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Glacial Fluctuation and Vegetation Succession on Tyndall Glacier, Mt Kenya

Dramatic changes are taking place in the glacier-covered high mountains of Africa. The glacial area on Mt Kilimanjaro is now only half as large as it was in the 1970s. The Tyndall Glacier on Mt Kenya, which retreated at approximately 3 m/yr from 1958 to 1997, retreated at about 10 m/yr from 1997 to 2002. Pioneer species such as Senecio keniophytum, Arabis alpina, mosses, lichen, and Agrostis trachyphylla have advanced over areas formerly covered by the glacier. The rate at which this vegetation migrated up the former bed of the glacier (2.1–4.6 m/yr from 1958 to 1997) is similar to the rate of glacial retreat (2.9 m/yr). In the interval from 1997 to 2002, pioneer species advanced at a rapid rate of 6.4–12.2 m/yr, while the glacier retreated at 9.8 m/yr. Rapid glacial retreat has been accompanied by rapid colonization by plants. Pioneer species improve soil conditions and make habitat suitable for other plants. If warming continues, alpine plant cover may extend all the way to mountain summits, and then eventually diminish as trees colonize the areas formerly occupied by alpine plants. Larger woody plants such as Senecio keniodendron and Lobelia telekii, which showed no obvious advance prior to 1997, have advanced quickly since that year.

Keywords: *Vegetation; deglaciation; global warming; environmental change; alpine zone; Africa.*

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Introduction

Vegetation at glacier fronts is commonly affected by glacial fluctuations (Coe 1967; Spence 1989; Mizuno 1998). Coe (1967) described vegetation zonation, plant colonization, and the distribution of individual plant species on the slopes below the Tyndall and Lewis glaciers. Spence (1989) analyzed the advance of plant communities in response to the retreat of the Tyndall and Lewis glaciers for the period 1958 to 1984. Mizuno (1998) addressed plant communities' responses to more recent glacial retreat by conducting field research in 1992, 1994, 1996, and 1997. These studies illustrated the link between ice retreat and plant colonization near the Tyndall and Lewis glaciers. In addition, till age and substrate stability are critical controls on vegetation patterns around the glaciers (Mizuno 1998).

Numerous studies have been carried out on the glaciers of Mt Kenya (Gregory 1894, 1900; Mackinder 1900; Troll and Wien 1949; Charnley 1959; Coe 1964; Kruss and Hastenrath 1983; Hastenrath 1983a, 1983b, 1984, 1991). Many of these studies dealt with glacial fluctuations and deposits (Baker 1967; Mahaney 1979, 1982, 1984, 1989, 1990). Recently, mountain glaciers in Africa have been retreating at an accelerated rate (Hastenrath 1997; Thompson et al 2002). The present study focuses on glacial fluctuations for the period 1997 to 2002. It clarifies the response of plant communities to recent glacier retreat, and discusses the effects of glacial retreat on ecosystems. The habitats of large woody plants such as *Senecio keniodendron* and *Lobelia telekii*, which are characteristic of tropical high mountains, are examined.

Study area

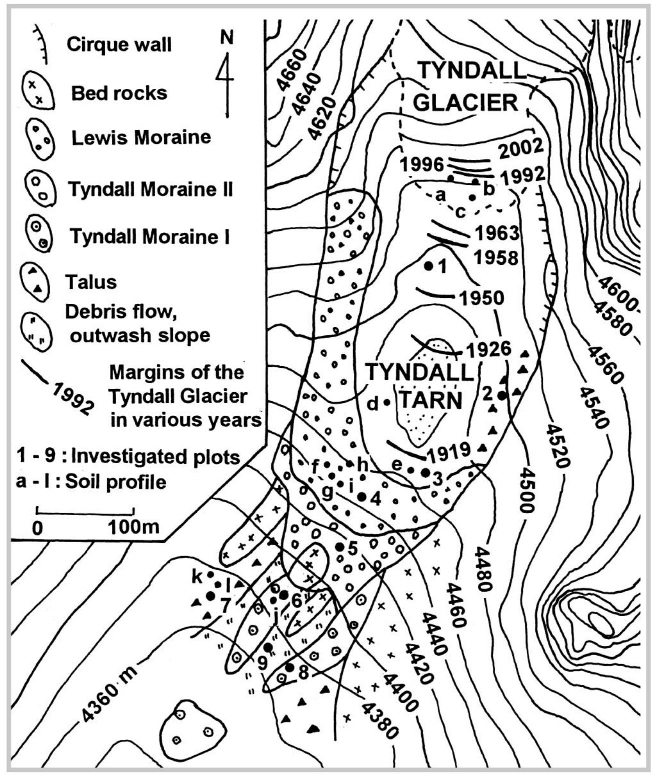
Mt Kenya is an isolated, extinct, denuded volcano that lies on the equator (0°6′S, 37°18′E), approximately 150 km NNE of Nairobi. Its summit, Batian, rises to 5199 m. The mountain was formed by intermittent volcanic eruptions between 3.1 and 2.6 million years ago (Bhatt 1991), and the volcanic plug has been dated to 2.64 million years ago (Everden and Curtis 1965; Mahaney 1990). Rocks of the volcanic massif consist of basalt, phonolite, kenytes, agglomerates, trachyte, and syenite (Baker 1967; Baker et al 1972; Bhatt 1991; Mahaney 1990).

The Tyndall Glacier is the second largest glacier on Mt Kenya, after the Lewis Glacier. Fluctuations of these glaciers have been recorded in detail (Gregory 1894, 1896, 1900, 1921; Mackinder 1900, 1901; McGregor Ross 1911; Dutton 1929; Light 1941; Howard 1955; Hastenrath 1984; Mahaney 1990). Mahaney (1984, 1990) subdivided neoglacial deposits into 2 advances (the Tyndall advance and the Lewis advance) on the basis of several relative dating (RD) criteria, including topographic position, weathering characteristics, and degree of soil profile expression.

The Lewis and Tyndall moraines formed in front of the Tyndall Glacier (Figure 1). The Lewis Till (the Lewis Moraine, ca 100 BP) and the Tyndall Till (the Tyndall Moraine, ca 900 BP) are considered late Holocene in age, based on soil development and weathering features (Spence and Mahaney 1988; Mahaney 1989, 1990; Mizuno 1998). The Tyndall Moraine is divided into Tyndall Moraine I and Tyndall Moraine II, on the basis of topographic position, weathering characteristics, and relative soil development (Mizuno 1998, 2003a).

The elevations at which the annual minimum, mean, and maximum temperatures of the free atmosphere in East Africa are 0°C are approximately 3500 m, 4750 m, and 6000 m, respectively (Hastenrath 1991).

FIGURE 1 Geomorphological map for the environs of the Tyndall Glacier, Mt Kenya. Margins of the Tyndall Glacier for 1919, 1926 and 1963 are from Hastenrath (1983a); for 1950 and 1958 from Charnley (1959). Lewis Moraine (Lewis Till) and Tyndall Moraine (Tyndall Till) are from Mahaney (1982, 1987) and Mahaney and Spence (1989). (Map by Kazuharu Mizuno, based on Hastenrath et al 1989)



The precipitation is southeasterly maximum, resulting from the classical monsoon, and secondary maximum on the western side (Mahaney 1990). Annual precipitation is about 2500 mm per year at 2250 m on the southeast slopes of Mt Kenya, declining to less than 1000 mm per year at the same altitude on the north slope (Hastenrath 1991; Mahaney 1984). Annual rainfall is highest between 2500 and 3000 m on the south, west, and east slopes, and decreases towards the peak (<900 mm at 4500–4800 m). Above 4500 m most of the precipitation falls in the form of snow and hail.

Vegetation on Mt Kenya has been classified in the Alpine Belt (>3600 m), the Ericaceous Belt (3600 to 3400 m on the south slope, 2900 m on the north slope), and the Montane Forest Belt (<3400 m; Hastenrath 1984). The vertical distribution of *Senecio keniodendron* and *Senecio brassica* is used to distinguish the upper and lower alpine zones, although there is considerable overlap in their distribution (Hedberg 1951). In the lower alpine zone, tussock grasses, *Senecio brassica*, and *Lobelia keniensis* occupy the wetter areas, and *Alchemilletum* predominates in dry areas. In the upper alpine zone, *Senecio keniodendron* is present up to 4500 m, together with *Carex monostachya*, *Agrostis* spp, *Cardus platyphyllus, Arabis alpina, Senecio keniophytum,* and *Lobelia telekii.*

Methodology

The position of the Tyndall Glacier's snout was established by measuring the distance from a sign at Tyndall Tarn. The leading edge of plant cover was measured from the terminus of the glacier. Moraine positions were compiled on a topographic map (*The Glaciers of Mount Kenya*, 1:5000, Hastenrath et al 1989) from field surveys and aerial photographs (1:50,000).

Bones and skin of leopard remains were dated by accelerator mass spectrometry (AMS) in the Dating and Material Research Center of Nagoya University (Mizuno and Nakamura 1999).

Plant communities and their environments were surveyed at 9 sites (Plots 1 to 9, each 2 m × 2 m and representing different terrain conditions). At each survey site, surface materials, land surface stability, lichen coverage on exposed rock, vegetation coverage, and species composition were investigated. The particle sizes in the surface rubble layer were measured by the long axis of rubble (30 to 100 measurements at each quadrant). Substrate stability was established using the deflection of a painted line. Lichen cover was used as a cross check to identify stability and to estimate the elapsed time from glacier release. Lichen coverage is the percentage of the exposed part of the debris covered by lichen. Soil profiles were surveyed at 12 sites (Plots a to l). A till age for each plot was estimated using its distance from the glacier front and established glacial retreat rates [2.9 m/yr (1958–1992); 3.8 m/yr (–1958); Charnley 1959].

Habitats of large woody plants such as *Senecio keniodendron* and *Lobelia telekii* were investigated around Plot 6. The relationship between the clast size of surface material and the height of *Senecio keniodendron* and *Lobelia telekii* was studied at 2 sites (15 m × 15 m): Plot A (4390 m, on Tyndall Moraine I) and Plot B (4390 m, on a debris flow and outwash slope).

Results

Fluctuation of the Tyndall Glacier and glacial topography on Mt Kenya

Leopard remains were discovered from the snout of the Tyndall Glacier in 1997 (Figure 2). The upper half of the body of a leopard appeared from the upper surface of the ice. The remains, including skeletal material, spotted skin, and whiskers probably first emerged from the glacial ice in 1997, as they had not been discovered in 1996. Radiocarbon dating (AMS) of the leopard remains determined an age of approximately 900±100 BP (Table 1). This date corresponds to the time when the climate was cooling, and does not conflict with an interpreted cool interval that lasted until the 19th century (Dansgaard et al 1975). Hastenrath (1983b) estimated that representative residence time for ice in the

FIGURE 2A–2D Tyndall Glacier in 1992, 1997, 2002, and leopard remains discovered on the Tyndall Glacier in 1997. (Photos by Kazuharu Mizuno)

Lewis Glacier is a few centuries. Radiocarbon dating of leopard remains in the Tyndall Glacier is inconsistent with the time of the Lewis Glacier.

The climate fluctuated between warm and cold periods prior to 100 BP, accompanied by moraine deposition. In the last 100 years, however, the Tyndall Glacier has retreated constantly and no new moraine material has been deposited. Figure 2 shows the extent of the Tyndall Glacier in 1992, 1997, and 2002, during which time it retreated rapidly. This very rapid rate of retreat from 1997 to 2002 (ca 10 m/yr) contrasts with an average rate of ca 3 m/yr for the period 1958–1997 (Figure 3).

Plant succession in response to deglaciation

Figure 3 shows changes in the position of the glacier front and the leading edge of each advancing plant species (arrow indicates speed of advance). For example, in 2002, no plants were present within 12 m of the glacier front, and *Senecio keniophytum* and *Arabis alpina* were in areas >12 m away from the glacier front. Moss and lichen were present at distances of 27 m and more.

The first species to colonize new till was *Senecio keniophytum*, which advanced at an average rate of 2.7 m/yr from 1958 to 1984, and 2.1 m/yr from 1984 to 1992. These rates of advance are similar to the rate of glacial retreat (2.9 m/yr). Other pioneer species, such as *Arabis alpina*, moss, lichen, and *Agrostis trachyphylla*, advanced at rates between 2.1 m/yr and 4.6 m/yr in response to glacial retreat rates of 2.9 m/yr. *Senecio keniophytum* advanced at 8.8 m/yr and *Arabis alpina* advanced at 12.2 m/yr, in response to the glacial retreat of 9.8 m/yr for the interval from 1997 to 2002. *Arabis alpina* eventually overtook *Senecio keniophytum*: the front edge of the area containing *Arabis alpina* was 11.56 m from the glacier front, whereas that of *Senecio*

TABLE 1 ^{14}C dates for the animal (leopard) discovered on Tyndall Glacier (Mizuno and Nakamura 1999).

Sample number	Material	^{14}C data (yr BP)	Calendar dates calibrated from ^{14}C ages by Calib ETH 1.5b	$\delta^{13}C_{PDB}$ (‰)	Laboratory code number (NUTA-)
1	Bone	973±111	985AD–1200AD	–22.5	5917
2	Bone	893±118	1032AD–1235AD	–22.0	5918
3	Skin	879±175	1004AD–1291AD	–	5920

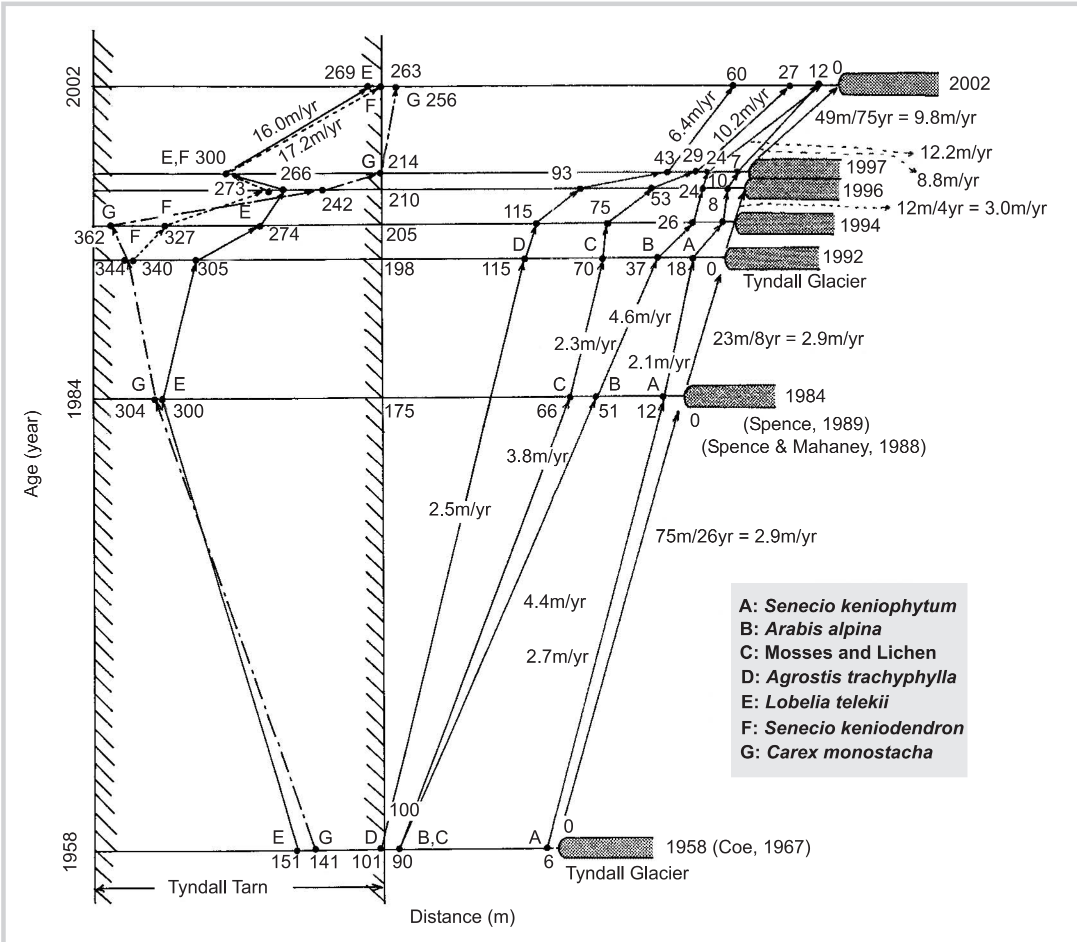


FIGURE 3 Glacial fluctuations and succession of alpine plants. The horizontal axis: distance (m) from the margin of Tyndall Glacier to the front of each plant distribution. The vertical axis: date (the length of the vertical axis indicates years). The arrows indicate movement of the glacial margin or the front of each plant distribution (the inclination of the arrow indicates speed of movement).

keniophytum was 11.80 m. Mosses and lichens advanced at a rate of 10.2 m/yr, and *Agrostis trachyphylla* also advanced at the rapid rate of 6.4 m/yr. Large woody plants such as *Senecio keniodendron* and *Lobelia telekii*, which did not advance prior to 1997, advanced rapidly at 17.2 m/yr and 16.0 m/yr respectively, from 1997 to 2002.

Near the glacier, the earliest colonizing species, *Senecio keniophytum*, is sparse in the eastern area, which receives less solar radiation owing to the shade of the summit. This species prefers cracks in bedrock on convex slopes such as ridges or banks, because the fine material within the cracks retains water and the bedrock slope is stable.

Plant succession and soil development

Plants change the environments they colonize when they advance into areas formerly covered by glacial ice.

FIGURE 4 Soil profiles of plots (see Figure 1). Till ages (yr) of the plots are estimated from glacial retreat rates [2.9 m/yr (1958–1992); 3.8 m/yr (–1958); Charnley 1959]; the color codes are in Universal Color Language, level 3.

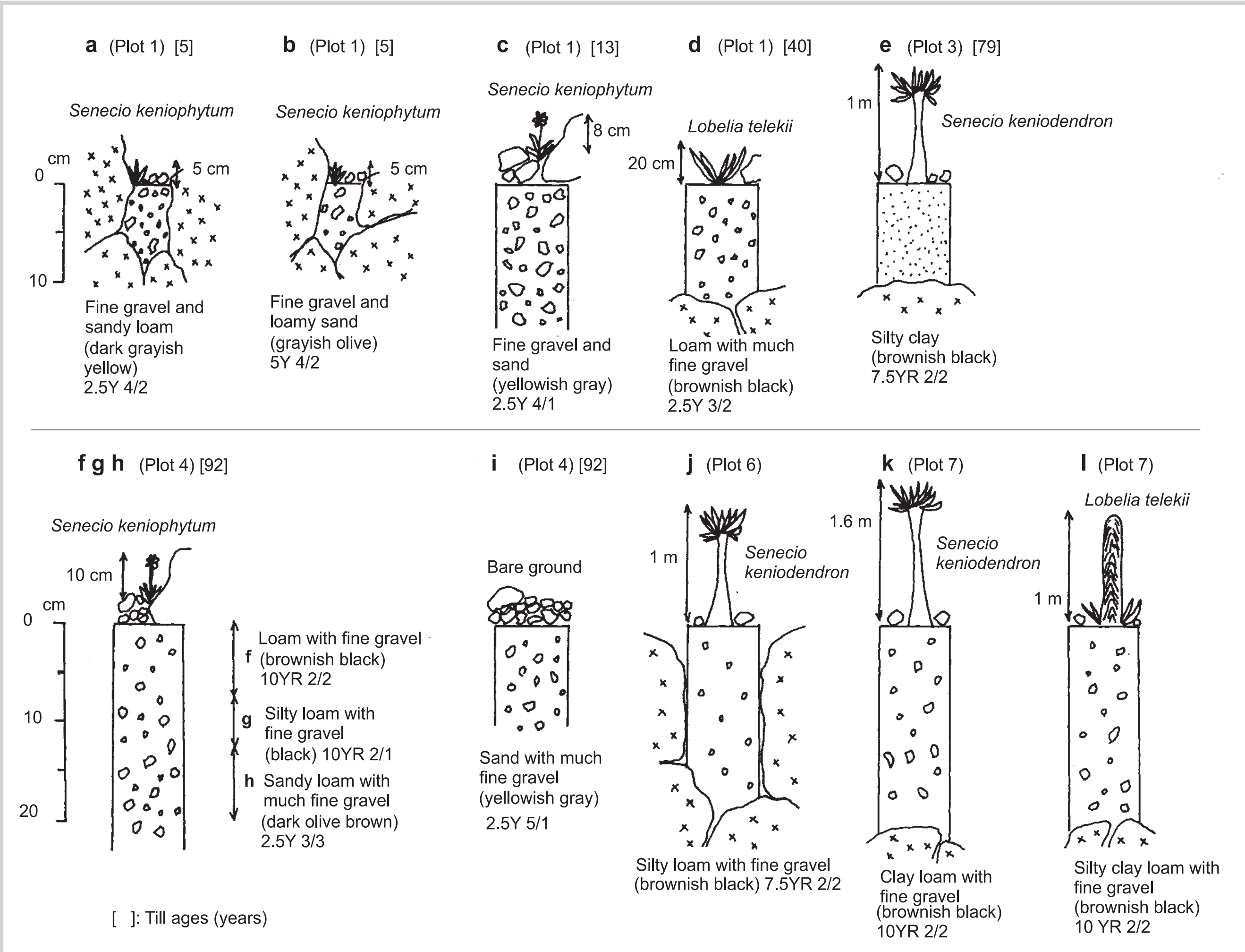


Figure 4 shows the soil profile and till ages for the study plots, or the time elapsed since release from glacial ice. This age is estimated using the distance between the glacier front and each plot, and the glacial retreat rates [2.9 m/yr (1958–1992); 3.8 m/yr (1926–1958)]. For example, the time since release from glacier ice at Plots a, b, and c (ie, the till ages) was estimated at 5–13 years. Soil near the glacier is sandy (loamy sand, sandy loam, and sand) with much fine gravel. Soils are immature and lack humus content, and thus exhibit dark grayish yellow (2.5Y4/2), grayish olive (5Y4/2), and yellowish gray (2.5Y4/1) colors. In the area closest to the ice front, only *Senecio keniophytum* grows abundantly. At Plot e, where 79 years have elapsed since glacial release, soil is fine-grained (eg, silty clay), and brownish-black (7.5YR2/2, 10YR2/2) owing to significant humus content. Soils of this type can support growth of the large woody plant *Senecio keniodendron*.

Soils capable of supporting the growth of diverse plants develop in environments near the glacier front as a result of improvements made by the roots and humus of pioneer species. Dense growth of *Senecio keniodendron*, *Lobelia telekii*, and tussock grass was possible in areas where ice retreat took place ca 500 BP, judging by moraine location and the retreat rate of the glacier. At other sites, such as Plot i, few plants were growing in the sandy, yellowish-gray (2.5Y5/1) soil, despite a period of 92 years since glacial retreat, owing to substrate instability (Table 2). The maximum movement of land surface in the Lewis Moraine (Plot 4, Plot i) was 610 cm, from 1994 to 1996, and 3200 cm from 1994 to 2002 (Table 2). The air temperature changed from 0.2°C (8:00AM) to 5.4°C (3:00PM), and the soil temperature of bare ground (5 cm in depth) changed from –0.4°C (8:00AM) to 10.7°C (3:00PM) at Plot 4 on 5 August, 1994 (Mizuno 1998). Land surface is unstable due to daily active solifluction from freeze–thaw.

TABLE 2 Environments and composition of alpine plant communities at each plot (see Figure 1) around the Tyndall Glacier.

	Plot	1	2	3	4	5	6	7	8	9
	Till age (years)[a)]	40		79	92					
	Landform	Cirque bottom	Talus	Hollow	Lewis Moraine	Tyndall Moraine II	Tyndall Moraine I	Talus	Tyndall Moraine I	Debris flow & outwash slope
	Grain size distribution of surface rubble layer in cm (average)	1–500 (70)	Debris over fine-grained materials 1–500 (30)	1–300 (50)	Debris over fine-grained materials 1–500 (30)	50–500 (150)	20–300 (100)	1–300 (50)	50–500 (150)	1–200 (30)
	Stability of land surface Stable ⟷ Unstable A B C	A	C	A	C[b)]	A	A	A	A	B
	Distance from margin of the glacier	Short ⟵								⟶ Long
	Lichen coverage on exposed block (%)	0	0	30	30	90	95	70	90	40
Vegetation	**Vegetation cover (%)**	1	1	9	2	10	36	45	40	28
	Senecio keniophytum	1	1	5	2	8	5		5	2
	Arabis alpina	+		1			+			
	Tussock grass (*Agrostis trachyphylla*, etc)	+		+			18	15	14	20
	Carex monostachya			+						
	Lobelia telekii			1	+	1	3	10	1	1
	Senecio keniodendron			1		1	10	20	20	5

[a)] Till ages of the plots are the estimated ages based on glacial retreat rates (2.9 m/yr [1958–1992], 3.8 m/yr [–1958], Charnley 1959).
[b)] The maximum movement of land surface was 610 cm during 2 years from 1994 to 1996 and 3200 cm during 8 years from 1994 to 2002.

Vegetation cover is thin on the Lewis Moraine, because of substrate instability and steep slope. In places with large daily air and soil temperature fluctuations, such as tropical high mountains, daily freeze–thaw cycles cause substrate instability, which heavily influences the distribution of vegetation.

Discussion

Deglaciation in the high mountains of East Africa

The Tyndall Glacier of Mt Kenya retreated at a rate of ca 3 m/yr from 1958 to 1997, but at a more rapid rate of ca 10 m/yr from 1997 to 2002. Recently, accelerated glacial retreat has been prevalent among East African mountains. Figure 5 shows glaciers on Mt Kilimanjaro in the 1970s (Hastenrath 1984, 1997) and in 2002 (Mizuno 2003b). Glacier distribution in the 1970s is based on aerial photographs taken on 18 March 1972 (Geosurvey Ltd., Peter Gollmer, Nairobi), a photograph taken during a hot-air balloon flight over the Kibo crater on 10 March 1974 (Alan Root, Nairobi), and field observations by Hastenrath in 1971, 1973, and

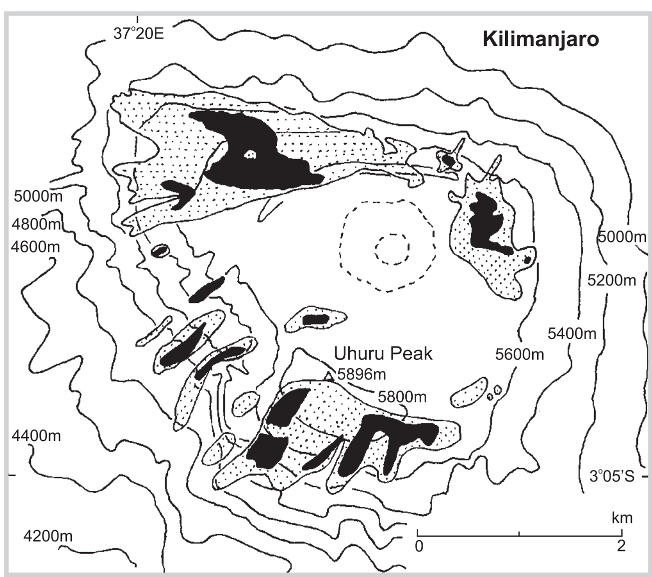


FIGURE 5 Glacial cover of Mt Kilimanjaro in the 1970s (stippled; Hastenrath 1984) and in 2002 (black).

1974. Glacier distribution in 2002 is based on photographs taken from a light aircraft on 17 August 2002 (Mizuno 2003b).

The area covered by glaciers in 2002 was about half of what it was in the 1970s. This is a dramatic change after only 30 years. The retreat of glaciers on Mount Kenya is well documented for the periods 1899–1963 and 1963–1987 (Hastenrath and Kruss 1992; Mahaney 1990). Ice recession between 1899 and 1963 was closely correlated with solar radiation geometry on any given glacier. In contrast, ice thinning between 1963 and 1987 amounted to about 15 m for all glaciers, regardless of location. This suggests that climatic factors other than solar radiation played a more important role. The long-term precipitation records for the Kenyan highlands do not support precipitation deficits of such massive magnitude (Hastenrath and Kruss 1992).

Vegetation succession in response to deglaciation

All plant species near the glacier advanced as the glacier retreated. The first colonists of new till were *Senecio keniophytum*, *Arabis alpina*, moss, lichen, and *Agrostis trachyphylla*. Their rate of advance of 2.1–4.6 m/yr from 1958 to 1997 was similar to the rate of glacial retreat (2.9 m/yr). When glacial retreat accelerated to 9.8 m/yr, from 1997 to 2002, pioneer species advanced at a faster rate: 12.2 m/yr for *Arabis alpina*, 10.2 m/yr for moss and lichen, 8.8 m/yr for *Senecio keniophytum*, and 6.4 m/yr for *Agrostis trachyphylla*. *Senecio keniodendron* and *Lobelia telekii* showed no obvious advances before 1997, but advanced rapidly at rates of 16.0 m/yr and 17.2 m/yr after 1997.

Rapid glacier retreat generally leads to a succession of vegetation, and causes subtle but serious ecological changes. Pioneer species improve soil conditions and make the habitat suitable for other plants. One hundred years after glacial retreat, large woody plants such as *Senecio keniodendron* and *Lobelia telekii* can grow in formerly glacier-covered areas.

Spence (1989) points out that pioneer succession in front of the Tyndall and Lewis glaciers proceeded with the appearance first of *Senecio keniophytum*, followed by *Arabis alpine*. The *Senecio* has fruits with morphological features, aiding in wind dispersion, while the *Arabis* and the grasses lack such features. Species such as *Senecio keniophytum* and *Arabis alpina* that can live at nival elevations on the mountain (>4500 m), appear to establish themselves most successfully (Spence 1989).

Frost soil activity is intense on the till, and cold adiabatic winds sweep off the ice surface (Coe 1967). In particular, when the particle size of surface material is small, high water content in the soil causes periglacial processes such as frost creep and solifluction (Benedict 1970; Washburn 1973; Iwata 1983). These processes, in turn, destabilize the land surface and restrict plant growth (Mizuno 1998, 2002; Mizuno and Nakamura 1999).

Conclusions

Atmospheric warming is causing global diminution of glacier cover. Mt Kenya had 18 glaciers in the early 20th century, some of which have gradually disappeared; at present, only 11 glaciers remain (Hastenrath 1984). When glaciers covering mountain summits melt, plant cover can expand up the mountains. If warming continues, alpine plant cover may extend all the way to mountain summits, and then eventually diminish as trees colonize the areas formerly occupied by the alpine plants. The Tyndall Glacier has retreated by approximately 300 m in horizontal distance since 1919. In extensive mountain ranges such as the Alps or the Andes, if alpine plants were to be eradicated from a given mountain, they could be replaced by the dispersal of seeds from another mountain. On isolated mountains such as Mt Kenya or Mt Kilimanjaro, if alpine plants disappeared because of warming, it would be difficult for them to regenerate if the climate then cooled. Ecosystems on high mountains are very sensitive, and apparently even small environmental changes can cause obvious changes in vegetation. Understanding the relationship between alpine vegetation and its environment is critical to tracking global environmental change.

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