



Soil development and soil biology on King George Island, Maritime Antarctic

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Abstract: This review covers aspects of soil science and soil biology of Antarctica with special focus on King George Island, South Shetlands, the maritime Antarctic. New approaches in soil descriptions and soil taxonomy show a great variety of soil types, related to different parent material, mainly volcanic origin, as well as on influences by soil biological processes. The spread of higher rooting plants attract microorganisms, nematodes and collembolans which in turn build new organic material and change the environment for further successors. Microbial communities are drivers with respect to metabolic and physiological properties indicating a great potential in a changing environment. The literature review also shows a lack of investigations on processes of carbon and nitrogen turnover, despite wide knowledge on its standing stock in different environments. Further, only few reports were found on the processes of humification. Only few data are available which can be regarded as long term monitorings, hence, such projects need to be established in order to follow ecological changes.

Key words: Antarctic, King George Island, soil development, soil microbial communities.

Introduction

Soils of Antarctica are widely regarded as poor with respect to nutrients, places for plants and habitats for organisms. Tedrow and Ugolini, pioneers in soil science of this continent described them as young soils without horizons and raw in terms of their functions for soil processes (Tedrow and Ugolini 1966); their material, however, derived from the Antarctic deserts on the continent. Campbell and Claridge (1987) made a first comprehensive attempt to review soils and soil development on the Antarctic continent, a main focus was put to weathering processes. Another synthesis of soils for Antarctica was published by Bockheim and Ugolini (1990). Detailed studies in these coastal areas show a great variety of soils with special characteristics providing various niches for plants and soil organisms from bacteria to insects. Impacts of climate warming has been documented widely, *e.g.* Guglielmin (2008). This review will focus on King George Island soils while viewing on soil scientific steps to its actual state-of-art.

Soils of King George Island

A view on the soils of the area of the Antarctic Peninsula and its islands gives a more differentiated picture, which started with investigations on Signy Island and first spots at South Shetlands (Everett 1976). Here, like in other coastal areas, soils with developed plant stands by *Deschampsia antarctica* and *Colobanthus quitensis*, large moss beds and turfs as well as wide lichen heaths formed by usnean species and surface covers of *Prasiola crispa* at wet areas were found as significant indicators for soil development. This restricted growth pattern, however, probably results not only from late deglaciation, but also from climatic conditions, as buried plant debris of sorted circles at King George Island have been dated between 720 and 4710 years ago (Jeong 2006).

The maritime Antarctic has attracted much interest as retreating glaciers are forming new landscapes. Plant colonization and subsequent soil formation processes are regarded as a big natural laboratory. An eco-climatic description of the Antarctic Peninsula and islands adjoined to the west side show soils of this region, they are affected by grass-herb-fellfields, as well as turbels with different suborders (Bockheim and Hall 2002). A recent review of Antarctic soils has been published under special regard of climate warming (Ugolini and Bockheim 2008; Ramos *et al.* 2009).

King George Island has an ice-free area of about 8%, weathered soils derived mainly from volcanic rock (andesite basalts and their pyroclastics), however, sedimentary rock may be also important in few sites. The periglacial condition with cryoturbation widely prevents active plant growth. Nevertheless, a great variety of soils has been described for *Arctowski* region, such as Haplothels, Umbriturbels, Umbriorthels, Aquiturbels, Haploturbels, Sapristels, Mollorthels, and Psammorthels as determined according to Soil Survey Staff 1998 (Blume *et al.* 2002). Cryosols, Leptosols, Regosols and Fluvisols (WRB taxonomy) are described as main types by Francelino *et al.* (2006) for the Keller Peninsula region.

Soil development is generally related to actual vegetation and general environmental factors (Blume *et al.* 1996, 1997), but it is also important to explain soil's historical role when used as data archives (Tatur and Myrcha 1993, Fabiszewski and Wojtuń 1993). A detailed view on soil formation in the region is presented by Blume *et al.* (2002). Another attempt to characterize the soils of King George Island has been made by Zhao and Li (1996), based on features of diagnostics of soil developmental stages. Schaefer *et al.* (2007) identified by GIS mapping of the *Arctowski* region 20 units of soil scapes and typed them due to their vulnerability and thus presented a geo-environmental map, partly comparable to that of Blume *et al.* (2002).

Antarctic soil formation

The new version of the US Soil Taxonomy summarises the dry permafrost-affected soils as Anhydrous soils (Soil Survey Staff, 2003) and Gelisols, where

pedogenetic processes like cryoturbation, brunification and podzolization occurred (Blume *et al.* 1997; Beyer *et al.* 1999). The latter process, podzolization, originally typical for the northern boreal areas, has been under great dispute after its first description for soils of the continental Antarctic (Blume and Bölker 1993a, b). Podzolization was also found in the maritime Antarctic (Blume and Bölker 1994, Blume *et al.* 1997; Blume *et al.* 2002). The proof for this process was given by the spodic horizons formed by derivatives from high molecular matter of lower plants and chitin but other than lignin (Beyer *et al.* 1997).

The low temperatures hamper physical weathering processes at the level of inorganic as well as organic matter. Clay-sized minerals are widely distributed in soils from King George Island and its ongoing chemical weathering is enhanced by soil dwelling organisms (Sinan *et al.* 2006). Frost activities are responsible for formations of silt and clay, Feldspars and pyroxens, main components of rock, weathered very easily, but actual activation of nutrients is poor for the region of *Arctowski* Station.

The inputs of inorganic nutrients by chemical weathering processes are small but detectable. Nutrient leaching in form of water soluble ions is high due to the coarse material with only few contents of humics but it is hard to state the behaviour of nutrients in the soil profiles, as biological and soil physical factors have to be considered adequately (Chen and Blume 2000). Another important factor for soil development took place while the Island's uplifting during the Holocene. Nutrients rich in phosphatic remains of fossil penguin rookeries promoted the establishment of vegetation (Tatur *et al.* 1997). Some spots have been accepted suitable for humus accumulation (Beyer *et al.* 1997, 1998; Beyer and Bölker 1999). Underneath moss beds and lichen cover some humification occurs with results in brown humus and fulvic acids (Fabiszewski and Wojtuń 1993; Vlasov *et al.* 2006) although only little is known about the formation of humics. Sokolovska *et al.* (1996) found on Livingston Island both, humic and fulvic acids, but no real humus, they describe it as semi-humified organic material. Beyer *et al.* (1995) analysed organic materials from Podzols sampled on relict penguin rookeries from the continental Antarctic (*Casey* Station) and also found fulvic acids and humic acids. Podzols of the Antarctic are less acid and have lower C/N-ratios than those of lower latitudes (Blume *et al.* 1996; Beyer *et al.* 2004).

Soil forming process in relict penguin rookeries are also described by phosphatisation (Tatur 2002). Carbonization, salinization and alkalization were not found in the regions of *Arctowski* or *Casey*, present carbonate on young moraines obviously derived from till (Blume *et al.* 1997).

Direct links to soil development could be established not only for organic matter, but also mainly for water relations which pose in many cases dominant limiting factor for life reactions (Bölker 2005). Soils of glacier forelands are greatly influenced by its coarse structure and high stone content, combined with low contents of humic material they provide only low water holding capacity, its dryness is further a

result of strong winds, which enhance evaporation and erosion. Thus, especially top layers are under strong erosion stress preventing plant colonization and subsequent stable habitat formation. Just crust forming microalgae and cyanobacteria and here-with connected associations can provide a kind of stability in young soils (Elster 2002), a fact which is generally described for both, poor cold and hot environments. Inoue (1991) proposed that water relation is the dominant factor for lichen distribution on King George Island rather than temperature, as precipitation dilutes salt from wind-blown sea spray. The variability in isotopic contents of N and C underlies that N sources are locally of different origin and intensity (Lee *et al.* 2009).

Constitutive nitrogen inputs are mainly related to birds, *i.e.* penguin rookeries, sea spray and nitrogen fixing autotrophs, either by free-living cyanobacteria or by associations in symbiosis. Most of the ammonia-N in the atmosphere is derived from volatilization in rookeries, whereas percolation and run off transports much N directly back to the sea (Tatur and Myrcha 1983). For soils near *Arctowski* Station, N-fixation rates were in the range between 1 and 6 ng N g⁻¹ soil h⁻¹ (Bölter 1995a), data which could be related to other Antarctic and to alpine sites. However, it remains hard to estimate the bulk N content of these soils as most of it is present as salts and not in organic matter (Beyer *et al.* 1997).

Phosphates could be traced back to parent rocks (Chen and Blume 2000). Generally, phosphates are rare in this environment and thus limiting for biological processes. Studies at Fildes Peninsula showed considerable weathering processes and enrichment of phosphates Liu (1991). Relatively high values for total phosphates were found at King George Island (>2 g kg⁻¹, Blume *et al.* 2002). Penguin rookeries, both active and abandoned, have been recognized as main sources for phosphate in soil (Juchnowicz-Bierbasz and Rakusa-Suszczewski 2002; Michel *et al.* 2006) and were analysed in detail for this aspect at King George Island (Tatur 1989; Tatur and Keck 1990; Tatur 2002; Barczuk and Tatur 2003). They significantly promote the growth of *D. antarctica* by their formations of large tussocks among mosses and mats of *Prasiola crispa* and *Nostoc commune* (Olech 2002). Although nutrient input (both, N and P) by precipitation is lower than in other world regions, its contribution is significant for fertilisation and thus might also promote soil biological activities in remote places (Nędzarek and Rakusa-Suszczewski 2007).

Estimates for soil carbon contents for the region of the Antarctic Peninsula soils are about 600 Mt (Claridge *et al.* 2000). Its relevant production derives from mosses and higher plants, although they are limited by harsh environmental conditions. The evolution of environments for soil biological communities depends on growth of higher plants which provide food and shelter. Sites with *D. antarctica* and *C. quitensis* were found as places with elevated levels of soil activity and active food webs (Bölter 1995b; Bölter *et al.* 1997), where the root system is the dominant place of a shared community of bacteria, nematodes and collembola. Such embedded environments are local spots with apparent biotic interactions, although they are still under question for higher trophic levels (Hogg *et al.* 2006).

Soil formation related to soil organisms

Biological soil forming processes in Antarctica are promoted by rooting plants and soil dwelling organisms, *i.e.* microorganisms (bacteria, cyanobacteria, microalgae and fungi), nematodes and collemboles, soils provide them various habitats. Despite low levels of fresh organic material in most areas, a basic community of microbes is present working at almost lowest metabolic rates. More complex food webs can be found in areas with plant growth, especially when rooting plants are available, although the abundance of higher plants needs several years to influence the soil environment (Strauss *et al.* 2009). Several surveys of soil microbial abundances and activity were performed in soils near *Arctowski* Station (Bölter 1995; Bölter *et al.* 1997, 2002; Bölter and Blume 2002; Beyer *et al.* 2002).

Mosses and lichens form associations on moraines, protecting the primary barren soils from direct weather influences and thus forming basic environments making them suitable for microbes and lower organisms. Such mats, as described by Lindsay (1969) are of different associations and widely spread over the maritime Antarctic, recent phyto-sociological reviews show their dominant role in *Arctowski* region with differences in areas affected by penguin rookeries and dryness on moraines (Kappen 2000; Olech 2002; Smykla *et al.* 2007; Victoria *et al.* 2009). These mats can be regarded as stimulating agents for further chemical weathering processes leading to precursors of podzolic environments (Beyer *et al.* 2002; Pereira *et al.* 2008).

The nutritional environment and moisture conditions do not only change the phenotype of *D. antarctica* but is also reflected in genetic differences due to adaptation processes (Chwedorzewska *et al.* 2004). *D. antarctica* and *C. quitensis* are typical for moraines which have been found as abandoned penguin rookeries (Tatur *et al.* 1997). The spread of the two native herb plants, especially *D. antarctica*, has also been used as an indicator for environmental change due to global warming (Komárková 1985; Komárková *et al.* 1990; Smith 1994). They have been monitored as indicators for soil development also on other places of the Antarctica Peninsula (Kim *et al.* 2007; Strauss *et al.* 2009). Its growth and expansion on glacier forelands has shown them also as primary colonists (Kozeretka *et al.* 2010). These plants have formed brownish soils with high contents of organic matter providing habitats for communities of microbes, nematodes and collemboles (Bölter *et al.* 1997; Mouratov *et al.* 2001; Maslen and Convey 2006; Yergeau *et al.* 2007; Gryziak 2009). Thus, nematodes can be regarded as main indicator of progressive soil development.

The taxonomic diversity of microbes also has been described as low (Wynn-Williams 1996) but this needs to be seen in the light by an euryoecious capability of the flora to cope the conditions of environmental changes even in short times and for diverse stress factors (Bölter *et al.* 2002; Bölter 2005). Comparable to the findings with *D. antarctica* (Chwedorzewska *et al.* 2004), microbes also react in their diversity to environmental factors (Chong *et al.* 2009, 2010). But not only adaptations to

constraints of the soil environment has been reported, also protection against UV-radiation is described in spores of *Bacillus subtilis* (Cockell *et al.* 2003).

Divers communities of bacteria in the foreland of Ecology Glacier were found by Greziak *et al.* (2009). The great diversity of microorganisms is also shown by high species numbers of actinomycetes, which showed the pattern of psychrophiles (Hu *et al.* 1993; Christova and Naidenova 1996) as well as by their physiological capacities (Pietr 1986; Zdanowski and Węgleński 2001). The complexity of the microbial community in glacier forelands has been studied by an example at Svalbard and showed that cyanobacteria play an important role, the dominance of heterotrophic bacteria are obviously more related to vegetated plots (Kastovska *et al.* 2005). All three groups of microorganisms, bacteria, inclusive cyanobacteria, microalgae and fungi have been found as primary colonizers in mineral soils (Bölker 1997; Elster *et al.* 1999; Mataloni *et al.* 2000).

Fungi even dominate the bacterial community by biomass in soils of Livingston Island (Bogoev and Gyosheva (1996). High adaptability is probably also true for fungi (Azmi and Seppelt 1998; Yergeau *et al.* 2007). Further, several new species of bacteria and fungi have been isolated and determined, partly with special properties for live in this environment, mainly psychrotolerance (*e.g.* Bozal *et al.* 2003; Yi *et al.* 2005). The latter property is probably also an important survival strategy for fungi (Robinson 2001, Stchigel *et al.* 2001).

Microbial activity is probably less influenced by a primary plant cover, moss (*Sanionia uncinata*) or grass (*D. antarctica*). Data of CO₂-evolution show similar levels, however, microbial biomass was found highest at sheltered locations under the moss cover indicating, *e.g.* by different respiratory quotients, different eco-physiological states of the communities (Lavian *et al.* 2001). Close relationships between microbial activity, determined by soil respiration and microcalorimetry can generally be attributed to elevated carbon levels (Bölker 1994).

Microbial processes are basically controlled by temperature, moisture and the availability of organic matter. The control about the degradation of particulate matter, *i.e.* fresh debris, to a form which makes it available to microbes passes primary steps by collemboles and nematodes and finally the extracellular enzymes of fungi and bacteria. This serves as a main link between dead material and its return to biomass and the food web via microorganisms (Bölker and Kandeler 2004).

During a long term experiment on the decomposition of debris from *D. antarctica* an increase in fungi could be monitored, whereas the bacterial community did not show significant changes (Malosso *et al.* 2004). It is further an interesting finding, that penguin rookeries, *i.e.* the related microbial communities, evolve methane and nitrous oxide in ranges like emissions from northern mesic tundra sites (Sun *et al.* 2002). Such emissions, although at lower rates have also been measured in the Dry Valley region (Gregorich *et al.* 2006). This high variability in physiological and metabolic properties of the microbial community, especially the copiotrophic bacteria shows a high potential of heterotrophic and

autotrophic processes in this environment. Hence, a high potential can be seen which can create new biological niches and soil development.

Further tasks

Ongoing climate warming affects Antarctic environments like others in the world. Several indicators show these effects which can be seen in ecological studies. The spread of the endemic higher plants to new places, so far only covered by lichens or mosses, leading to new environments with higher trophic relationships, followed by significant changes in the soil environment and preparing it on the long run for a change from desert to larger tundra regions. This is accompanied by invaders of higher plants and probably animals. Further, seedlings from plants may find better places for growth and spreading. On the other hand, not only effects by invading organisms has to be taken into account.

The changing atmospheric circulation, local and global, and human impacts have to be taken into account as well as inputs from melting glaciers (Leal *et al.* 2008). The changing of general environmental conditions are more and more reflected in new and stabilized habitats, which can be better related and compared to those from other regions and be categorized by ecological frames (Blume and Bölter 2004). Thus, comprehensive monitoring programs for distinguished places or organisms, like for crustose lichens (Sancho and Pintado 2004), successions on new moraines after glacier retreat (Tscherko *et al.* 2003), or revisits to formerly analysed places be related methods and commonly accepted protocols (Bockheim *et al.* 1993) are necessary to follow the changes in soil development and ecology. An idea which is currently developed by the Polish team in the ClicOPEN IPY project.

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