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Review

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Terrestrial ecosystems of the Antarctic Peninsula and their responses to climate change and anthropogenic impacts

Abstract. Antarctica and the Southern Ocean are unique natural laboratories where organisms adapted to extreme environmental conditions have evolved in isolation for millions of years. These unique biotic communities on Earth are facing complex climatic and environmental changes. Terrestrial ecosystems in the Antarctic Peninsula Region (APR) have experienced the highest rate of climate warming and, being the most impacted by human activities, are facing the greatest risk of detrimental changes. This review provides an overview of the most recent findings on how biotic communities in terrestrial ecosystems of the Antarctic Peninsula Region (APR) are responding and will likely respond to further environmental changes and direct anthropogenic impacts. Knowledge gained from studies on relatively simple terrestrial ecosystems could be very useful in predicting what may happen in much more complex ecosystems in regions with less extreme temperature changes. The rapid warming of the APR has led to the retreat of glaciers, the loss of snow and permafrost and the increase of ice-free areas, with a consequent enhancement of soil-forming processes, biotic communities, and food web complexity. However, most human activity is concentrated in APR coastal ice-free areas and poses many threats to terrestrial ecosystems such as environmental pollution or disturbances to soil communities and wildlife. People who work or visit APR may inadvertently introduce alien organisms and/or spread native species to spatially isolated ice-free areas. The number of introduced non-indigenous species and xenobiotic compounds in the APR is likely to be greater than currently documented, and several biosecurity and monitoring activities are therefore suggested to Antarctic national scientific programs and tourism operators to minimize the risk of irreversible loss of integrity by the unique terrestrial ecosystems of APR.

Keywords: Antarctic Peninsula, anthropogenic impacts, climate change, terrestrial ecosystems

1 Introduction

The Antarctic Peninsula Region (APR) is a bedrock archipelago encompassing the western Antarctic Peninsula, the South Shetland, South Orkney and South Sandwich archipelagos, and the isolated islands of Bouvetøya and Peter 1 Øy. The APR extends northward from continental Antarctica to the sub-Antarctic (63° S) and such exceptionally wide latitudinal and climatic gradients make the region a unique environment on Earth with specific ecological characteristics (e.g. Neumann et al., 2019). However, unlike continental Antarctica, the mean annual temperature in some parts of APR has increased by 3 °C between the 1950s and 2000 and contributed to one of the fastest environmental changes globally. Despite a recent pause, the rising greenhouse gas concentrations raise concerns that APR will experience rapid warming again by 2100 (Turner et al., 2016). Furthermore, the seas surrounding the Antarctic Peninsula have been exploited (sealing, whaling, fishing and harvesting of birds including penguins) and impacted by human activities since the 18th century (Kock, 2007; Headland, 2009). During the last 100 years many scientific research stations and facilities have been established in the APR, providing simultaneous housing for a few thousand people in the summer and a few hundred in the winter. The first commercial cruises to Antarctica began in the late 1960s, and the number of tourists visiting the APR coastal sites grew from a few thousand to nearly 42,000 people landing in the austral summer 2017/2018 (IAATO, 2018); in addition, several thousand service staff and crew members usually travel along with tourists. As the Antarctic region is very close (about 1,000 km) to another continent with less extreme climatic conditions (South America), ongoing climate change and human activity (in APR and South America) are increasing the risk of environmental contamination (from local and remote sources of pollutants; e.g. Bargagli, 2005) and colonization of terrestrial ecosystems by non-indigenous species (Chown et al., 2012; Tin et al., 2014; Hughes et al., 2020).

After the establishment of international conventions and governance mechanisms such as CAMLR (Conservation of Antarctic Marine Living Resources, in 1982), the exploitation of marine resources is regulated through ecosystem-based management approaches. The Protocol on Environmental Protection to the Antarctic Treaty, in force since 1998, requires the assessment of the environmental impact for any kind of human activity and establishes specific forms of protection. However, despite this comprehensive management framework for environmental protection and conservation, the growing number of people travelling to APR (for visit or work) and the volumes of imported cargo increase the risk of environmental contamination and make more likely the introduction of non-native species (Frenot et al., 2005). Terrestrial and marine ecosystems in the APR have been under climatic and anthropogenic pressure for many years, but unfortunately relatively little is known about the ways they have responded and will continue to respond to these impacts. By providing a picture of the current state of knowledge of the structure and functioning of APR's terrestrial ecosystems and main environmental and biodiversity concerns, this review aims to highlight the most recent findings and research gaps to stimulate future ecological studies.

2 Results

2.1 Terrestrial ecosystems of maritime Antarctic

Antarctica is enormous and encompasses regions with very different climatic and environmental conditions. However, while the Southern Ocean contains very diverse and complex communities, those in terrestrial ecosystems are rather simple and have traditionally been ascribed to three ecological and biogeographic regions: Continental Antarctic, Maritime Antarctic, and sub-Antarctic (e.g. Smith, 1984). Air temperature, radiation and the availability of free water and nutrients are the most important factors promoting the development of terrestrial communities. Thus, the most diverse terrestrial ecosystems usually occur in milder coastal areas with nutrient inputs, especially from large breeding colonies of seabirds. In these areas photosynthetic activity is not restricted to bare grounds and a recent study combining remote sensing data with "in situ" measurements shows that nutrients from marine environments can also promote algal blooms with an important primary production also in coastal snowfields (Gray et al., 2020).

Compared to the continental zone and the east coast of the Peninsula, the APR has a milder climate (summer temperature around 0—3 °C and the annual average about –1.8 °C), with maritime influences and relatively higher amount of precipitation. Smith (1996) distinguished in the APR two geo-botanical regions: the Northern Province (extending from about 63° S to 68° S; with temperature usually >–10 °C in winter and 35–60 cm year^{-1} of water equivalent precipitation) and the Southern Province (from 68° S to about 73° S, air temperature in winter rarely <–15 °C and annual precipitation <35 cm). Due to the increasing aridity and the persistence of sea ice, which reduce nutrient input from the marine environment, the southernmost portion of APR has much less diverse terrestrial communities and has often been identified as a broad region of separation between Maritime

Antarctic and continental cold desert ecosystems (i.e. the Gressitt Line; Chown & Convey, 2007). Most Antarctic ice-free areas have a surface <1 km^2 and are separated (on a scale of meters to tens of kilometers) by sea, permanent ice or mountain ranges. Several taxa of terrestrial organisms have limited dispersal capability and often occupy spatially isolated and fragmented microhabitats in a single region or even single ice-free areas (e.g. the tardigrade *Mopsechiniscus franciscae* Guidetti, Rebecchi, Cesari & McInnes, 2014 inhabiting Crater Cirque in Victoria Land; Guidetti et al., 2014). Past and present environmental constraints and biotic processes underpinning the biodiversity and composition of Antarctic terrestrial communities are still poorly known and there is a growing awareness that the biogeography of Antarctica and its surrounding islands is more complex than previously thought. Halanych and Mahon (2018) argue that relatively recent processes such as glacial patterns are more important drivers of organism distribution than geological events in the Eocene and Miocene and that life history cycles probably have little influence on the structuring of genetic patterns. However, the fossil record and modern time-calibrated molecular phylogenies and population genetic studies are challenging the view that all Antarctic terrestrial life was driven to extinction at Neogene and Late-Pleistocene glacial maxima, and that the present biodiversity is due to the recent colonization of areas that have become ice-free at the beginning of Holocene. Evidence is accumulating that many species of Antarctic biota are not a subset of globally distributed taxa adapted to extreme environmental conditions, but they are the result of an ancient evolutionary history in isolation. Among Antarctic cyanobacteria and green algae there is a high number of endemic species and calibration of their phylogenies suggests that their evolution in Antarctica began 330 Ma ago (Vyverman et al., 2010). Several current species of lichens, nematodes, and microarthropods probably survived and diversified in isolated refugia for multi-million years and sometimes their distribution does not conform to the conventional pattern of decreasing diversity at increasing latitudes (e.g. Convey et al., 2008; Caruso et al., 2009; Green et al., 2011; Collins et al., 2020). If some terrestrial taxa show higher levels of diversity at more southern locations, it is likely that the composition of their assemblages is driven by local environmental factors (e.g. microhabitats, elevation and distance from the sea) and involves a balance between processes operating over short time scales (e.g. dispersal, colonization, motility and reproduction, biotic interactions and extinction due to changes in geophysical and climatic conditions) and factors operating over longer time scales such as historical glacial events, geographic barriers, speciation and extinction processes. Physical stressors such as low temperature, high winds, desiccation and UV radiation combined with physical isolation and geographical barriers strongly limit inter- and intra-ecosystem connectivity and underlie the high levels of endemicity in Antarctic communities (Chown et al., 2015). Moreover, although it is widely accepted that Antarctic terrestrial communities are abiotically driven, with biotic interactions playing a minor role, studies on microarthropod communities of moss-turf habitats in the APR and on three nematode species dominating the soil food web of the McMurdo Dry Valleys have suggested that biotic interaction might be an important factor in soil meta-community dynamics (Caruso et al., 2013; Caruso et al., 2019). Thus, by combining a number of recognized environmental domains, expert consultation and multivariate analyses of data on various taxonomic groups, 16 Antarctic Conservation Biogeographic Regions (ACBRs) have been delineated (Terauds et al., 2012; Terauds & Lee, 2016). These bio- or ecoregions reflect the most current representation of Antarctic terrestrial ecosystems and were endorsed at the XXXV Antarctic Treaty Consultative Meeting as a tool for a better understanding, conservation, management and policy of Antarctic ice-free areas. ACBRs are currently used for spatial analysis of biodiversity (e.g. Chown et al., 2015) and to assess current levels of area protection (e.g. Hughes et al., 2016), and they are included in new plans for proposed Antarctic Specially Protected Areas (ASPAs). The Maritime Antarctic contains 4 ACBRs (the South Orkney Islands, North-east Antarctic Peninsula, North-west Antarctic Peninsula, and Central South Antarctic Peninsula). This review will mainly focus on terrestrial ecosystems on the western coast of the mainland Peninsula and offshore islands, from Hope Bay in the north to Alexander Island in the south (i.e. ACBR 2, 3 and 4; Table). In general, compared to all other Antarctic ecoregions, those in the APR have smaller mean areas and higher annual mean temperatures. Thus, South Shetland Islands and South Orkney have a discontinuous permafrost (less than 100 m deep, with a depth of the seasonal thaw layer ranging from 1.0 to 2.0 m), whereas in the Dry Valleys (East Antarctica) permafrost is continuous, with a depth >1,000 m and the active layer's depth ranging from 0.5 to 1.0 m (Bockheim & Ugolini, 1990).

The greater availability of liquid water promotes chemical weathering processes on exposed metamorphic and volcanic rocks predominating in the APR, leading to the formation of clay-sized materials and rather evolved soils, with reduced amount of salt encrustations compared to those in cold desert ecosystems (e.g. Bargagli, 2005). Soils comparable to brown soils may occur in small areas on northfacing slopes where temperature, moisture and nutrient availability allow the development of vascular plants. At Admiralty Bay (King George Island), for instance, Bölter et al. (1997) found that solifluction, cryoturbation and ice segregations on basic volcanic rocks contribute to the formation of a variety of soils such as cambisols, umbrisols, regosols, podzols, leptosols and gleysols. In general, most soils have a low content of organic matter, but pads of humus can develop beneath isolated plant cushions at poorly drained sites and peat-like materials can accumulate under moss turfs. Roberts et al. (2009) found that the two native Antarctic vascular plant species, *Deschampsia antarctica* E. Desv. 1837 and *Colobanthus quitensis* (Kunth) Bartl. 1831 (which have been expanding rapidly over the past decades), affect the cycling of C and N in soil much more significantly than mosses and lichens. Along the APR, continental shelf nutrients feed large blooms of phytoplankton that sustain Antarctic krill, which is subsequently consumed and excreted by numerous marine vertebrates that breed and/or moult in coastal areas. Myrcha and Tatur (1991) estimated that Adélie and chinstrap penguins deposit annually about 200 million kg of C and 20 million kg of P in Maritime Antarctica rookeries. Thus, ornithogenic soils have lower pH and base saturation and very high concentrations of organic C (>4%), N (>2%) and P (>1%) compared to the other Antarctic soils. In cold polar desert the deposition of guano has little influence on alteration of silicate minerals (Bockheim & Ugolini, 1990), but under APR climatic conditions the intense cryoturbation and water percolation leach the guano into the subsurface with the formation of clay minerals and secondary phosphate minerals. From areas with direct impacts from manure, nutrients can return to the sea through water solutions and contribute to the productivity of coastal marine ecosystems, or they can spread inland by wind erosion and ammonium volatilization. Bokhorst et al. (2019) studied the terrestrial N footprint size of penguin colonies along APR coasts and found that N inputs and $\delta^{15}N$ signatures from marine vertebrates can spread kilometers from colony borders. Nutrients from marine vertebrates influence so strongly microbial processes and the diversity of terrestrial communities that Bokhorst and colleagues believe that changes in the distribution of penguins and elephant seals due to climate change or anthropogenic disturbance will have greater impact on terrestrial biodiversity patterns than the increase in temperature and water availability.

Table. Summary statistics for ACBRs 2, 3 and 4 (data from Terauds & Lee, 2016)

ACBR	Total area (km^2)	Mean area (km^2) of each ice-free site	Mean altitude (m)	Mean annual T (°C)	Areas of ASPA in ACBR (km^2)	Number of stations or permanent infrastructure
2.South Orkney Islands	160	1.52	21.0	–3.2	4.8	2
3.North-west Antarctic Peninsula	5183	1.00	572.2	–6.9	103.1	38
4.Central South Antarctic Peninsula	4986	1.09	911.8	–11.6	77.4	1

2.2 Biodiversity of terrestrial communities

The APR's indigenous flora comprises two phanerogams (*D. antarctica* and *C. quitensis*), 250 species of lichens, 125 of bryophytes, and several liverworts, macro-algae, cyanobacteria and higher fungi (e.g. Smith, 1996; Øvstedal & Smith, 2001). The terrestrial fauna consists of one vertebrate (a scavenger bird associated with penguin and marine mammals colonies: the sheathbill *Chionis albus* Gmelin, 1789), two species of chironomid midges (Diptera), 46 of microarthropods (Acari and Collembola) and many meiofaunal invertebrates such as Tardigrada (26 species), Protozoa, Nematoda (>200 species), and Rotifera (>50 species) (Convey, 2013; and references therein). The number of terrestrial species of eukaryotes decreases progressively at increasing latitude or altitude and microbial communities become increasingly dominant as the severity of environmental conditions increases. Different species of bacteria and fungi are morphologically indistinguishable and although considerable progress has been made in recent years using 16S rRNA gene sequences as phylogenetic markers, the understanding of their diversity, dispersal mechanisms and colonization patterns in Antarctic ice-free areas is largely inadequate. However, as suggested by Chong et al. (2015) at spatial scales such as that of APR, prokaryotic communities are mainly affected by local physico-chemical parameters, whereas at scale >1000 km the dispersal limitation and historical speciation probably play stronger influences. Studies based on modern deep sequencing techniques show that the strong separation existing between plant, algae and soil invertebrate communities in the APR and those in the remainder of the continent (i.e. "the Gressitt Line") applies also to Antarctic microbial communities. Thus, in Antarctic Conservation Biogeographic Regions prokaryotic and eukaryotic communities are probably affected in their evolutionary differentiation and biogeography by the same abiotic and biotic factors (e.g. Chong et al., 2015, and references therein). At higher phylogenetic levels (phylum or class), the Antarctic microbiome shows some similarities to bacterial isolates from soil of tropical and temperate regions with a widespread distribution of eurythermal mesophiles. However, when compared with close representatives of other desert habitats, cold-adapted Antarctic bacteria species form distinct and specific mono- and/or paraphyletic clusters. Furthermore, communities in APR soils are dominated by taxa affiliated with Alpha proteobacteria and Actinobacteria with few Bacteriodetes, while soils from the Ellsworth Mountains (continental Antarctica) show a reverse pattern (Yergeau et al., 2007); and Peeters et al. (2012) found that in bacterial culture collection developed from APR and continental soil samples, only a small percentage (3.4%) of total isolates were common to more than one site. Thus, the decomposition of organic matter and the energy flow in Antarctic terrestrial ecosystems is supported by highly diverse and region-specific bacterial communities, including those in extreme and less studied habitats such as hypo- and endolithic environments (Cowan et al., 2010). Despite its extreme conditions, even permafrost is an important microhabitat for bacteria, for spores or other resistant structures of fungi allowing them to survive in dormant state for many years (Jansson & Taş, 2014). In Antarctic ice-free areas, fungi are the dominant generalist decomposers and play many other important roles as mycobiont partners in lichen symbiosis, by forming arbuscular mychorrizae on roots of the grass *D. antarctica* and mycorrhiza-like associations on liverworts. More than 70 species of fungi have been reported from the Antarctic permafrost (e.g. Zucconi et al., 2012) and a recent survey at some Maritime Antarctic islands (da Silva et al., 2020) recovered in soils 213 viable fungal isolates (27 taxa) from the permafrost and 351 (31 taxa) from the active layer. There was an indication of potential new species, including some genetically close to *Pseudogymnoascus destructans* (Blehert&Gargas) Minnis&D.L. Lindner, 2013 which can cause extinction of bats in Eurasia and North America. Considering the potential melting of permafrost in the APR there is a need of further studies on the diversity of extremophiles and their potential capability to expand from permafrost to other habitats in and out of Antarctica.

2.3 Climatic and environmental changes

The most significant factors for the development and functioning of APR terrestrial ecosystems such as air temperature, snow and ice melting, water availability and the dynamics of permafrost, ice shelves and colonies of marine vertebrates are experiencing macroscopic changes. With an increase over the past 50 yrs of more than 3.0 °C in mean annual temperature and more than 6.0 °C in mid-winter temperature, the APR is a "hotspot" of the world's climate warming. This strong warming trend is underlain by regional rather than global processes and it has paused since around the 2000, however, it will likely resume (e.g. Turner et al., 2016). To the west of APR, the Bellingshausen Sea temperature increased by 1 °C (Meredith & King, 2005) between 1950 and 2000 and continuous satellite observations (which began in late 1978) have shown a decrease in sea-ice duration and coverage of about 40%. Despite the recent pause in air temperature increases, ice shelves and coastal glaciers are still receding (e.g. Cook et al., 2016) enhancing the influence of the marine environment on terrestrial ecosystems. Along the APR the sea-ice cover has declined by as much as 90 days and satellite color imagery has shown that in the northern portion of the peninsula phytoplankton blooms decreased by up to 90% in 1998—2006 with respect to the 1978—1986 baseline (Montes-Hugo et al., 2009). The Antarctic krill (*Euphausia superba* Dana, 1850) is strongly dependent on sea-ice and the reduced availability of sea-ice, together with exploitation probably contributed to its regional decline and to the increase of non-palatable gelatinous salps, which prefer warmer and more ice-free waters of the Southern Ocean (Atkinson et al., 2004). Although long-term trends in zooplankton along APR are still unclear, the reduced availability of krill and sea-ice cover can affect populations of upper levels trophic consumers. In the northern APR for instance, Adélie penguins have declined by over 80% since 1975 (Fraser et al., 2013) and in the same period populations of some subpolar species such as gentoo penguin and Humpback whales have increased (Obryk et al., 2016).

By using a temperature-index melt modeling and IPCC (Intergovernmental Panel on Climate Change) climate forcing scenarios, Lee et al. (2017) estimated that melt across Antarctica will lead to nearly 25% increase of ice-free areas by the end of this century. More than 85% of new exposed grounds will emerge in the Antarctic Peninsula, with an almost threefold increase of total ice-free areas in the North West Antarctic Peninsula and the ice disappearance from South Orkney Islands. Antarctic terrestrial biota is well adapted to highly variable and stressful environments and in the absence of long-range colonization by competitors, resident communities will probably take advantage of increasing temperature and water availability. In the APR there is abundant evidence of biological responses to climate amelioration such as the rapid local expansion of higher plants and the rapid colonization by plants and animals of new grounds exposed by receding snow and ice. In general, changes in the extent and distribution of ice-free areas could increase biodiversity, but can also allow the spread of invasive species destabilizing the equilibrium of ecological communities. Moreover, if single patches of ice-free areas coalesce, the increased habitat connectivity can promote genetic homogenization and loss of genetic diversity.

Permafrost is a sensitive indicator of climate change and in Antarctica the boundary between continuous and discontinuous permafrost corresponds to mean annual air temperature isopleths of –8 °C and –1 °C, respectively (Bockheim, 1995). In the Antarctic Peninsula the warming has resulted in historical degradation of permafrost: by using five different approaches Bockheim et al. (2013) have found that permafrost is discontinuous in the South Shetland Islands, occurs sporadically in the Palmer Archipelago and Biscoe Islands, and becomes continuous only on Alexander Island (71—74° S). Prior to 1980 at Palmer station the occurrence of permafrost in organic soils was reported at depths of 25—35 cm, but recent measurements suggest that it is absent or close in temperature to 0 °C in the upper 14 m of the highest ice-free areas (Bockheim et al., 2013). Permafrost is susceptible to rapid thawing when its temperature ranges from –0.4 to –3.1 °C and Bockheim et al. (2013) measured values in this range in the South Shetland Islands and at Adelaide Island. Thus, many ice-free areas in the APR are experiencing a progressive increase in active-layer thickness with serious implications for terrestrial ecosystems such as frost creep and heaves, landslides, solifluction, gelifluction and hydrological changes.

Impact of human activity

Visiting or working in Antarctica may have a number of impacts on terrestrial ecosystems. Some impacts such as the construction and use of infrastructure are difficult to reverse, others are difficult to monitor and can remain undetected for long periods (e.g. the effects of noise and human interactions with wildlife, the impact of trampling or vehicle driving on soil communities, the unintentional introduction and spread of microorganisms or seeds and propagules of non-native species through food, personal clothing or cargo) (e.g. Woehler et al., 2014). The number of truly pristine and unvisited Antarctic ecosystems is progressively decreasing and this reduces the availability of control sites for future evaluation of the effects of climate change and human activities in Antarctica (e.g. Cowan et al., 2011). While several anthropogenic impacts remain largely unidentified or rarely evaluated, those due to the occurrence and bioaccumulation of persistent contaminants such as heavy metals, Polycyclic Aromatic Hydrocarbons (PAHs), Polychlorinated biphenyls (PCBs), Dichlorodiphenyltrichloroethane (DDT) and other chlorinated pesticides are relatively well known (e.g. Bargagli, 2005; 2008; Tin et al., 2014; Cabrerizo et al., 2016, and references therein). Although Antarctica is the most remote continent and protected from the inflow of lower latitude water and air masses by oceanic and atmospheric circulation (e.g. Bargagli, 2005), most of these contaminants come from other continents. Pesticides were neither produced nor applied in Antarctica, but DDT and its congeners were detected in Antarctic marine organisms as far back as the 1960s (Sladen et al., 1966) and since then many other Persistent Organic Pollutants (POPs) such as PCBs, HCB (Hexachlorobenzene), HCHs (Hexachlorocyclohexanes), aldrin, dieldrin, chlordane and heptachlor have been found in biotic and abiotic matrices from marine and terrestrial ecosystems (e.g. UNEP, 2002). Under ambient temperature many POPs can volatilize into the atmosphere where they are unaffected by breakdown reactions and, through repeated volatilization-condensation-deposition cycles, can be redistributed globally (Wania & Mackay, 1995). In polar regions POPs condense and settle out and the low temperature blocks their evaporation, thus producing relatively high environmental concentrations and their biomagnification along aquatic food chains, potentially threatening the health of top-predators such as marine birds and mammals. In contrast to other heavy metals emitted by anthropogenic and natural sources (in Antarctica and the Southern Hemisphere) and usually associated with atmospheric aerosols, Hg occurs in the atmosphere as gaseous elemental Hg° which has a long lifetime (from months to more than one year). Once the metal is deposited on terrestrial and aquatic ecosystems, it can be re-emitted into air assuming the characteristics of global pollutants such as POPs. By biomonitoring Hg with epilithic lichens in costal ice-free areas of northern Victoria Land, an unexpected accumulation of the metal was found in samples collected around the Nansen Ice Sheet (Bargagli et al., 1993). At that time it was impossible to explain why lichens from a remote and pristine area had Hg contents in the same range as those measured in samples from polluted environments in the Northern Hemisphere. Some years later, Schroeder et al. (1998) described in Arctic coastal sites the springtime depletion of Hg°, due to photochemical reactions with bromine compounds. Terrestrial ecosystems in the Nansen Ice Sheet face the Terra Nova Bay coastal polynya and ice crystals ("frost flowers") growing in the polynya are a source of sea salt aerosols and bromine compounds, which at the spring sunrise, oxidize Hg° determining an enhanced Hg^{++} deposition in coastal terrestrial ecosystems (Bargagli et al., 2005). Therefore, in view of the increasing anthropogenic emissions of Hg in many countries of the Southern Hemisphere and the decrease in sea ice coverage, several ice-free coastal areas in the APR could become important sinks in the global Hg cycle.

Organic and inorganic contaminants are transported to Antarctica through marine and especially atmospheric pathways and as a rule their concentrations are higher in sub-Antarctic islands and the Antarctic Peninsula than in the continent. Concentrations of most "legacy POPs", Pb and other heavy metals in Antarctica show a general decreasing trend (e.g. Wang et al., 2019) and their levels in most Antarctic organisms are usually lower than those documented to have significant biological effects on related species in temperate and Arctic regions. However, a large proportion of Antarctic organisms are endemic and have unique ecophysiological characteristics resulting from a long evolutionary history in isolation, so they may be more stressed and more vulnerable to the toxicity of persistent contaminants than related species on other continents. Moreover, a number of contaminants of emerging interest are detected in Antarctic ecosystems and recently microplastic fragments, which are becoming an overwhelming global environmental issue in marine ecosystems, have been found in the gut of collembolans from the shores of the Fildes Peninsula (King George Island; Bergami et al., 2020).

Although the Protocol on Environmental Protection to the Antarctic Treaty establishes the principles for planning and conducting all activities in Antarctica, localized environmental impacts due to the combustion of fossil fuels (for transportation and energy production) and waste incineration are inevitable. Fuel oil spill, especially in areas for refueling aircrafts and vehicles, scattered rubbish or emissions from incinerators, generators and vehicles, are among the most widespread sources of pollutants generating local hotspots of environmental contamination near scientific stations. Most of the stations and sites visited by tourists are in coastal areas where large amounts of wastewaters are discharged into the sea. Over 30% of the permanent bases and 60% of those operating in the summer lack wastewater treatment plants and where the plants have been installed they often show operational problems and malfunctions (Gröndahl et al., 2009). Environmental monitoring in terrestrial and marine ecosystems near scientific stations has historically focused on heavy metals, polycyclic aromatic hydrocarbons (PAHs) and legacy POPs, but in recent years, especially in the APR, many others emerging contaminants related to human presence were identified, which can pose significant risks to the environment and wildlife (e.g. Esteban et al., 2016; Gonzáles-Alonso et al., 2017). Using available data from water bodies in the north of APR, Olalla et al. (2020) assessed the environmental risk posed by 54 emerging contaminants (drugs/medicines of abuse, endocrine disruptors, perfluorinated compounds, pyrethroids and sunscreens) and suggested closer monitoring of them by environmental protection bodies.

2.3 Responses of biotic communities

Future temperature trends in APR are uncertain, however recent warming, glacier retreat, increased precipitation and length of melt season, are driving significant changes in terrestrial ecosystems. Amesbury et al. (2017), for instance, by studying plant and microbial materials stored in moss bank cores, collected along a 600-km transect from Green Island (65.3° S) to Elephant Island (61.1° S), found that during the past ca. 50 years there has been a widespread (4 to 5-fold) increase in moss growth and abrupt changes in microbial populations. The diversity and biomass of prokaryotic communities in APR is increasing (e.g. Newsham et al., 2016) with positive effects on soil formation processes and the biogeochemical cycle of essential macro- and micronutrients. Thawing of permafrost and the increasing depth of the active layer might also contribute to increase the biological activities of microbial communities and the bioavailability of essential elements. Although the formation of the ozone hole over Antarctica can limit the development of primary producers (which must synthesize UV-B absorbing compounds), ameliorated climatic and environmental conditions are promoting the growth and expansion of communities of algae, cyanobacteria, mosses, lichens and vascular plants in most APR terrestrial ecosystems. The growth of prokaryotic, cryptogamic and vascular plants is likely increasing the role of APR soils as a carbon sink and the enhanced development of primary producers will positively affect the abundance, biodiversity and biomass of soil invertebrates and the complexity of soil food webs (Nielsen & Wall, 2013). The germination of propagules residing in soils, melting snow and ice contributes to the colonization of new microhabitats by cryptogams and the two native species of vascular plants (e.g. Golledge et al., 2010; Cannone et al., 2017). On Signy Island, for instance, over the past 50 years, *D. antarctica* and *C. quitensis* have increased in the number of sites occupied (104%

and 35%, respectively) and in percent coverage (191% and 208%, respectively; Cannone et al., 2016). On analyzing the role of climate, permafrost and biotic factors underlying these changes and the spatial heterogeneity of biological responses, these Authors highlighted the large increase in fur seals, which exert a negative impact on vegetation below 20 m a.s.l., but with their nutrients favor considerable development of plants between 20–60 m a.s.l. Although vegetation is usually limited in the immediate vicinity of penguin and seal colonies, primarily as result of trampling, Bokhorst et al. (2019) show that nitrogen inputs from APR colonies can increase abundance and richness of terrestrial invertebrates up to many kilometers inland, and the spatial distribution of colonies allows to predict the location and size of Antarctic terrestrial hotspots. By using molecular techniques, Clucas et al. (2014) evaluated the demographic history of Pygoscelis penguins in the Scotia Arc and found that southern gentoo penguins are expanding their range southwards (just as they did during the Last Glacial Maximum warming), whereas Adélie and chinstrap penguins are declining in the APR. Thus, demographic changes in seals and penguin colonies throughout APR is another important local factor affecting the distribution and development of soil ecosystems.

Biodiversity has been less affected by human presence in Antarctica than elsewhere, however, among fragile Antarctic terrestrial ecosystems those in the APR are at the highest risk. As APR is the closest region to another continent, the least climatically extreme and with the greatest climatic and anthropogenic impacts, the biotic communities in expanding ice-free areas are particularly exposed to natural or anthropogenic introduction of alien species. Moreover, the combined increase of connectivity between distinct ice-free areas on one side and human activities on the other can contribute to the redistribution of indigenous Antarctic species and to the genetic homogenization of biotic communities. According to Convey and Peck (2019), since the first human contact with APR (around 200 years ago) there has been no known example of natural immigration of new species, while there currently are an increasing number of non-native organisms inadvertently introduced by humans, especially in the vicinity of research stations and visitor sites (Hughes et al., 2020). Heated soils in geothermal areas allow many organisms to thrive in conditions that are unusual in Antarctica and represent the most favorable habitat for alien species (e.g. Bargagli et al., 1996; 2004). In the APR, Deception Island is one of the most frequently visited sites by tourists and researchers and its volcanic heated ground hosts the highest number of introduced and established non-native species. Through a long-term monitoring Enriquez et al. (2019), for instance, recorded six non-native species of collembolans.

In the Arctic and high altitude regions there are several pre-adapted species possessing dispersive capability enabling them to exploit, alongside or in competition with the native counterparts, climatically suitable Antarctic ice-free areas. For instance, propagules of the globally invasive grass *Poa annua* L., 1753 have been independently introduced onto King George Island from Europe and from South America. Moreover, like the flightless chironomid midge *Eretmoptera murphyi* Schaeffer, 1914 (accidentally introduced on Signy Island from South Georgia), *P. annua* has the potential to spread southwards along the APR (e.g. Pertierra et al., 2017).

3 Concluding remarks and perspectives

Antarctica is a unique natural laboratory to study relationships between genome functions and ecophysiology of organisms evolved in isolation, in an extreme environment. In this context, the native biodiversity and integrity of APR terrestrial ecosystems are very important, because they are unique on Earth, having intermediate ecological characteristics between those in continental cold deserts and sub-Antarctic islands. In recent decades, the Antarctic Peninsula has been one of the regions on Earth experiencing the highest rate of climate warming and environmental changes. Although most of the public and scientific attention has been drawn to the spectacular collapse of ice sheets such as the Wordie Ice Shelf and the Larsen Ice Shelf, rapid warming on land has led to the retreat of glaciers, the loss of snow and permafrost and

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a threefold increase in ice-free areas. Ameliorated climatic and environmental conditions are promoting the development and expansion of soil communities of prokaryotes, primary producers and soil invertebrates with an increase in soil formation processes and food web complexity. Studies of these changes can provide insights into the early responses of terrestrial ecosystems to rapid warming, and the knowledge gained will be very useful in predicting what could happen in much more complex terrestrial ecosystems in regions with less extreme temperature changes. Unlike the other Antarctic Conservation Biogeographic Regions (ACBRs), those in the APR are close to another continent and are the most affected by anthropogenic impacts. Human activities are mainly concentrated in APR coastal ice-free areas and pose many threats to terrestrial ecosystems, over and above those associated with climate changes. Ships, research stations, travel activities and logistic support for remote operations produce environmental pollution, damage soil communities, disturb wildlife and through the dispersion of dust affect the albedo of surface snow. The "human footprint" is not assessed in Antarctica (e.g. Brooks et al., 2019); however, the recovery from vehicle tracks and disturbances to local land flora and fauna may require many decades. Furthermore, some recent surveys show that in addition to heavy metals, PAHs and legacy POPs, many other contaminants of emerging ecotoxicological interest are released around scientific stations. Although some bioremediation approaches have been developed for sites polluted by oil spills (the most widespread pollutant in Antarctic soils) (e.g. de Jesus et al., 2015) it is necessary that environmental protection bodies prevent, reduce and monitor all impacts, including those of contaminants of emerging interest.

Visitors, scientists and logistic personnel can inadvertently introduce propagules of alien organisms into terrestrial ecosystems through clothing, personal equipment, food and vehicles, or they can spread native species across spatially isolated ice-free areas. In general, there is little understanding of the arrival and establishment of non-native organisms in Antarctica; however, among the seeds reaching Antarctica there are plant species known as invaders of cold climate regions (e.g. Chown et al., 2012). Moreover, the growing number of non-native species of soil invertebrates recorded at highly visited ice-free sites such as Deception Island suggests that the actual rate of introduction in the APR is probably greater than currently documented. The legislation applying within the Antarctic Treaty Area to prevent the establishment of non-indigenous species does not adequately protect Antarctic biological assemblages (Hughes & Convey, 2010). Therefore, national Antarctic scientific programs and tourism operators need to minimize the risk of irreversible biodiversity loss by adopting higher biosecurity standards and by monitoring the effectiveness of measures adopted.

Seabirds and marine mammals are the major exchangers of nutrients between marine and terrestrial Antarctic ecosystems. Although the excrements can affect the Earth's climate through the emission of N_2O, CO_2, CH_4, and especially NH_3, nutrients in coastal ice-free areas promote the development and biodiversity of terrestrial ecosystems. Climatic and environmental change affect the distribution and size of marine vertebrates colonies along APR coasts (e.g. the expansion of Antarctic fur seal and gentoo penguin colonies and the decline of colonies of Adélie and chinstrap penguins) and studies on the dynamics of marine vertebrate colonies will be necessary to predict possible effects on terrestrial communities.

In conclusion, Antarctica being dedicated to science and peace, many biosecurity and monitoring procedures must be endorsed by the Antarctic Treaty Nations to reduce the risk of irreversible loss of biodiversity and before ongoing and future research in these unique terrestrial ecosystems are compromised.

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Наземні екосистеми Антарктичного півострова
та їх відгук на кліматичні зміни і антропогенний вплив

Реферат. Антарктика й Південний Океан — унікальні природні лабораторії, де організми, пристосовані до екстремальних умов існування, еволюціонували в ізоляції мільйони років. Ці унікальні угруповання постали перед складними кліматичними та іншими змінами довкілля. Наземні екосистеми Району Антарктичного Півострова (APR) переживають найшвидші темпи потепління клімату, а також найбільше ризикують зазнати руйнівних змін, оскільки саме там найсильніше проявляється присутність людини. Ця робота надає огляд найновіших розвідок про сучасну, а також ймовірну подальшу реакцію біотичних угруповань наземних екосистем APR на зміни довкілля та прямі антропогенні впливи. Знання, здобуті при вивченні відносно простих наземних угруповань, можуть виявитися дуже корисними при передбаченні розвитку подій у значно складніших екосистемах регіонів з не такими різкими змінами температурного режиму. Швидке потепління в APR призвело до відступу льодовиків, скорочення снігового покриву в районах багаторічної мерзлоти, збільшення областей, вільних від криги з наступним підсиленням ґрунтотвірних процесів, біотичних угруповань та складності трофічної мережі. Однак, більшість людської активності сконцентрована в APR у прибережних ділянках, вільних від криги, і представляє численні ризики наземним екосистемам, такі як забруднення середовища чи порушення ґрунтових угруповань та дикої природи взагалі. Люди, що працюють чи відвідують APR, можуть, не бажаючи того, занести в регіон видиінтродуценти та/або розповсюдити місцеві види в ізольовані ділянки, вільні від льоду. Кількість інтродукованих немісцевих видів та ксенобіотичних речовин в APR, імовірно, більша за описану наразі; через це туроператорам та керівним структурам національних антарктичних наукових програм було запропоновано низку моніторингових та природоохоронних заходів для мінімізації ризику незворотної втрати цілісності унікальних наземних екосистем APR.

Ключові слова: Антарктичний півострів, антропогенні впливи, зміни клімату, наземні екосистеми