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The status of Lewis Glacier of Mount Kenya and the threat to Novel microbial communities

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Abstract

The disappearance of African glaciers is of great concern. Most important is the status of Lewis glacier, the smallest glacier in Africa that is rapidly melting. Lewis glacier is a well-documented tropical glacier that experiences a rapid retreat establishing deglaciated foreland. The steep elevation and lack of accumulation layer for Lewis glacier is a possible factor to the rapid loss of its content. The greatest concern is the microbial communities that are lost through the flowing glacier material. The psychrophilic microbes of the glacier are lost in the supraglacial and subglacial to the glacier melting points. The glacier melt, however, creates a deglaciated terrestrial foreland that is recolonized by bacteria, fungi and vascular plants. Most of the foreland community structures are dynamic and differ from the glacier ecology due to various microbial activities including nutrient cycling and mineralization of the rocks. These geochemical process make the glacier foreland to be a chronological ecosystem with spatial biodiversity. The primary foreland is colonized by the bacteria, that prepare the habitat for the saprophytic and mycorrhizal associations. Most of the plants, especially the *Senecio keniophytum* form symbiotic association with some of the nitrogen fixing microorganisms. The ecological change from glacier ecosystem to foreland soil totally creates a new ecosystem with spatial biodiversity that need to be fully investigated for informative conclusions.

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Introduction

Glaciers and ice sheets are known to be biotic ecosystems (Hodson *et al.,* 2008; Stibal *et al.,* 2010) characterized with the complex cryoconite aggregates and diverse microbial community structures (De Smet and Van Rompu, 1994; Takeuchi *et al.,* 2001; Simon *et al.,* 2009; Hodson *et al.,* 2010; Langford *et al.,* 2010). Glacier ecosystems are habitable due to the available melt water, debris and aerosol deposits (Stibal and Tranter, 2007; Hodson *et al.,* 2008) as a result of episodic atmospheric processes (Kühnel *et al.,* 2011), external environment activities (Hodson *et al.,* 2008) and the psychrophilic microbial activities on the glacier surfaces (Hodson *et al.,* 2010; Langford *et al.,* 2010; Stibal *et al.,* 2012; Telling *et al.,* 2012).

The diversity of the microbial communities and their activities on the surface snow, ice and glacier surfaces varies due to spatial biogeochemical processes within the cryoconite material (Stibal *et al.,* 2012; Telling *et al.,* 2012). The biology of cryoconite is known to consist of the organic and inorganic substances (Takeuchi *et al.,* 2010). These substances are however, important in the glacier surface energy budget, slope avalanching and melt water runoff redistribution (Kustas *et al.,* 1994; Hock and Holmgren, 2005).

A number of studies have focused on the diversity of microorganisms on the surface glacier and in the cryoconite aggregates of the polar and mid-polar ecosystems. Polar glaciers are known to harbor unique microbial ecosystems with significant contribution to cryoconite aggregation through the production of cohesive extracellular polymeric substances (Langford *et al.,* 2010; Telling *et al.,* 2010; Stibal *et al.,* 2012). However, the information on microbial ecology, the accumulation of organic and regulation of inorganic substances is limited and no attempts have been made to study these processes on the tropical glaciers of Africa.

This review addresses the critical ecological status of the surviving African glaciers, especially the fast disappearing Lewis glacier of Mount Kenya. These high altitude ecosystems are the most neglected sites with more research focusing on the low altitude terrestrial ecosystems in Africa. The ecological shift from the glacier area to the foreland soil of Lewis glacier indicates the development of an ecosystem of diverse organisms with the loss of novel psychrophilic microorganisms in the glacier.

The foreland chronosequence is a clear indication of this shift with the chronological occurrence of Lichens, Mosses, herbs and vascular trees along the foreland soil.

African glaciers

Africa has a few glaciers (Mt. Kilimanjaro, 5895m, Mt. Rwenzori, 5109 m and Mt. Kenya, 5199m) existing to the East of the continent and a number of evident for Pleistocene glaciations (Anwar, Flickr, & Kilimanjaro, n.d.). The biology of the African glaciers is, however, less studied. Most studies have focused on the glacier length, area-volume change and global warming (Prinz *et al.,* 2011; UNEP, 2012). To an extent, the knowledge on climate change remains scarce and inconclusive due to lack of observational data (Trenberth *et al.,* 2006).

Uetake *et al.* (2014) identified a large black bio-aggregating matter as a glacier moss gemmae aggregation (GMGA) at the summit of Mt. Stanley, Rwenzori. The studies on mid latitude and polar regions have revealed such kind of materials are only formed by the filamentous *Cyanobacteria* (Takeuchi *et al.,* 2010), which was not the case on Mt. Stanley glacier finding. The occurrence of the GMGA in African glacier suggests a possible diverse microbial structures on the disappearing glaciers. These psychrophilic and psychotropic biodiversity organisms remain threatened by the rapid melt of such tropical glacial ecosystems.

Lewis Glacier, Mt. Kenya

Lewis glacier in Mt. Kenya is one of the best documented tropical glaciers globally, with about 80 years of frequent observations of the length, area and volume change (Hastenrath, 1983, 2006; Prinz *et al.,* 2011). The glacier is characterized with supraglacial dust particles that consist of the organic and the inorganic materials (Takeuchi *et al.,* 2010). These studies have enabled the continued measurements of the surface mass balance of this glacier (Prinz *et al.,* 2012). Currently, Lewis glacier is approximately $0.105 \pm 0.001 \times 10^6$ m^2 (Prinz *et al.,* 2012), making it the smallest glacier in Africa, though the biggest in Mt. Kenya, that is rapidly shrinking (Prinz *at al.,* 2011) by rapid melting (Thomson *et al.,* 2009; Rabatel *et al.,* 2013).

Schematic and Hydrological structure of Lewis Glacier

The current status of Lewis glacier (approximately 0.1Km^2; Prinz *et al.,* 2012) compared to its size in 29 year ago (Fig. 1A, Kruss, 1983; Prinz *et al.,* 2011) is an indication of quick loss of glacial biodiversity. Mt. Kenya Lewis glacier is structured into two sites (Fig. 1B, C) ranging between 4875m and 4675m above sea level (Prinz *et al.,* 2012) with slope gradients of 17.4 degrees and 19.8 degrees, respectively (unpublished data).

It also lacks accumulation zone, which is an important region of a typical glacier to hold the glacier content (Prinz *et al.,* 2012).

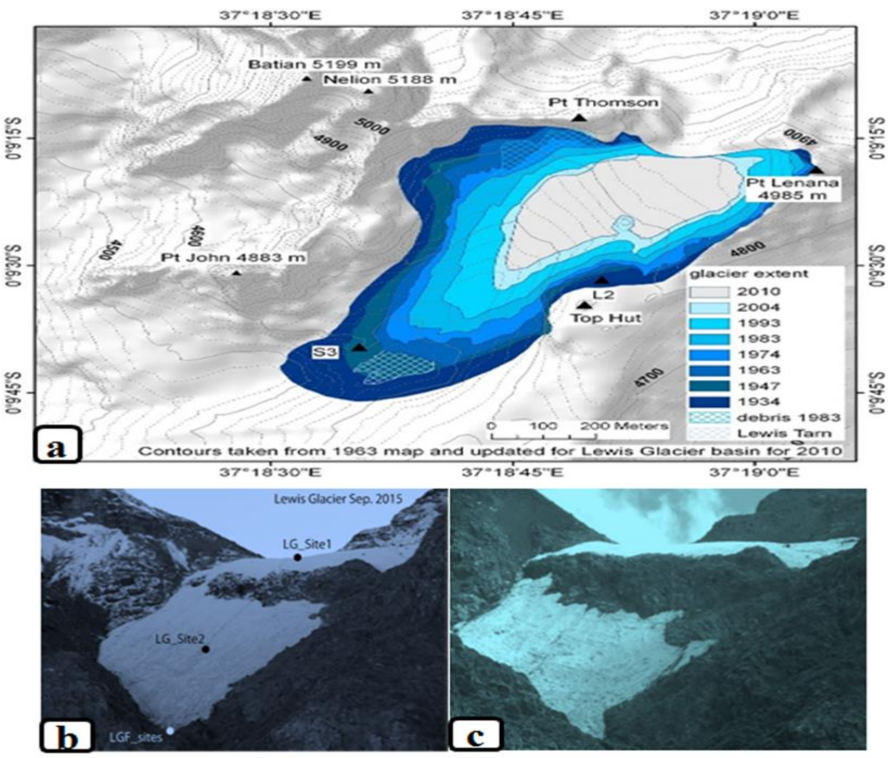

Fig. 1. Status of Lewis since 1934 to 2010 (A, modified from Prinz *et al.,* 2011), later 2015 and 2016 September (B and C respectively) showing the rapid disappearance of the tropical glacier.

The schematic orientation of the two sites facilitates the deglaciation process through avalanching and crevassing as compared to the known glaciers (Hodson *et al.,* 2008). Lewis glacier is highly affected due to its steepness and no accumulation (Prinz *et al.,* 2012), especially the lower site (19.8 degrees), which is characterized by the flowing subglacial river. Crevassing enhances glacier basal sliding and till deformation (Paterson, 1994). The flow of supraglacial microorganisms, snow water and nutrients are enhanced rap by the crevassing processes, which couples the supraglacial and subglacial ecosystems by hydrological transfer within the glacier ecosystem (Hodson *et al.,* 2008).

Glacier hydrological structure is also affected by the turbulence, which result to channeled drainage down the sub-glacier zone (Hodson *et al.,* 2008). The tropical subglacial drainage system advances rapidly due to the network of till channels to an efficient channelized flow due to the input of the large volumes of the surface snow melt (Walder and Fowler, 1994; Hodgkins *et al.,* 2013). When the supraglacial materials descend to the subglacial ecosystem, turbulence highly influences the erosion and sedimentation of the flowing materials, which finally settle at the glacier bed or pressure melting points (Hodson *et al.,* 2008), where microbial community restructures to colonize to colonize the new ecosystems.

Cryoconite materials on Lewis glacier

Lewis glacier is highly characterized by the rich cryoconite materials and surface dust particles just like most glaciers globally (Takeuchi *et al.,* 2010). The cryoconite materials are the habitats for the microorganisms (Des Met and Van Rompu, 1994; Hoham and Duval, 2001; Takeuchi *et al.,* 2001; Segawa *et al.,* 2005; Turchetti *et al.,* 2008; Hodson *et al.,* 2010; Langford *et al.,* 2010), coupled with complex extracellular polymeric substances (Hodson *et al.,* 2008) making it act as a micro-biogeochemical reactor (Hodson *et al.,* 2008; Stibal *et al.,* 2010), which are also connected to the inefficient network of pathways and finally joins the efficient channelized large volume of flowing melts (Walder and Fowler, 1994; Hodgkins *et al.,* 2013).

The slope of the glacier surface is suggested elsewhere (Zarsky *et al.,* 2013) to affect the development of the cryoconite aggregates due to erosive action of the meltwater. The different slope gradient on Mt. Kenya Lewis glacier is a probable factor affecting the stability and residence time of the cryoconite holes and granules through the connecting flow pathways. When the large volume of sediments flows down the glacier bed to the pressure melting points, microorganism experience varying environments where they can either form new colonies or get washed away due to high turbulence (Hodson *et al.,* 2008).

The flowing melt volume consist of the supraglacial and subglacial ecosystems. The phototrophic organisms that colonize the snowpack and the supraglacial zones such as the snow algae, phytoflagellates and cyanobacteria form part of the melt flow (Hodson *et al.,* 2008). During the efficient flow of the large volume of glacial melt (Walder and Fowler, 1994; Hodgkins *et al.,* 2013), the organic and the inorganic content are redistributed unevenly towards the pressure melting points due to the forces involved (Hodson *et al.,* 2008).

The rapid melting of Lewis glacier is also affected by the organic and the inorganic materials in cryoconite holes. The cyoconite materials form dark particles that regulate the glacier surface heat budget. Glacial surface heat budget is linked to glacial surface albedo, which is the light reflectance of snow and ice (Takeuchi *et al.,* 2001). Glacial surface albodo affect glacial melting by the retention of light reflections (Hoham and Duval, 2001). A number of the cryoconite materials are covered with a large amount of snow algae, phytoflagellates and bacteria (Takeuchi *et al.,* 2001). Usually, the melting rates of the intact surfaces are reported to be 3 times larger than that of the surfaces without the cryoconite (Takeuchi *et al.,* 2001). Thus, microbial activity on the glacier possibly affects heat budget and mass balance of glaciers leading to rapid deglaciation.

Microbial ecology of the cryoconite holes

The microorganisms in the cryoconite holes is much greater than that of the ice cover and the mats (Takeuchi *et al.*, 2000; Porazinska *et al.,* 2004; (Säwström *et al.,* 2002; Hodson *et al.,* 2008).

However, the variability of the microbial community structure is dependent on the environmental conditions; especially the glacier slopes and inter-cryoconite hole mixing that leads to continuous colony flushing by the large volume melt water and ecosystem homogenization, respectively (Hodson *et al.,* 2008).

Cryoconite holes from the polar glaciers have been reported to harbour filamentous fungi and yeast (Margesin *et al.,* 2003). However, most cryoconite are known to be dominated by the *Cyanobacteria,* phytoflagallate bacteria, algae and other fungi (Kaštovská *et al*., 2007; Hodson *et al.,* 2008). Viruses are no exception to the cryoconite regions (Säwström *et al.,* 2002), they have been isolated from the melt water, cryoconite granules and sediments (Mac Donell and Fitzsimons, 2008). The role of viruses on glacier is highly significant as they control the bacterial and fungal availability through cell lysis of the hosts (Hodson *et al.,* 2008). The viral activity, however, requires further investigation to understand their role and impact on the glacier ecosystem.

Preliminary studies on Mt. Kenya Lewis glacier show that it is a rich ecosystem with diverse microbial community structures. Using culture dependent and culture independent methods, some of the microbes that have been sequenced from the Lewis glacier include the Archaea; *Euryarchaeota*, Bacteria; *Cyanobacterium*, *Cryobacterium, Agreria, Bacteriodetes*, *Actinobacteria, Acidobacteria, Chlamydiae, Chloroflexi, Firmicutes, Nitrospirae, Fibrobacteres, Plantomycetes, Proteobacteria, Spirochaeta* and fungi such as *Penicillium,* yeast, *Fussarium* (Unpublished data). Some of these microbes have got historical significance in medicine, drug production, redox potential reactions, organic compound mineralization, therefore, they should be conserved for future biotechnological references and ecological applications, especially within the tropical glacial zones that are rapidly melting (Thomson *et al.,* 2009; Rabatel *et al.,* 2013).

Lewis Glacier Foreland

Glacier foreland is a heterogeneous ecosystem consisting of a vertical and horizontal chrono-sequence of organisms (Schütte *et al.,* 2010). The predetermining factor of the foreland succession depends on the nutrient content of the large volume channelized flow melt deposits from the glacier ecosystem. The melt deposits are nutritious materials resulting from the cyanotoxin remains and the organic or the inorganic materials from the cryoconite runoffs (Nemergut *et al.,* 2007).

The microbial community succession of the primary foreland is usually affected by the patchy resource distribution (Tscherko *et al.,* 2003). However, the patchiness is replacement with time as the foreland soil incorporates new associations with species turnover (Welden and Slauson, 1986).

There are two models, directional replacement and directional non-replacement, which explain the spatial microbial community structures of the glacier foreland (Svoboda and Henry, 1987; Matthews, 1992). The directional replacement model describes the horizontal replacement of primary colonizers through a competitive interaction between microorganisms (Walker and Del Moral, 2003), while the directional non-replacement model explains the progressive change and persistence taxa occurrence (Vater and Matthews, 2013).

The foreland microbial community structure is also affected by the accumulation of organic nutrients like carbon and nitrogen which are produced by the succession plants (Zumsteg *et al.,* 2012). The directional non-replacement model reveals that the interaction of the foreland succession is more steady for the mycorrhizal organisms, especially the plant root-associated microorganisms (Davey *et al.,* 2015). The analysis of the 16S rRNA has shown given contradicting information on the phylogenetic diversity along the foreland overtime, Nemergut *et al*. (2007) published an increase in the bacterial community along the foreland while Sigler *et al.* (2002) revealed the opposite.

Elsewhere, it has been established that bacterial biomass dominates the foreland primary succession while fungal community increase along the foreland ecosystem overtime (Bardgett *et al.,* 2007). This is possible due to the bacterial activities like biogeochemical cycling that facilitates colonization by plants and other saprophytic organisms (Schutte *et al.,* 2009).

Lewis glacier is a tropical glacier characterized with a spatial historic foreland that is highly colonized with macro-morphological organisms such as Lichens, Moss, and the *Senecio keniophytum* plants (Fig. 2). The foreland is dated to last 80 years (Prinz *et al.,* 2012).

The primary foreland is characterized with a melt ice lake scanty plant and falling rocks (Fig 2C). The presence of rocks in the foreland is an indication of the mineralizing bacteria (Yoshitake *et al.,* 2010), that prepare the foreland for further succession by the saprophytic organisms. Senecio plant (Fig. 2B) must be the beneficial plants from the mycorrhizal root-association by the symbiotic microorganisms (Davey *et al.,* 2015).

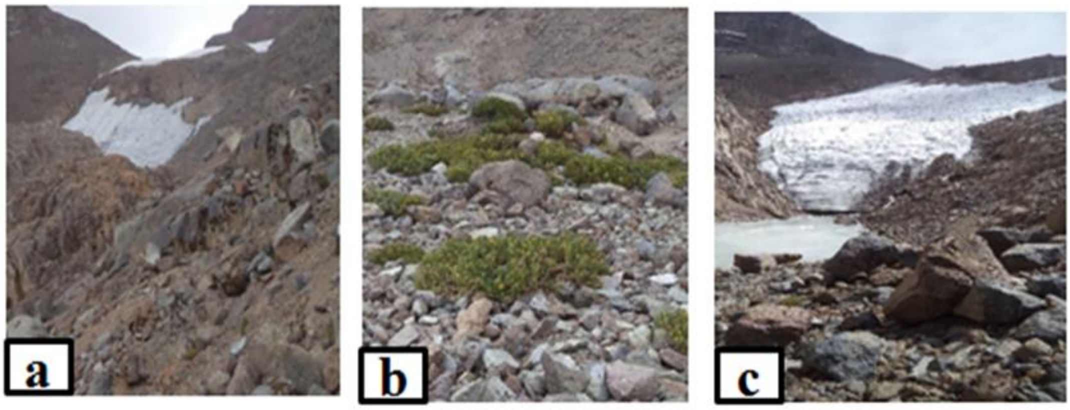

Fig. 2. Characterized Lewis glacier. Lichen and Moss on rocks (A), succession *Senecio keniophytun,* (B) and Lewis glacier primary foreland (C).

Conclusions

Lewis glacier in Mt. Kenya is rapidly disappearing. This phenomenon endangers the possible novel psychrophilic organisms that inhabit such ecosystem. The quick deglaciation is due to the glacier elevation and the accumulation of organic and inorganic materials that lower the supraglacial albedo. The low albedo, therefore, increases the absorption of the sun light radiations striking the glacier surface.

Most of the organic and the inorganic materials are lost through the channelized tillage that couples the supraglacial and the subglacial surfaces. The melt flow leads to a gradual loss of the indigenous psychrotrophs at the glacier bed and melting point. The latter results to recolonization of the deglaciated foreland that is characterized with microbial dynamics due to high levels of nutrients for plants and saprophytes.

Mass balance and the retreat of Lewis glacier is well documented, though there is need to understand the microbial community structures of the glacier zone.

This will lead to the establishment of the microbial diversity, their functional roles in relation to biogeochemical processes on the tropical glaciers and conservation of the threatened unique biodiversity. This can be achieved through a chronosequence of microbial community structures on the glacier and its foreland.

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