

Antarctic Microorganisms: Biodiversity Hiding in Plain Sight

*Jill: Daddy, when I grow up I want to be an explorer, discover hidden worlds!
Daddy: well, I think it would be interesting for you to become a microbiologist
and go to Antarctica – there is sooooo much to see... and uncover!*



Panoramic view of Potter Cove with the Fourcade Glacier on the background during the austral summer. King George Island (Isla 25 de Mayo), South Shetland, Antarctica, 62°14.27'S 58°39.87'W. Photo: Cecilia G. Flocco (CC BY-NC-ND 2.0)

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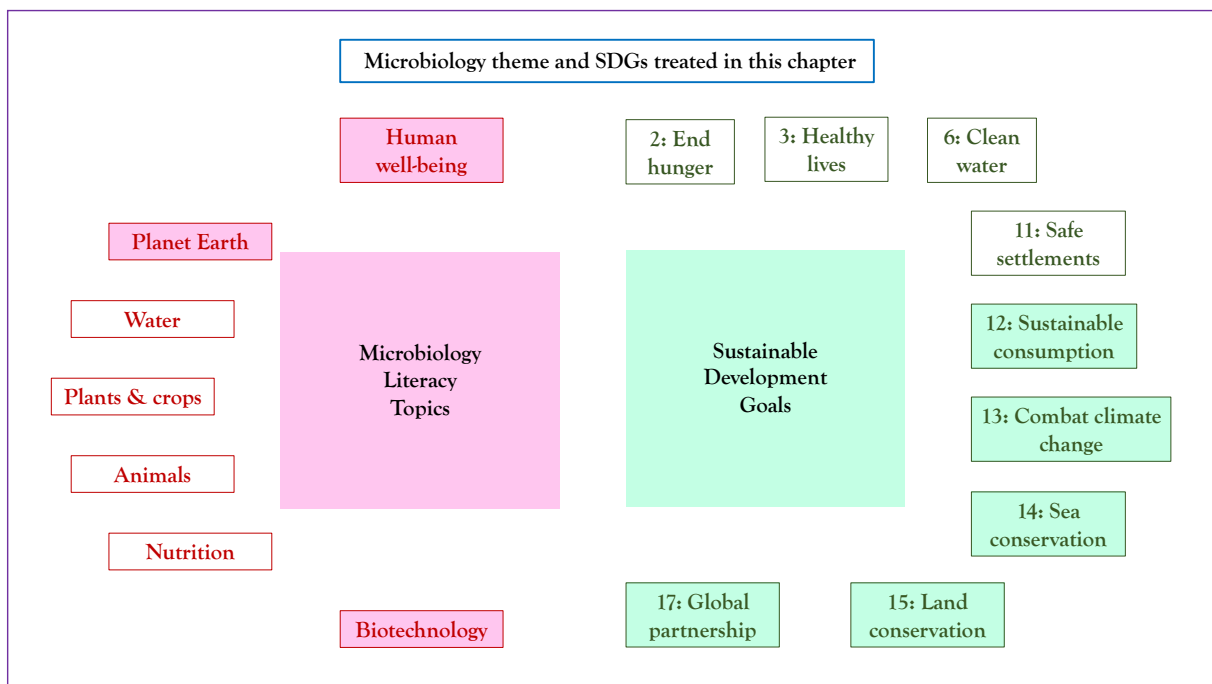
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Antarctic Microorganisms

Storyline

Among the Earth's polar regions, Antarctica is perhaps the one less known to students, and the general public, due to its geographical isolation from other land masses, restricted access, and lack of permanent human settlements. Therefore, Antarctica is usually perceived as more distant and disconnected from 'everyday life' taking place on the rest of the continents, in comparison with the Arctic, and less likely to be impacted by lifestyle choices and activities taking place on the populated regions of the world. However, the Antarctic region has a profound effect on human and environmental wellbeing at a planetary scale, due to its role in the circulation of the Earth's water masses and temperature regulation and the provision of bioresources. In turn, human activities can have direct and indirect impacts on Antarctica and its ecosystems, in spite of the perceived isolation of the region.

Antarctica holds record numbers for several environmental extremes: it is on average the coldest, driest, highest, windiest and southernmost continent on Earth. Under such poly-extreme environmental conditions, most forms of macroscopic life (organisms we can see with our eyes) found on temperate lands of the planet do not stand a chance to survive. However, Antarctica is home to a multitude of invisible microorganisms very well adapted to the prevailing environmental conditions, and such microbes constitute the dominant terrestrial forms of life. The communities of microbes living in Antarctica play a key sustainability role at both the local level and beyond the Antarctic boundaries, through the provision of ecosystem services on site and as source of unique bioresources of industrial and biotechnological interest. Antarctica constitutes a harsh and at the same time fragile region of Earth and a place of incredible biodiversity and beauty that must under all circumstances be preserved for current and future generations. Antarctic microbial communities are a central component of interdisciplinary research and conservation efforts.



The Microbiology and Societal Context

The microbiology: planetary and human well-being; environmental pollution; anthropogenic impact, microbial biodiversity and bioresources, extremophiles, cold-adapted microorganisms, biotechnology. *Sustainability issues:* healthy environments; environmental pollution remediation; global environmental change, biodiversity and ecosystems conservation; bioresources and human well-being (health, food, industrial processes), global partnerships. In addition, *rounding up the storyline:* Antarctica and its bio-geographical and physical features, the commons and management of environmentally protected areas, science diplomacy and international partnerships.

Antarctica and its unique features

1. ***The Antarctic region.*** The Antarctic is a hostile, essentially uninhabited and geographically isolated region in the Southern Hemisphere, comprising the continent, with the peninsula and islands, and the circumventing Southern Ocean waters. The boundaries of the Antarctic region are defined by the Antarctic Convergence, a wavy frontline built by the cold Antarctic waters expanding towards the north meeting the warmer waters of the Earth's oceans system. The region's dominating feature is the Antarctic Ice Sheet, the Earth's largest continuous ice mass. It covers nearly the totality of the land and expands over the surrounding waters, with its size varying dramatically between winter and summer seasons. Two main land sections with different geological origin, can be distinguished: West Antarctica, comprising also the peninsula and islands, and the higher, colder East Antarctica with the Transantarctic Mountains rising amid both regions. Antarctica's main geographic features can be seen in the figure below.

2. ***A continent with many flags but no countries.*** Antarctica is a unique place in many ways. Of all continents, it's the only one that has no indigenous population, there are no 'Antarcticans', or permanent human settlements. Prior to the first expeditions in the 1800s, no human foot had set on the place. Nowadays, human presence is represented by crews living seasonally at research stations operated by several countries, and by visitors participating in tourist expeditions that mostly explore the Antarctic peninsula.

Although some nations claim different, and sometimes overlapping, areas of the Antarctic region, and operate research stations, they do not own Antarctic territory. The Antarctic region and its international interactions are managed by the Antarctic Treaty System (ATS). Its main document, the Antarctic Treaty, was signed in 1959 (entering into force in 1961) by 12 countries, whose national flags planted at the South Pole are shown below, with other nations joining over the next decades. Among other regulations, the treaty prohibits military activities and the exploitation of natural resources south of 60° S latitude. Another important component of the ATS is the Environmental Protocol to the Antarctic Treaty, the so-called Madrid Protocol (entered into force in 1998), which designates Antarctica as "a natural reserve, devoted to peace and science". Today, the Treaty has 52 signatory countries, which operate more than 70 research stations and refuges with capacity to host from a few persons up to large crews. The largest base and research station in Antarctica is McMurdo Station, maintained by the United States, which can host approximately 1200 people, rendering it an Antarctic village!

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Antarctica overview map showing the main geographic features of the continent and surrounding waters. Source: NASA Goddard Earth Science Research, Cryospheric Sciences Laboratory http://lima.nasa.gov/pdf/A3_overview.pdf



South Pole, Amundsen-Scott Station. The ceremonial marker at the South Pole is surrounded by the flags of the 12 original signatory nations to the Antarctic Treaty. Photo: Elaine Hood, U.S. Antarctic Program Photo Library, National Science Foundation.

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3. *Environmental extremes and contrasting facts.* Antarctica is the southernmost continent and contains 90 % of the Earth's ice masses and 70% of the planet's freshwater reserves. Given these facts, 'a desert' is probably not the first description coming to mind when thinking of the frozen Antarctic landscapes. But, in fact, the continent is considered an extremely dry and cold desert, since precipitation, mostly in the form of snow, is very scarce. The large masses of Antarctic water are locked in ice, which compacted over millennia forming a kilometer-deep sheet (reaching up to 5 km depth!). Thus, for the most part, water is not freely available to living organisms. The only portions of land that are not permanently covered by ice or snow are narrow coastal strips and some continental portions, together with the highest mountain summits that 'perforate' the surrounding ice sheets and glaciers, also known as 'nunataks'. These non-permanently ice-covered land areas represent less than 2% of the continental surface and concentrate most forms of terrestrial life as well as the human activities.

The most extreme temperatures are measured in the interior of the continent, reaching approximately -60 °C in winter and -20 °C in summer, with a record of -89.2 °C at the Russian Vostok Station. The coastal areas, a region defined as Maritime Antarctic, present relatively milder conditions, with temperatures ranging between -10 °C to -20 °C in winter and reaching up to 10 °C in summer. Daylight exposure varies greatly over the year, from days without night in the Austral summer to a 6-month long winter period of complete darkness. Antarctica is also the windiest continent on the planet, with gusts reaching approx. 300 km/h, (that is three times faster than a strong hurricane!). The extreme dry and cold conditions, strong winds, high UV radiation exposure and a low nutrient environment are not the only hardships that living organisms have to endure. The dramatically fluctuating conditions, for example complete darkness in the winter and continuous light exposure in summer, the repeated freeze and thawing cycles with a day-night rhythm or coupled to sunlight and shade exposure, make the adaptation to such an environment even more challenging.

4. *Antarctica and the Arctic: alike but different.* The Arctic region comprises a frozen ocean surrounded by land, whereas Antarctica is a frozen land mass, surrounded by the ocean, a feature that has an important influence on temperature regulation. Unlike the Arctic, which can be reached by land transportation, has permanent human settlements, commerce and natural resource exploitation activities, Antarctica remains quite isolated and relatively 'untouched' due to the challenging geographical barriers. It is separated from other land masses by the Southern Ocean's rough waters and it can only be reached during the summer months by icebreakers and relatively small size logistic aircraft. Those air-bridges can only cover relatively short haul distances from the closest continental logistic bases in the Southern Hemisphere. Large aircraft cannot land on the short Antarctic runways which are sometimes just flat areas on top of glaciers. The closest land mass is the tip of South America, located more than 1000 km away. The southernmost human habitation is the Amundsen-Scott base (operated by USA) at the geographic South pole: 90°00'S 00°00'W; this is the coolest postal address in the world, literally speaking!



Impressions from the landscape, human presence and macroscopic wildlife of the Maritime Antarctic region. a) Panoramic view of Carlini Station area and Potter Cove, South Shetland, Antarctica. b) Coastal line displaying icebergs' debris lining the shore and a *nunatac* emerging from the Fourcade glacier on the background; c) colonies of sea lions and penguins are found in the direct vicinity of Carlini research station; d) field work, sampling vegetation and soil for microbiological analyses; the 'prairie' seen on the picture is a mixed mat composed by Antarctic hair grass (*Deschampsia antarctica*) and Antarctic Pearlwort (*Colobanthus quitensis*), the only two vascular plants that thrive under the harsh and fluctuating environmental conditions prevailing in the region. Photos: Cecilia G. Flocco (CC BY-NC-ND 2.0)

5. The human footprint in Antarctica. Due to these geographical features, the continent has remained largely preserved from the impact of human activity. But not completely, since where humans go, traces are left. Tourism and the activity at the research stations constitute the main direct human influence source in Antarctica. These activities are concentrated on coastal

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areas, due to their relatively better accessibility and milder environmental conditions. The human population is represented by approximately 1500 people living seasonally at the research stations (mostly concentrated within the austral summer and coastal areas) and a flux of approximately 40,000 tourists over the last seasons, increasing alarmingly over the years! Human activities in distant parts of the world, such as the generation of particles produced by burning forests and fossil fuels, or the microplastics in the ocean, can travel long distances and reach the Antarctic region. Also, the environmental consequences of a changing climate are impacting the dynamics of the Antarctic ice masses and ocean currents. This, in turn, facilitates the proliferation of alien species from warmer regions and, with the melting ice, the release of legacy land contaminants that were previously buried in the permafrost (ground zones that remain frozen for two or more years), among other impacts visible in a short period of time. The long-term consequences of the changing environmental conditions and the interplay at ecosystems level are not fully understood.

Pandemic times: Covid-19 and Antarctica

In spite of the isolation of Antarctica, COVID-19 reached it in December 2020, when a crew at the Chilean base General Bernardo O'Higgins Riquelme tested positive. The outbreak was contained, but scientists are concerned about potential routes of transportation of such a ubiquitous virus (that includes humans and migratory animals as vectors) and the potential impact of the evolving virus to the wildlife and ecosystems' stability. The pandemic-bound restrictions have also affected the logistic and activities of research stations: crews were reduced to a minimum, and travel restrictions affected the evacuation of deployed personnel and the execution of expeditions.

6. *Everyday life at an Antarctic station.* Any enterprise in Antarctica, from traveling to that region to taking a warm shower after a long day on the field, depends on huge logistic and on-site management efforts. Usually, military crews are in charge of the transport of personnel and supplies to the stations, including the operation of icebreakers, helicopters, cargo and postal planes and, when needed, rescue missions. There are no shops, industries or complex hospital facilities. All supplies for human activity, including food, fuel, housing materials and any element for research and exploration has to be brought from the continent. And, in turn, most of the waste has to be brought back to the mainland, since it cannot be treated on site. The Antarctic Treaty prohibits the introduction of alien species, including plants, animals and microorganisms and regulates the environmental management and protection of the region. Therefore, all personnel deployment and on-site activity has to be precisely defined and approved in an action plan, and that includes the amount of personal stuff that researchers and crews can bring for a stay at a base. Along the same lines, the physical and psychological health of the personnel to be deployed in Antarctica is thoroughly checked prior to joining a mission. Each research station has a doctor on site and a basic facility to provide primary care, but situations demanding complex treatment necessitate evacuation to the continent. Although every effort will be made to manage emergencies, an evacuation implies a dedicated transportation and logistical effort that cannot always be always fulfilled, in particular when inclement weather precludes any travel, or during the dark winter months, when all travel is stopped due to a lack visibility and the formation of impenetrable icepacks.

Examples of international cooperation and solidarity

The spirit of cooperation and solidarity is captured in the articles of the Antarctic Treaty and is prevalent among teams working in Antarctica, accentuated by the harsh conditions for human activities and the isolation. Scientific activities are the fertile ground where international cooperation flourishes. For example, Carlini station operated by Argentina, offers logistic support and facilities to marine research scientists from the Alfred Wegener Institute from Germany and jointly operate the Dallmann laboratory. Another cooperation with the Institute of Atmospheric Physics (IFA) from Italy focuses on the study of the greenhouse effect. That cooperation vocation extends to situations in which international logistic efforts are needed, such as medical emergencies and accidents. In spite of strict operation rules and efforts to prevent the occurrence of dangerous situations, accidents and unforeseen events do happen and crews from different nations step in to help. For example, in the year 2014 the Russian icebreaker Akademik Shokalskiy got stranded on ice and several nations joined efforts to evacuate the passengers, in a very dramatic, but at the same time courageous rescue mission. In 2016, astronaut Buzz Aldrin, who was visiting the South Pole station as part of a tourist contingent, had to be medically evacuated to the nearest hospital - located in New Zealand - which demanded huge logistic efforts. Antarctica is tough... even for moonwalkers!

Antarctic Microorganisms and Sustainability

1. ***Antarctic microorganisms: biodiversity hiding in plain sight.*** The harsh environmental conditions in Antarctica are deemed too extreme not just for humans, but for most forms of life. Although the oceans are teeming with biodiversity, on land or ice only penguins, seals, and marine birds are seen. They rely on the ocean for food, so they are not considered truly terrestrial animals. The plant kingdom is represented mostly by mosses, lichens, liverworts. Nematodes (worms), mites and microscopic animals called tardigrades live in these Antarctic 'micro-forests'. Only two flowering plants, commonly called Antarctic hair grass (*Deschampsia antarctica* É.Desv.) and Antarctic pearlwort (*Colobanthus quitensis* (Kunth) Bartl.) are able to grow under harsh environmental conditions, located in the relatively milder environment of the Antarctic peninsula and sub-Antarctic islands. This scarcity of plant species contrasts with the Arctic, for which approximately 80 plant species have been described. The lack of macroscopic life on the surface led the first explorers to describe the Antarctic soils as sterile, deprived of life. Over the years, with the advances in microscopy, microbiology, cultivation methods and molecular biology techniques, a rich hidden microscopic world emerged. Microorganisms are the dominant biota adapted to thrive under conditions deemed too extreme for most forms of life. Their crucial role in biogeochemical cycles supports life at both the microscopic and the landscape level. Furthermore, their intrinsic detoxification capacities can be harnessed to deal with pollution arising from human activities, as it will be commented below.

2. ***Thriving in Antarctica - and beyond.*** The exploration of the microbial life on Antarctic lands has revealed a wide range of physiological- and habitat-selection strategies which enable life under the extreme and dramatically fluctuating environmental conditions prevailing in the region. Such strategies are studied with great interest by multiple interdisciplinary teams. Understanding the intrinsic mechanisms that allow microbes to grow under environmental poly-extremes is of great interest for the development of biotechnological applications, for example in the food, textile, pharmaceutical and other industrial sectors. It may also enable us to envision how life could thrive in outer space, a focal topic of a discipline called astrobiology. Antarctica is

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considered a great natural outdoor laboratory for the rehearsal of space missions, testing the equipment and the performance and adaptability of different forms of life, including humans, plants and microbes.

Microorganisms thriving in the cold are classified according to the preferred temperature ranges for their activity and growth. Psychrophiles (meaning: *cold-loving*) can grow below 0 °C, but not beyond 20 °C, with an optimum range between 10-15 °C. They are mostly found in polar regions and the depths of oceans. Psychrotrophs, sometimes referred to as psychrotolerant (meaning: *cold-tolerant*) can grow beyond 25 °C but not below 0 °C, with an optimum range between 15-30 °C. These microorganisms are mostly found in cold to temperate environments. The main physiological and structural strategies allowing microbes to thrive in the Antarctic environment comprise:

- the production of polymeric substances and proteins that prevent the formation of damaging ice crystals
- the alteration of the chemical composition of cell structures (walls, membranes) and enzymes that allow those structures to remain fluid and functional under freezing conditions
- the production of pigments, such as carotenes, phycobilin, melanin, flavonoids and others, which capture light, protect from ultraviolet light damage and oxidative stress and help maintain fluid membranes at cold temperatures. In some cases, the pigments exhibit antibiotic activity, providing a defense against grazing by other microorganisms.
- changes in the life cycle, such as the formation of dormant, resistant structures called endospores and other desiccation-related mechanisms. Endospore-forming bacteria comprise mostly Gram-positive bacteria belonging to the *Bacillaceae* family.

Microbes display as well habitat selection strategies, such the colonization of cryptic niches (these are defined areas with habitat conditions that differentiate them from the larger habitat they are part of) and the generation of microenvironments (that is, the colonizing microbes and their products modify the physical-chemical properties of the environment surrounding them, creating micro-zones with differentiated habitat conditions) that, in turn, support the development of other forms of life. This 'habitational' pattern creates a micro-heterogeneity in the microbial composition of Antarctic soil microbial communities, showing great variations within short distances or constrained areas.

For example, lithobiontic microbial communities (lithos: rock; bios organism) can colonize rocks surfaces, cracks, internal pores and the surface in contact with the soil. These niches represent a refuge protecting from the poly-extremes of the Antarctic environment. Most of the Antarctic lithobiontic communities described so far were found in the Antarctic Dry Valleys, which are described as one of the most hostile regions on the planet for any form of life. Cyanobacteria and lichen-associated bacteria are common members of these communities, with Actinobacteria and other phyla detected to a lesser extent. Also, marked differences in microbial community composition were detected, depending on the localization of those on and in the rock, as described above. The common point of all lithobionts is the dependency of photoautotroph organisms, such as cyanobacteria and mosses, that can capture light and provide a carbon source to the community.

Resiliency Champions: Tardigrades

A prominent example of desiccation-triggered resiliency mechanisms is given by tardigrades (Phylum: Tardigrada) -also known as ‘water bears’ or ‘moss piglets’ due to their external, chubby appearance. They are not unicellular microbes, but amazing microscopic animals. Tardigrades are ubiquitously found lurking in moss beds across the globe, but also on mountain tops, volcanoes, tropical forests, and the harsh, dry, icy, and high UV radiation exposed polar regions. These hostile environmental conditions trigger a process called



Microscopic image of a tardigrade

cryptobiosis in which tardigrades ‘shut down’ all metabolic processes, but remain alive: they lose almost all their water content, retract their legs and curl...till things get better! Tardigrades’ remarkable resiliency features allow them to survive even in outer space conditions. And yes, on top of those amazing features, they look extremely cute! Image source: Schokraie E, Warnken U, Hotz-Wagenblatt A, Grohme MA, Hengherr S, et al. (2012), CC BY 2.5, via Wikimedia Commons.

3. *Invisible multitudes sustain ecosystems.* In a region with practically no vegetation to harvest carbon dioxide from the atmosphere and transform it into organic materials, microbes are the main primary producers and drivers of biogeochemical cycles. As mentioned, cyanobacteria play a central role in the turnover of carbon and nitrogen, for example, cold-adapted members of the orders *Nostocales*, *Oscillatoriales* and *Chroococcales*. Together with lichens and green algae, cyanobacteria are the primary energy producers, i.e. the base of the food web, and thus the enablers of other forms of life. Microbes can also modify the surrounding environment creating ‘more habitable’ micro-niches that can sustain other forms of life that could not exist without the associations. Yes, it takes a village!

In addition to the mentioned fundamental ecosystem support functions, several microorganisms are equipped to degrade or render harmless environmental pollutants generated by human activities on site or originated remotely and transported to the Antarctic region by wind or ocean currents. Common examples of environmental pollutants are organic compounds (mostly polycyclic aromatic hydrocarbons) and heavy metals. They are derived from the fossil fuels used for transport, heating and the generation of electricity at research stations. Although such bioremediation capacity has been widely described for microorganisms of temperate environments, it is important to note that those could not be used in Antarctica for bioremediation purposes, due to biological and legal reasons: microorganisms from temperate areas may not survive or display biodegradation activity under the harsh Antarctic conditions, and the Antarctic Treaty prohibits the introduction of alien species. Among bacteria, representatives of the genera *Pseudomonas*, *Rhodococcus*, *Planococcus*, *Sphingomonas*, *Arthrobacter*, *Stenotrophomonas* and *Nocardioides*, among others, have been described as active biodegraders of fuel derived compounds under Antarctic conditions. Fungi of the genera *Penicillium* and or black pigmented *Exophiala* species have been described as able to biodegrade such compounds as well.

Considering that invasive and disruptive physical or chemical remediation systems are not allowed in Antarctica’s environmentally protected areas and that transporting large volumes of soil or fluids for treatment on the continent is logistically challenging and prohibitively expensive, in situ remediation strategies - enabled by indigenous, adapted microorganism - emerge as a valuable bioresource to support the sustainability of Antarctic ecosystems.

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4. *A biodiversity treasure chest.* Microbes thriving in remote Antarctic regions also contribute to societal and environmental well-being by providing cells, enzymes and other biomolecules of biotechnological, pharmacological and industrial interest. As commented in previous sections, cold-adapted microorganisms possess a metabolic machinery that is functional at temperatures that preclude any activity or growth of non-adapted ones. This feature makes them very attractive for a wide range of biotechnological applications and processes that allow saving energy and resources, thus reducing the associated environmental footprints. Some examples are listed below:

- enzymes used in the formulation of detergents for energy-saving cold-washes
- enzymes used in the production of food and compounds that require refrigeration
- pigments and fragrances
- polyunsaturated fatty acids (PUFAs, which are essential to the functioning of higher organisms' cellular membranes, including humans) used as food additives
- anti-freezing biomolecules and ice nucleating proteins, used in the frozen-food industry (for example, to improve the texture of ice-cream products) or in agriculture (as plant frost-protectants), among other uses
- bioremediation of fuel derived pollutants
- biosensors for environmental monitoring
- novel antimicrobials and other pharmaceutical compounds

As can be inferred from the examples given above, the benefits of the rich biodiversity contained in the Antarctic microbial communities reach everyday life in numerous ways - although it might not be apparent.

Wrapping up: Antarctica does matter

Despite the geographic isolation and harsh conditions for life, Antarctica has deep connections to the global environmental and human well-being and provides information on the Earth's history, in numerous ways. For example, the dynamics of the Antarctic ice masses have a profound effect on Earth's climate. In the opposite direction, the region has experienced the impact of the deliberate release of man-made chemicals into the atmosphere, as revealed by the degradation of the ozone layer, regardless of the distances to industrial zones and urban centers. As time capsules, the gas bubbles trapped in ancient ice and other molecules keep a historical record of the planet's climate over the past millennia, which can help understand current processes. Its pristine skies make it an ideal place for astronomic observations and the harsh environmental conditions represent a natural laboratory for testing life at the extremes and rehearsals for space missions. An overview of the main Antarctic research topics - and their implications for life on the planet - can be found on the website pages of the Scientific Committee on Antarctic Research (SCAR), which is the organization initiating, facilitating and coordinating the scientific research and international cooperation in the region (<https://www.scar.org/science/research-overview>).

And last, but not least, there's the hidden microbial life, the dominant form of terrestrial life that can not only survive but thrive under the poly-extreme environmental conditions in Antarctica. These adapted microbial communities represent a treasure trove of novel biomolecules and biological mechanisms that can be harnessed for the benefit of humans and the environment -on site and beyond the Antarctic boundaries. Due to the tough environmental conditions and complicated logistics bound to conducting research in Antarctica, this rich biodiversity remains largely unexplored. Therefore, internationally harmonized efforts to preserve it from potential detrimental effects and, at the same time, characterize and catalogue it are

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needed. The Antarctic Treaty System and participating nations work together to coordinate those preservation efforts and the scientific research activities in the region. Since ‘out of sight, out of mind’ applies, in particular for microscopic life of a remote place, this educational resource aims to reveal to the kids’ eyes the amazing features that polar Antarctic microbes possess and their connections to everyday life.

Relevance for Sustainable Development Goals and Grand Challenges

The Antarctic region is intrinsically connected to everyday life due to its role on the regulation of the planet’s temperature and the provision of unique bioresources. In turn, human activities and choices can have an impact in the region due to the alteration of global environmental parameters and on site activities. Due to Antarctica’s geographical isolation and perceived remoteness, such connections and links to sustainability might not become (immediately) apparent. The following section aims to highlight those connections, focusing on the hidden microscopic multitudes.

- **Goal 12. Ensure sustainable consumption and production patterns** (*achieve sustainable production and use/consumption practices, reduce waste production/pollutant release into the environment, attain zero waste lifecycles, inform people about sustainable development practices*). Antarctic bioresources, among those, the cold-adapted microbes, contribute to the improvement of industrial processes through the use of their unique enzymes and biomolecules working at low temperature and enabling a reduction of the environmental impact of such processes (by lowering energy consumption and waste, for example).

- **Goal 13. Take urgent action to combat climate change and its impacts** (*reduce greenhouse gas emissions, mitigate consequences of global warming, develop early warning systems for global warming consequences, improve education about greenhouse gas production and global warming*). The Antarctic region has a key role in the circulation of the Earth’s water masses and temperature regulation and in the provision of bioresources. Global environmental change can alter the Antarctic ecosystems (due to changes of temperature patterns or alterations of the habitat’s physical-chemical conditions by pollutants, for example) with long term consequences that are not yet well known.

- **Goals 14/15. Conserve and sustainably use the oceans, seas, marine resources and terrestrial ecosystems for sustainable development** (*reduce pollution of marine systems by toxic chemicals/agricultural nutrients/wastes like plastics, enhance sustainable use of land and oceans and their resources*). Antarctic ecosystems’ delicate equilibrium can be altered by human activities taking place, both directly on the region (such as tourism or the operation of Antarctic bases) or remotely (due to the production of persistent pollutants that can migrate to the region or chemicals impacting the climate). Microbes’ crucial role in biogeochemical cycles supports life in Antarctica at both, the microscopic and the landscape level and should be protected from adverse impacts produced by human activities.

- **Goal 17. Partnerships for the goals, strengthen the means of implementation and revitalize the global partnership for sustainable development.** The Antarctic Treaty System and its provisions for environmental management and protection are prime examples of global partnerships aiming at keeping peace, protecting nature and providing the regulatory framework for the sustainable execution of activities in the Antarctic region, such as tourism and scientific enterprises. Such international partnerships and agreements should be maintained and reinforced in front of an increasing interest on the exploitation of natural and mineral resources in the region.

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Potential Implications for Decisions

1. *Individual*

- a. Consider the various ‘everyday decisions’ that can entail long-reach and long-term environmental impacts, such as potential contributions exacerbating global environmental change
 - i. Consumption patterns (food, clothes, personal care, recreation)
 - ii. Household waste generation and management
 - iii. Transportation

2. *Community and national policies*

- a. Promotion of environment-friendly industrial processes and household systems (buildings, heating, cooling, cooking) to reduce global environmental impacts
- b. Environmental pollution regulations: in particular, **regarding** persistent global pollutants which could migrate via ocean currents and air plumes (such as particulate matter arising from the combustion of fossil fuels and plastic waste)
- c. Greenhouse gas emissions and the production of chemicals affecting the ozone layer.

3. *International policies*

- a. Promote, fund and harmonize research efforts aiming at uncovering and preserving the Antarctic microbial biodiversity and fragile ecosystems.
- b. Instrument educational and science communication efforts raising awareness of the interconnections and links of global environmental issues with Antarctica and vice versa, of the contributions from the remote region to environmental and human wellbeing.
- c. *Non-microbial parameters: observe policies relating to the regulation of touristic companies operating in Antarctica harmonized with the Antarctic Treaty and environmental protection mandates.*

The Evidence Base, Further Reading and Teaching Aids

The contents of this Topic Framework are based on the research and on-site experiences of this author and colleagues of the Microbiology Group of the Antarctic Argentine Institute, collected in the following book chapter (among other publications):

Flocco C.G., Mac Cormack W.P., Smalla K. (2019). Antarctic Soil Microbial Communities in a Changing Environment: Their Contributions to the Sustainability of Antarctic Ecosystems and the Bioremediation of Anthropogenic Pollution. In: Castro-Sowinski S. (eds). *The Ecological Role of Micro-organisms in the Antarctic Environment*. Springer Polar Sciences. Springer, Cham (https://doi.org/10.1007/978-3-030-02786-5_7). ISBN 978-3-030-02785-8, pp133-161 (*). This chapter, and other contributions collected in the book, present an overview of the most important microbial systems in the Antarctic terrestrial environment and the role they play in the ecosystems’ dynamics and sustainability. This material can serve as a general consultation resource for teachers, educators and advanced students interested in Antarctic science and microbiology. In addition to the overview provided by the above-mentioned material, dedicated activities and resources for teachers and students are provided and displayed in association with the individual learning topics described in this curriculum. Such materials can be adapted to the pedagogic requirements of the different school levels.

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In addition, it is encouraged that the educators and students explore the vast learning resources freely available on the websites of Antarctic institutions and programs of the countries participating in the Antarctic Treaty System. These websites (available in several languages and most commonly in English) provide additional classroom resources, including excellent cartography, impactful pictures, videos and live webcams, which can be harnessed to generate an immersive Antarctic experience.

(*) copies of the chapter for educational purposes can be facilitated on request.

Pupil Participation

Suggested Classroom Activities and Resources (for students and teachers)

The Antarctic region

Activities

1. Identify Antarctica's main geographical features on a map
2. What is the size of the Antarctic Ice Sheet? Is it always the same?
3. How do those sizes compare with other Earth's landmarks? (for example: the size of the Arctic ice sheet, of other continents, countries, etc.).

Resources

- National Geographic Education, resource library: Antarctica
<https://www.nationalgeographic.org/encyclopedia/antarctica/>
- CONMAP. Antarctic information and Maps:
<https://www.comnap.aq/antarctic-information/>

A continent with many flags but no countries

Activities

1. Explore a map showing the location of the Antarctic research stations: Where are most research stations located and why? (Reply: stations are built mostly on coastal locations, which are not permanently covered with ice, due to their accessibility and facilitated logistics.)
2. Why do nations claim territory in Antarctica? Which nations are those? How are these claims treated? (Reply: due to strategic localization for surveillance, natural resources prospecting; claims are periodically reviewed and the status quo is maintained, till next revision.)
3. If I visit Antarctica, can I get my passport stamped? Can I receive post from Antarctica? (Reply: yes, but it has no nationality officially bound to it; similarly, postal stamps are produced as a souvenir.)

Resources

- The Antarctic Treaty explained. British Antarctic Survey
<https://www.bas.ac.uk/about/antarctica/the-antarctic-treaty/the-antarctic-treaty-explained/>
- BBC News Article: Why do so many nations want a piece of Antarctica?
<https://www.bbc.com/news/magazine-27910375>
- Catalogue of Antarctic stations. CONMAP. Council of Managers of Antarctic Programs.
https://www.comnap.aq/wp-content/uploads/2019/11/COMNAP_Antarctic_Station_Catalogue.pdf
- CONMAP. Antarctic information and Maps:
<https://www.comnap.aq/antarctic-information/>

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Environmental extremes and contrasting facts

Activities (subjects: Natural Sciences, Geography; activities apply also to the next section's topic)

1. Compare temperatures with the Arctic, which region is colder and why? (Reply: Antarctica is colder because it is on average higher (up to 4000 mts elevation); the ice sheet is thicker than that of its northern counterpart in Greenland (average thickness one half of that of the Antarctic ice sheet); also, the strong Antarctic wind makes the temperature feel colder.)
2. Localize Vostok station on a map. It's reported as the coldest recorded point on Earth, why? (Reply: it's localized high on the continental plateau; it's also called the Southern Pole of Cold.)
3. Which are the austral and boreal summer and winter months? What is the explanation for that? (Reply and additional activities (depending on age group): discussion about Earth's rotation and axis inclination, the seasons, day and night, the solar incidence angle at the Equator and the poles, and other features. Classical hands-on representations, such as a globe illuminated with a flashlight, could be used as teaching aids.)

Resources

- National Geographic Education, resource library: Antarctica
<https://www.nationalgeographic.org/encyclopedia/antarctica/>
- CONMAP. Antarctic information and Maps:
<https://www.comnap.aq/antarctic-information/>
- Why is Antarctica colder than the Arctic?
<https://www.auroraexpeditions.co.uk/blog/why-is-antarctica-colder-than-the-arctic/>

Antarctica and the Arctic: alike but different

Activities (Natural Sciences/Geography)

1. Is there a sign indicating the South Pole? Is there more than one South Pole? (Reply: yes, there's a stick indicating the South Pole, but its position has to be adjusted manually since it's placed on an ice sheet that drifts! And yes, there is also a geographical South Pole, a magnetic and a geomagnetic South Pole. Their locations change and have to be recalculated as well.)
2. What's below the South Pole? (Reply: Ice and if removed, rocky land with mountains and canyons. What's below the North Pole? Reply: Ice and below it, the ocean.)
3. Is the North Pole marker stick also moving? (Reply: there's no official stick indicating the North Pole since it's located on a mass of ice floating on the ocean and it moves more than the South Pole's ice sheet.)

Resources

- Australian Antarctic Division:
<https://www.antarctica.gov.au/>
- Why is Antarctica colder than the Arctic?
<https://www.auroraexpeditions.co.uk/blog/why-is-antarctica-colder-than-the-arctic/>
- Five Things You Didn't Know About the North Pole. National Environmental Satellite Data and Information Service:
<https://www.nesdis.noaa.gov/news/five-things-you-didnt-know-about-the-north-pole>
- For kindergarten and primary school levels: Ice is nice! all about the North and South Poles (Cat in the Hat's Learning Library), ISBN 0375828850 (ISBN13: 9780375828850).
- The South Pole
<https://www.coolantarctica.com/Antarctica%20fact%20file/antarctica%20environment/south-pole.php>

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- More on Earth's water and Antarctica in this curriculum of the American Museum of Natural History:
<https://www.amnh.org/content/download/132762/2211960/file/grace-curriculum-teacher-passage1.pdf>

The human footprint in Antarctica

Activities:

1. What are the main direct and indirect impacts of human activities to Antarctic ecosystems?
2. Can one make a vacation in Antarctica? How is Antarctic tourism managed?
3. What are zoonoses? What is a reverse-zoonosis? How could such disease dynamics play in Antarctica?
4. What are the short- and medium-term implications of COVID-19 for Antarctica?
5. What precautions could be taken to reduce such potential impacts?

Resources:

- The impact of anthropogenic activities in Antarctica is summarized in Fig. 7.2, p138 in: Flocco C.G., Mac Cormack W.P., Smalla K. (2019). Antarctic Soil Microbial Communities in a Changing Environment: Their Contributions to the Sustainability of Antarctic Ecosystems and the Bioremediation of Anthropogenic Pollution. In: Castro-Sowinski S. (eds). The Ecological Role of Micro-organisms in the Antarctic Environment. Springer Polar Sciences. Springer, Cham (https://doi.org/10.1007/978-3-030-02786-5_7). ISBN 978-3-030-02785-8, pp133-161
- British Antarctic Survey- Antarctic Tourism. FAQs
<https://www.bas.ac.uk/about/antarctica/tourism/antarctic-tourism-frequently-asked-questions/>
- COVID has reached Antarctica. Scientists are extremely concerned for its wildlife. Article in: The Conversation by Michelle Power and Meagan Dewar.
<https://theconversation.com/covid-has-reached-antarctica-scientists-are-extremely-concerned-for-its-wildlife-154481>
- Antarctic Treaty System: General Guidelines for Visitors to the Antarctic (pdf)
https://documents.ats.aq/recatt/Att483_e.pdf
- Website of IAATO (International Association of Antarctica Tour Operators):
<https://iaato.org/>

Everyday life at an Antarctic station

Activities

1. Virtually explore several research stations, to gain a sense of the different habitational complexes and their locations (see COMNAP catalogue under Resources)
2. Discuss the construction features of some of the buildings (for example, those constructed on pillars) and the reasons for those designs.
3. Explore and talk about 'People in Antarctica' topics: clothing, food, water, recreation, health (described in Australian Antarctic program website in a didactic way, with wonderful illustrations) and discuss environmental management and sustainability aspects of the operation of Antarctic stations.

Resources

- Catalogue of Antarctic stations. COMNAP. Council of Managers of Antarctic Programs.
https://www.comnap.aq/wp-content/uploads/2019/11/COMNAP_Antarctic_Station_Catalogue.pdf

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- Australian Antarctic Program -People in Antarctica:
<https://www.antarctica.gov.au/about-antarctica/people-in-antarctica/>

Examples of international cooperation and solidarity

Resources

- Catalogue of Antarctic stations. COMNAP. Council of Managers of Antarctic Programs.
https://www.comnap.aq/wp-content/uploads/2019/11/COMNAP_Antarctic_Station_Catalogue.pdf
Carlini Station: https://en.wikipedia.org/wiki/Carlini_Base
- Dallmann Laboratory:
<https://www.awi.de/en/expedition/stations/dallmann-laboratory.html>
- NPR News. Buzz Aldrin Is medically evacuated from Antarctica
<https://www.npr.org/sections/thetwo-way/2016/12/01/503973422/buzz-aldrin-is-medically-evacuated-from-antarctica>
- The Guardian. Antarctic rescue: trapped Chinese icebreaker will try to break free
<https://www.theguardian.com/world/2014/jan/03/antarctic-rescue-chinese-xue-long-aurora-australis>

Thriving in Antarctica and beyond

Activities: Microbial growth and temperature, connections with everyday activities

1. Compare the growth rates of mesophilic and thermophilic microorganisms at different temperatures (see resources to explore graphs showing growth curves at different temperatures) Where could those microorganisms be found?
2. In which category would most human pathogens fall? (Reply: mesophiles, growing at body temperature.)
3. Which type of microorganisms can be responsible for food spoilage in the fridge and why? (Reply: psychrophiles, they can grow at low temperature).
4. How can bacteria affect my food in the refrigerator? Describe the two types of food-altering microorganisms: pathogens and spoilage bacteria (affecting organoleptic properties but not pathogenic).
5. How can I best preserve food in the refrigerator? (information in USDA resource, indicated below)

Resources

- A succinct summary for students is presented in this blog: Psychrophiles, Mesophiles, Thermophiles <https://microbeonline.com/psychrophiles-mesophiles-thermophiles/>
- Geelkens, M. (2012). Psychrophiles for all. Blog by the University Liège, section Reflexions: Earth, Environment
https://www.reflexions.uliege.be/cms/c_42267/en/psychrophiles-for-all?part=1
- About food safety and refrigeration:
https://www.atchison.k-state.edu/docs/food_safety_health_nutrition/Refrigeration%20and%20Food%20Safety.pdf

For teachers/advanced students:

- Madigan T., Bender K. S., Buckley, D. H, Sattley, W. M., & Stahl, D. A. (2018). Brock Biology of Microorganisms (15th Edition). Pearson.

Activities: Microbial pigments and niche habitats, resiliency mechanisms

1. Which colors do bacterial pigments have? Could one form a complete rainbow with them?
2. What could these pigments be useful for?

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3. Which other forms of life have carotenoids? (rabbits could tell...)
4. Can microbes live on or inside rocks?
5. What are tardigrades? Which mechanisms allow them to survive under conditions deemed too extreme for other forms of life?

Resources

- Tardigrades: National Geographic -Animals (as example; many free resources are available online).
<https://www.nationalgeographic.com/animals/invertebrates/facts/tardigrades-water-bears>

For teachers/advanced students:

- Marizcurrena J.J., Cerdá M.F., Alem D., Castro-Sowinski S. (2019). Living with pigments, the colour palette of Antarctic life. In: Castro-Sowinski S. (eds) *The Ecological Role of Micro-organisms in the Antarctic Environment*. Springer Polar Sciences. Springer, Cham ISBN 978-3-030-02785-8, pp.65-82.
- Amarelle V., Carrasco V., Fabiano E. (2019). The Hidden life of Antarctic Rocks. In: Castro-Sowinski S. (eds). *The Ecological Role of Micro-organisms in the Antarctic Environment*. Springer Polar Sciences. Springer, Cham ISBN 978-3-030-02785-8, pp. 221-237.

Invisible multitudes sustain ecosystems

Activities: unveil the contributions of the 'unseen majority' to ecosystems' sustainability and planetary well-being.

1. Explore the schematic representations and figures provided in the resources below (or simplifications of those made by the teachers), to gain a sense of the different contributions of microbes to ecosystems' functions.
2. Discuss the links of microbes and their contributions to the different SDGs and their relation to human well-being and everyday activities.
3. Discuss the above-mentioned issues and interactions with a focus on Antarctica. Which features can be unique to this particular region of the planet?

Resources

- Cavicchioli, R., Ripple, W.J., Timmis, K.N. et al. (2019). Scientists' warning to humanity: microorganisms and climate change. *Nature Reviews Microbiology*, 17, 569- 586.
<https://www.nature.com/articles/s41579-019-0222-5>.
- D'Hondt, K., Kostic, T., Mc Dowell, R., et al. (2021). Microbiome innovations for a sustainable future. *Nature Microbiology*, 6, 138-142.
<https://www.nature.com/articles/s41564-020-00857-w>
- Flocco C.G., Mac Cormack W.P., Smalla K. (2019). Antarctic Soil Microbial Communities in a Changing Environment: Their Contributions to the Sustainability of Antarctic Ecosystems and the Bioremediation of Anthropogenic Pollution. In: Castro-Sowinski S. (eds). *The Ecological Role of Micro-organisms in the Antarctic Environment*. Springer Polar Sciences. Springer, Cham (https://doi.org/10.1007/978-3-030-02786-5_7). ISBN 978-3-030-02785-8, pp. 133-161.

A biodiversity treasure chest

Activities: Food for thought - some starter questions for classroom discussion:

1. How can cold-adapted microorganisms and their enzymes reduce the environmental impacts and/or costs of industrial processes? (Reply – just some examples: since the microbial cells or enzymes work at low temperatures, less energy in the form of heating is

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needed; the loss of thermolabile compounds is reduced; enzymatic processes can be quickly terminated by thermal inactivation, among other advantages. Also, to discuss in the classroom: ice-nucleating proteins (proteins that help initiate the formation of ice) can be used for artificial snow production and ice-cream manufacture, products students can relate to. This can help emphasize the idea that microorganisms from such remote regions can have a direct input in everyday life.)

Resources

- Geelkens, M. (2012). Psychrophiles for all. Blog by the University Liège, section Reflexions: Earth, Environment
https://www.reflexions.uliege.be/cms/c_42267/en/psychrophiles-for-all?part=1
(based on the publication by Feller and Margesin, 2012, cited below)

For teachers/advanced students:

- Feller, G., Margesin, R. (2012). Polar microorganisms and biotechnology. In: Polar Microbiology: Life in a deep freeze, Washington, ASM Press, 2012.
- Cavicchioli, R., Charlton, T., Ertan, H., Mohd Omar, S., Siddiqui, K. S., & Williams, T. J. (2011). Biotechnological uses of enzymes from psychrophiles. *Microbial Biotechnology*, 4(4), 449–460. <https://doi.org/10.1111/j.1751-7915.2011.00258.x>

Wrapping up: Antarctica does matter

Activities: Free thinkers- Sustainability

The connections of the Antarctic region to several sustainable development goals (SDGs) are direct and indirect.

1. After working on the contents proposed in this curriculum, students can explore those connections and establish the links to the different SDGs
2. Next to the topics related to bioresources and the influence of the region on the global climate, students can be encouraged to brainstorm how the research stations could be operated in sustainable ways.
 - a. The topic of Antarctic tourism could be explored (analyze its possible impacts, devise ways by which most people can enjoy the beauty of the place while preserving it, explore the Madrid Protocol, connect to recent events, such as the presence of COVID-19 in Antarctica).
 - b. Living in and working in Antarctica: students can think of sustainable ways to generate power, treat waste, make housing facilities sustainable by design.

These 'free thinkers' activities can be organized as a contest or as an exhibition, which can greatly spark engagement and creativity. And perhaps, some of those ideas can be implemented in Antarctica or future outer space habitats!

Resources:

- UNESCO Sustainable Development Goals - Resources for educators: <https://en.unesco.org/themes/education/sdgs/material>
- The Antarctic Treaty explained. British Antarctic Survey <https://www.bas.ac.uk/about/antarctica/the-antarctic-treaty/the-antarctic-treaty-explained/>
- Antarctic Treaty System: General Guidelines for Visitors to the Antarctic (pdf) https://documents.ats.aq/recatt/Att483_e.pdf
- Website of IAATO (International Association of Antarctica Tour Operators): <https://iaato.org/>
- The impact of anthropogenic activities in Antarctica is summarized in Fig. 7.2, p138 in: Flocco C.G., Mac Cormack W.P., Smalla K. (2019). Antarctic Soil Microbial Communities in a Changing Environment: Their Contributions to the Sustainability of

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Antarctic Ecosystems and the Bioremediation of Anthropogenic Pollution. In: Castro-Sowinski S. (eds). The Ecological Role of Micro-organisms in the Antarctic Environment. Springer Polar Sciences. Springer, Cham (https://doi.org/10.1007/978-3-030-02786-5_7). ISBN 978-3-030-02785-8, pp. 133-161

- British Antarctic Survey- Antarctic Tourism. FAQs
<https://www.bas.ac.uk/about/antarctica/tourism/antarctic-tourism-frequently-asked-questions/>
- Catalogue of Antarctic stations. COMNAP. Council of Managers of Antarctic Programs.
https://www.comnap.aq/wp-content/uploads/2019/11/COMNAP_Antarctic_Station_Catalogue.pdf