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Soil priorities for Antarctica

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Introduction

While most of Antarctica is covered by ice sheets, a small part of the continent is permanently ice-free, sometimes for millions of years, where soils developed. Ice-free regions represent about 0.44% of the total area of Antarctica (~54, 000 km^2, although a precise estimate is still lacking), and are small 'islands' dotted along the coast, mountain ranges, and nunataks (Figure 1, Brooks et al., 2019). There, environmental conditions result in a diverse range of soils. The largest expanse of ice-free areas, the McMurdo Dry Valleys, is an arid, cold desert , with very low and fluctuating temperatures, almost no liquid water, often very high soil salinity, and typically slow rates of soil formation. Despite the small area they represent, Antarctic soils are scientifically remarkable: they harbour life, including arthropods, nematodes, rotifers and tardigrades, and a surprisingly high diversity of soil microbes, therefore representing the major part of the biomass of all Antarctica terrestrial systems (Convey et al., 2014). Ice-free areas also form essential breeding grounds for macrofauna, such as seals and seabirds. The trophic simplicity of those ecosystems make Antarctic soils a great model for studying broader ecosystem functioning. Some of the highest elevation ice-free areas and their dry permafrost conditions represent the closest Mars analogue on Earth.

FIGURE 1 HERE

The Protocol on Environmental Protection to the Antarctic Treaty (1991) provides for the comprehensive protection of the Antarctic environment and dependent and associated ecosystems, and designates Antarctica as a "natural reserve, devoted to peace and science". This Protocol requires all activities in the Antarctic Treaty area to be planned and conducted so as to limit adverse impacts on the Antarctic environment. Monitoring to allow assessment of the impacts of ongoing activities, including the verification of predicted impacts, should be carried out. Many non-binding guidelines and codes of conduct have been developed and adopted over time as practical management tools to further minimise environmental impacts. These are particularly important in the ice-free areas where impactful human activities are undertaken. Using satellite-based digitization of active and abandoned infrastructure (and surrounding visible disturbance) observed from satellite imagery, Brooks et al. (2019) estimate the total ice-free area disturbed by human activities was 5,242 km^2, approximately 10% of the already limited ice-free area. As a result of human activities and climate change, the ice-free areas that host Antarctic soils are under pressure. Within this context, we suggest four priorities for soil science research in Antarctica.

1. Improving information on functional soil properties

While the days of exploration mapping may be over, there is growing interest in generating spatially detailed soil information to inform environmental management (Roudier et al., 2013). In particular, specific soil properties (as opposed to soil classification), including soil texture, salinity, pH, are key to guide environmental decisions. Some physical properties, such as texture, allow assessing the impact of human activities on soils (e.g. foot trampling risk, O'Neill et al., 2013), while soil chemical properties are a major driver of the distribution of terrestrial biodiversity across the continent (Convey et al., 2014). Soil property maps have the potential to improve Antarctic environmental policy, e.g. by better refining biogeographic regions (Shaw et al., 2014). Scaling these properties up from sparse observations recorded in the landscape to continental scale is challenging, given the dispersed, very isolated nature of ice-free areas, limiting traditional soil survey methods. Populating soil property information over Antarctica will require the use of pedometrics (Bockheim, 2015), and advanced spatial prediction methods to interpolate between sparse observations (Roudier et al., 2013). This digital soil mapping effort will have to largely rely on existing data, collected over decades. To maximise their impact, these efforts need to be combined across the continent, and coordinated to achieve a complete and harmonised continent-wide coverage. Much inspiration for this endeavour can be drawn from the success of the Geomap initiative (Cox et al., 2019).

2. Quantifying and monitoring the impacts of climate change

Climate change represents a major threat for Antarctica, and its ice-free regions are no exception (Fountain et al. 2014). Modelling based on two IPCC climate forcing scenarios suggest that ice-free areas could expand by over 17,000 km^2 by the end of this century; almost a 25% increase (Lee et al. 2017).

a. Increase in soil moisture

Beyond the expansion of ice-free areas, exposing more parent material to pedogenic processes, the availability of water in liquid form is widely regarded as the most important abiotic stress influencing Antarctic soils and their associated biota (Convey et al. 2014). Precipitation is also predicted to increase by the end of the century with as much as 15% of that increase falling as rain on a whole-continent basis (Vignon et al., 2021), but much greater increments over the Antarctic Peninsula (+57% in a high emissions scenario). Increased availability of liquid water is likely to be a threshold crossing event affecting near surface soil physical, chemical and biological conditions and biogeochemical fluxes from soil, and will release and redistribute the soluble salts accumulated in arid soils. The potential for profound and rapid change emphasises the importance of thorough sampling and archiving of Antarctic soil samples to provide benchmarks. While several studies have assessed the effects of soil moisture on chemical or physical properties, monitoring of soil moisture at continental scale, and a clear assessment of its impact, are lacking.

b. Impacts on active layer depth

Permafrost is a key feature of Antarctic soils, and plays a central role in terrestrial ecosystems in ice-free regions. Despite its importance, Antarctic permafrost is much less well-characterised than its Arctic counterpart, leaving a scientific gap for Earth system modellers. Major advances in permafrost active layer monitoring were made following the International Polar Year (2007–2009), with almost 100 sites now instrumented across the continent (Hrbáček et al., 2021). However, the monitoring stations are mostly located in the McMurdo Dry Valleys and Antarctic Peninsula, leaving large spatial gaps in the dataset. The temperature dynamics of the permafrost are very slow, and its monitoring is a long-term effort, therefore, this current network needs to be maintained, and possibly expanded spatially to offer a more complete picture. While most monitoring efforts have focused on temperature, and active layer depth, soil moisture monitoring will grow in importance with the impacts of climate change.

c. Impacts on soil biota

A consequence of the continental-scale expansion of the ice-free areas is that previously isolated ice-free areas could coalesce, increasing connectivity between those regions, and regional-scale biotic homogenization (Lee et al., 2017). Added to radical changes in air temperature and water availability, these changes will increase the risk of spread of invasive non-native species. However, the exact impacts of habitat expansion on Antarctic soil biology are largely unknown. This uncertainty is reflected in the current environmental policy situation, with no internationally agreed response strategy for non-native species colonisation (Hughes et al., 2015). Therefore, as human activity and movement around the continent and between Antarctic and sub-Antarctic biogeographic regions continues to increase, with that comes the risk of intra-and inter-regional transfer of native and non-native species.

3. Assessment and monitoring of soil quality

Globally, the degradation of ecosystem services provided by soil have been increasingly recognized. In non-polar productive environments, this resulted in the monitoring of key soil quality indicators. As such, useful indicators for native polar ecosystems are lacking. Due to geographic remoteness and a short history of human occupation, Antarctic soils are assumed pristine. There is however increasing evidence of degradation by contaminants such as microplastics, persistent organic pollutants and heavy metals (Tin et al, 2009). Contaminant sources include natural rock weathering, long-range or ocean current transport, biological transportation, and local or non-Antarctic anthropogenic activities. Studies into the effects of emerging contaminants (e.g. microplastics, pharmaceuticals, fire retardants etc) on global soil ecosystems in general are in their infancy, and even more so in Antarctica. Their monitoring is necessary, and requires a better understanding of the spatial distribution of soil properties. . Once representative soil regions across the continent are delineated, a suite of soil health indicators and targets could be proposed and trends monitored.

4. Improved science-policy linkages to better manage Antarctic soil ecosystems

To make scientific observations impactful requires a powerful science-to-policy framework. In non-polar regions, holistic, trans-disciplinary frameworks have been used with success to address issues such as climate change. Some authors have suggested using the ecosystem services framework (Pertierra et al., 2021), or an Indigenous lens (Wehi et al., 2021) to improve the environmental management of Antarctica. These connections, especially in relation to soils, have yet to be adequately assessed. This leaves Antarctic policy-makers with the challenge of preserving Antarctic soils without having a complete picture of the different roles soils play, across scientific disciplines.

Conclusion

As the effects of climate change and an increase in human activities are putting pressure on Antarctic soils—a resource already limited and at risk of increased impact—this paper suggested four important research priorities for soil science in Antarctica. The challenges include improving our information base on Antarctic soil properties, assessment and monitoring of the impacts of climate change, and developing approaches that improve the integration of soil science within the specific environmental policy landscape of Antarctica.

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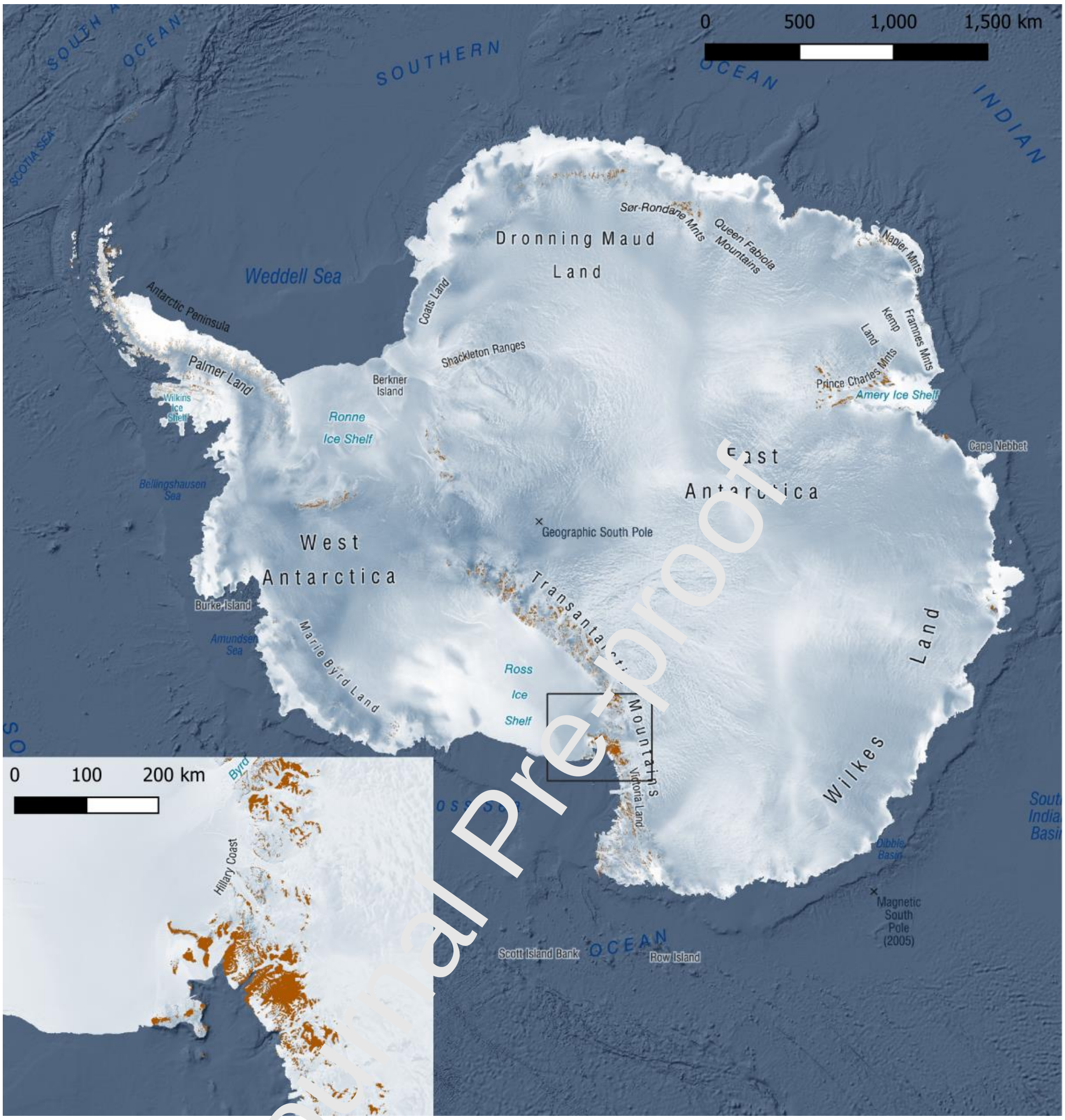

Figure 1. The ice-free regions of Antarctica are shown in brown (source: Antarctic Digital Database). The majority of the Antarctic soils are in the Transantarctic Mountains, with the McMurdo Dry Valleys and its surroundings (inset) being the largest contiguous region.

- Despite ice-free regions representing less than 0.5% of the contuinent, Antarctic soils are scientifically very significant
- Climate change and increased human activity dramatically puts pressure on Antarctic soils
- We discuss and propose four main challenges for soil science in Antarctica