T., RUHLAND C. and XIONG F. 2001. Influence of solar ultraviolet-B radiation on Antarctic terrestrial plants: results from a 4-year field study. *Journal of Photochemistry and Photobiology B: Biology* 62: 78–87.

DORAN P.T., PROSCU J.C., LYONS W.B., WALSH J.E., FOUNTAIN A.G., McKNIGHT D.M., MOORHEAD D.L., VIRGINIA R.A., WALL D.H., CLOW G.D., FRISTEN C.H., McKAY C.P. and PARSONS A.N. 2002. Antarctic climate cooling and terrestrial ecosystem response. *Nature* 415: 517–520.

EDWARDS J.A. 1979. An experimental introduction of vascular plants from South Georgia to the Maritime Antarctica. *British Antarctic Survey Bulletin* 49: 73–80.

EDWARDS J.A. and GREENE D.M. 1973. The survival of Falkland Is transplants at South Georgia and Signy I., South Orkney Is. *British Antarctic Survey Bulletin* 34: 33–45.

ENZENBACHER D.J. 1994. Antarctic tourism: an overview of 1992/93 season activity, recent developments, and emerging issues. *Polar Record* 30: 105–116.

FRENOT Y., AUBRY M., MISSET M.T., GLOAGUEN J.C., GOURRET J.P. and LEBOUVIER M. 1999. Phenotypic plasticity and genetic diversity in *Poa annua* L. (Poaceae) at Crozet and Kerguelen Is (subantarctic). *Polar Biology* 22: 302–310.

FRENOT Y., CHOWN S.L., WHINAM J., SELKIRK P.M., CONVEY P., SKOTNICKI M. and BERGSTROM D.M. 2005. Biological invasions in the Antarctic: extent, impacts and implications. *Biological Review* 80: 45–72.

FRENOT Y., GLOAGUEN J.C., MASSÉ L. and LEBOUVIER M. 2001. Human activities, ecosystem disturbance and plant invasions in sub-Antarctic Crozet, Kerguelen and Amsterdam Islands. *Biological Conservation* 101: 33–50.

FOWBERT J.A. and LEWIS SMITH R.I.L. 1994. Rapid population increase in native vascular plants in the Argentine Is, Antarctic Peninsula. *Arctic and Alpine Research* 26: 290–296.

GREENE S.W. and GREENE D.M. 1963. Check List of the sub-Antarctic and Antarctic Vascular Flora. *Polar Record* 73: 411–418.

GREEN T.G.A., SCHROETER B. and SANCHO L.G. 1999. Plant life in Antarctica. *In*: F.I. Pugneres and F. Valladeres (eds) *Handbook of plant Ecology*. Basel, New York: 495–543.

GREMMEN N.J.M. and SMITH V.R. 1999. New records of alien vascular plants from Marion and Prince Edward Islands, sub-Antarctic. *Polar Biology* 21: 401–409.

GROBE C.W., RUHLAND C.T. and DAY T.A. 1997. A new population of *Colobanthus quitensis* near Arthur Harbor, Antarctica: correlating recruitment with warmer summer temperatures. *Arctic and Alpine Research* 29: 217–221.

GURNEY A. 1997. *Below the convergence, voyages toward Antarctica 1699–1839*. W.W. Norton and Company Penguin Books, New York: 315 pp.

HANSON J.D. and GORDON J.E. 1998. *Antarctic environments and resources: geographical perspective*. Addison Wesley Longman Ltd, Harlow Essex: 402 pp.

HEADLAND R.K. 1989. *Chronology list of Antarctic expeditions and related historical events*. Cambridge University Press, Cambridge: 730 pp.

HILL J. 1967. An experiment in growing salad vegetables at an Antarctic station. *British Antarctic Survey Bulletin* 13: 47–69.

HOLDGATE D.D. 1964. An experimental introduction of plants to the Antarctic. *British Antarctic Survey Bulletin* 3: 13–16.

HOSHIAI T. 1970. Willow cultivation at Syowa station. *Polar News* 5: 30–31.

HUGHES K.A., OTT S., BÖLTER M. and CONVEY P. 2006. Colonisation Processes. *In*. D.M. Bergstrom, P. Convey, and A.H.L. Huiskes (eds) *Trends in Antarctic Terrestrial and Limnetic Ecosystems: Antarctica as a Global Indicator*. Springer, Dordrecht: 35–54.

KANDA H., OHTANI S. and IMURA S. 2002. Plant communities at Dronning Maud Land. *In*: L. Beyer and M. Bölter (eds) Geoecology of Antarctic Ice-free coastal landscapes. *Ecological Studies* 154: 249–264.

KAPPEN L. and STRAKA H. 1988. Pollen and spores transport into the Antarctic. *Polar Biology* 8: 173–180.

KAPPEN L. and SCHROETER B. 2002. Plants and lichens in the Antarctic. *In*: L. Beyer and M. Bölter (eds) Geoecology of Antarctic Ice-free coastal landscapes. *Ecological Studies* 154: 327–373.

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

KITTEL P. 2004. The centenary of the beginning of commercial whaling in Antarctica. XXX International Polar Symposium Gdynia. 23–25. IX. 2004. *Polish Polar Studies*: 179–189.

LEWIS SMITH L.R.I. 1984. Colonization and recovery by cryptogams following recent volcanic activity on Deception I., South Shetland I. *British Antarctic Survey Bulletin* 62: 25–51.

LEWIS SMITH L.R.I. 1991. Exotic sporomorpha as indicators of potential immigrant colonists in Antarctica. *Grana* 30: 313–324.

LEWIS SMITH L.R.I. 1993. The role of bryophyte propagule banks in primary succession: case study of an Antarctic fellfield soil. *In*: J. Milesand D.W.H. and Walton (eds) *Primary succession on land*. Blackwell Scientific Publishing, Oxford: 55–77.

LEWIS SMITH L.R.I. 1996. Introduced plants in Antarctica: potential impacts and conservation issues. *Biological Conservation* 76: 135–146.

LEWIS SMITH L.R.I. 2001. Plant colonisation response to climate change in the Antarctic. *Folia Facultatis Scientiarium Naturalium Universitatis Masarykianae brunensis. Geographia* 25: 19–33.

LINDSAY D.C. 1971. Vegetation of the South Shetland Is. *British Antarctic Survey Bulletin* 25: 59–83.

LINSKENS H.F., BERGAGLI R., CRESTI M. and FOCARDI S. 1993. Entrapment of long-distance transported pollen grains by various moss species in coastal Victoria Land, Antarctica. *Polar Biology* 13: 81–87.

LONGTON R.E. 1966. Alien vascular plants on Deception I. South Shetland Is. *British Antarctic Survey Bulletin* 9: 55–60.

MARSHALL W.A. 1996. Biological particles over Antarctica. *Nature* 383: 680.

MARSHALL W.A. and Convey P. 1997. Dispersal of moss propagules in the maritime Antarctic. *Polar Biology* 18: 376–383.

MCGRAW J.B. and DAY T.A. 1997. Size and characteristics of a natural seed bank in Antarctica. *Arctic and Alpine Research* 29: 213–216.

MOORE D.M. and SLADEN W.J.L. 1965. Some recent records of native and alien flowering plants from the Falkland Is. *British Antarctic Survey Bulletin* 7: 29–35.

OCHYRA R. 1998. *The moss flora of King George Island Antarctica*. Polish Academy of Science. W. Szafer Institute of Botany, Cracow: 278 pp.

OCHYRA R., LEWIS SMITH L.R.I. and BEDNAREK-OCHYRA H. 2008. *The illustrated moss flora of Antarctica*. Cambridge University Press, Cambridge: 685 pp.

OLECH M. 1996. Human impact on terrestrial ecosystems in west Antarctica. *Proceedings of the NIPR Symposium on Polar Biology* 9: 299–306.

OLECH M. 2002. Plant communities on King George Island. *In:* L. Beyer and M. Bölter (eds) Geoecology of Antarctic Ice-free coastal landscapes. *Ecological Studies* 154: 215–231.

OLECH M. 2004. *Lichens of King George Island, Antarctica*. The Institute of Botany of the Jagiellonian University, Cracow: 391 pp.

ROBINSON S.A., TURNBULL J.D. and LOVELOCK C.E. 2005. Impact of changes in natural ultraviolet radiation on pigment composition, physiological and morphological characteristics of the Antarctic moss *Grimmia antarctici. Global Change Biology* 11: 476–489.

RUDOLPH E.D. 1966. Terrestrial vegetation of Antarctica: past and present studies. *In*: J.C.F. Tedrow (ed.) Antarctic soil and soil forming processes. *Antarctic Research Series* 8: 109–124.

RUHLAND C.T. and DAY T.A. 2000. Effect of ultraviolet-B radiation on leaf elongation, production and phenylpropanoid concentrations of *Deschampsia antarctica* and *Colobanthus quitensis* in Antarctica. *Physiologia Plantarum* 109: 244–251.

SLABBER S. and CHOWN S.L. 2002. The first record of a terrestrial crustacean, *Porcellio scaber* (Isopoda, Porcellionidae), from sub-Antarctic Marion I. *Polar Biology* 25: 855–858.

SKOTTSBERG C. 1954. Antarctic Vascular Plants. *Botanisk Tidsskrift* 51: 330–338.

STONEHOUSE B. 1994. Tourism and protected areas. *In*: R.I.L. Smith, D.W.H. Walton and P.R. Dingwall (eds) *Developing the Antarctic Protected Area System.* IUCN, Gland: 79–84.

STONEHOUSE B. 1999. Antarctic shipborne tourism: facilitation and research at *Arctowski* Station, King George Island. *Polish Polar Research* 20: 65–75.

TAYLOR G. 1913. The western journeys. *In*: L. Huxley (ed.) *Scott's last expedition*. Smith, Elder and Co., London: 182–290.

TØNNESSEN J. and JOHNSEN O. 1982. *The history of modern whaling*. C. Hurstand Company, Australian National University, Press London–Canberra: 798 pp.

TURNER J., COLWELL S.R. and HARANGOZO S. 1997. Variability of precipitation over the coastal western Antarctic Peninsula from synoptic observations. *Journal of Geophysical Research* 102 (D12): 13999–14007.

WALTON D.W.H. 1975. European weeds and other alien species in the sub-Antarctic. *Weed Research* 15: 271–282.

WASLEY J. 2004. *The effect of climate change on Antarctic terrestrial flora*. Ph.D Thesis. University of Wollongong: 200 pp.

WASLEY J., ROBINSON S.A., LOVELOCK C.E. and POPP M. 2006. Some like it wet – an endemic Antarctic bryophyte likely to be threatened under climate change induced drying. *Functional Plant Biology* 33: 443–455.

WHINAM J., CHILCOTT N. and BERGSTROM D.M. 2005. Sub-Antarctic hitchhikers: expeditioners as vectors for the introduction of alien organisms. *Biological Conservation* 121: 207–219.

WISE T. 1973. *Polar Exploration*. Almark Publishing Co Ltd, London: 167 pp.

XIONG F. and DAY T. 2001. Effect of solar ultraviolet-B radiation during springtime ozone depletion on photosynthesis and biomass production of Antarctic vascular plants. *Plant Physiology* 125: 738–751.

Chapters address both Antarctic terrestrial and marine ecosystems, and the scientific and management challenges of the future are explored. Â Parts of Antarctica are showing some of the largest changes in temperature and other environmental conditions in the world. In this volume, published in association with the Royal Society, leading polar scientists present a synthesis of the latest research on the biological systems in Antarctica, covering organisms from microbes to vertebrate higher predators.