

# Geocology I: Retreating Glaciers, Plant Succession on Mount Kenya Due to Climate Change



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Pictures of Lewis Glacier, the largest glacier on Mount Kenya, captured in 1992 and 2017, respectively. The rapid retreat of glacier is evinced from these two images

**Abstract** Tyndall Glacier on Mount Kenya has retreated notably in recent years due to warming atmosphere, i.e., climate change. It was evinced that the fronts of four pioneering plant species have migrated uphill following the retreating glacier. Specifically, the front of *Senecio keniophytum*, the first to appear in areas exposed by glacier disappearance, migrated a speed similar to that of the glacial retreat. A permanent plot that was adjacent to the glacier terminus in 1996 exhibited a drastic increase in *Senecio keniophytum* population and cover in 2011. Near the terminus of the recently disappeared glacier, the population and cover of vegetation increased notably; however, this increasing trend was slower after the passage of 10 years since the disappearance of the glacier. *Helichrysum citrispinum*, a plant species which was not previously reported near the glacier terminus, was first confirmed in 2009, and its increasing distribution might be a direct result of increasing temperature. With the passage of years after the disappearance of the glacier, gravels become weathered and soil particles become finer. As the humus of the pioneering species

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accumulates, nutrient rich soil develops. The development of soil is also affected by the number of years elapsed after the disappearance of glacier and by the degree of plant establishment that stabilizes the soil layer.

**Keywords** Retreating glaciers · Climate change · Plant succession · Pioneer plant species · Large woody rosette plants

## 1 Introduction

In Africa, only the following three mountains have glaciers: Kilimanjaro, Mount Kenya, and Rwenzori Mountains. However, these glaciers have rapidly melted in recent years (Thompson et al. 2002). In the next 10–20 years, it is likely that these glaciers will disappear.

The proglacial areas associated with retreating glaciers have been well studied in North America, Scandinavia, other polar regions, and European Alps; however, such studies are lacking in tropical mountain regions.

Several studies worldwide have recorded and described the chronological changes in plant species in moraines from different time periods over the past hundreds of years (Mori et al. 2008). However, studies recording real-time glacial retreat and plant migration based on the chronological record of glacial expansion and historical records are largely lacking. Studies by Mizuno (1998, 2005a, b) elucidated the relationship between the process of glacial retreat and succession of a series of plant species in real time in over 50 years based on previous studies on Tyndall Glacier on Mount Kenya (Nagy and Grabherr 2009).

Several studies have shown that the main factor that dominates distribution of plant species is the time implied by the age of till (Matthews 1992). For example, it has been shown that plant succession on ground moraine could take several hundred years to reach the climax of alpine vegetation (Raffl and Erschbamer 2004). In general, pioneering plant communities with low cover grow on 20th century sediments. Meanwhile, communities with high cover were established on moraines that formed in the 19th century (Caccianiga and Andreis 2004). Garbarino et al. (2010) examined the distribution of larch on the Ventina glacier in central Italy; they demonstrated that the factors that had the greatest impact on the density and the age of larch were plant litter cover, elevation, distance to glacier terminus, and seed source.

Coe (1967) studied the plant communities in the individual vegetation belts on Mount Kenya, specifically, the invasion and establishment of plants in alpine zones. The study demonstrated the retreat of Tyndall and Lewis glaciers, and the advancements of distinct plant species. Spence (1989) detailed the retreat of these glaciers and the advancements of each plant community between 1958 and 1984. Mizuno (1998, 2005a, b) and Mizuno and Fujita (2014) showed that the pioneering plants

that grew near the terminus of Tyndall Glacier have advanced as the glacier retreated between 1992 and 2011. In addition to the time elapsed since the disappearance of the glacier, the stability of ground surface also has had a notable impact on plant distribution, specifically on glaciers located in tropical alpine environments, where daily temperature fluctuation is significant (Mizuno 1998, 2005a, b; Mizuno and Fujita 2014).

In contrast, plant species that were not previously reported around the glaciers of Mount Kenya were discovered in 2009. It was apparent that certain plant species had advanced their distribution regardless of glacial retreat. However, no study has yet examined the impacts of both glacial retreat and climate changes on plant succession, and their relationship is not yet clear.

In the present chapter, we discuss the recent climate changes, and the pattern of glacial retreat and landform development. We also discuss the reactions of each plant species to recent glacial retreat, environmental changes in relation to the distribution and succession of plants, and relationship between climate change and plant succession.

## 2 Surveyed Area

Mount Kenya or “Kirinyaga” is the second highest mountain in Africa and is located on the equator. The African country Kenya has derived its name from the mountain. Mount Kenya is an old volcano in the Great Rift Valley. The height of the Batian Peak is 5199 m. This volcano was formed through intermittent eruptions that occurred 3.1–2.6 million years ago. Its peak was eroded over a long period of time, leaving solidified lava that filled the pipes, thereby creating a sharp peak (Bhatt 1991). The rock types present in this region include basalt, phonolite, trachyte, and syenite, amongst others (Mahaney 1990; Bhatt 1991).

By the end of the 19th century, there were 18 glaciers in Mount Kenya; however today, there are only Lewis, Tyndall, and a few other glaciers remaining.

Annual precipitation on Mount Kenya is higher on the southeastern slope, and reaches approximately 2500 mm at an elevation of 2250 m. In contrast, on the northern slope, it is below 1000 mm (Mahaney 1984; Hastenrath 1991). The annual precipitation is the highest at elevations of 2500–3000 m on the southern, western, and eastern slopes. It becomes lesser close to the peak (900 mm or less at 4500–4800 m). At elevations of 4500 m or higher, most of the precipitation occurs in the form of snow or hail.

Mount Kenya has the following belts: Nival belt (above the snowline), Alpine belt, Hagenia-Hypericum belt, Bamboo belt, Montane forest belt, and Savannah belt (cultivation and grassland), from top to bottom (Coe 1967). The lower Alpine belt has tussock grasses that are dominated by *Festuca*, *Agrostis*, and *Descampsia*: a community that includes *Lobelia keniensis*. The upper Alpine belt has communities of *Senecio* (Asteraceae), especially *Senecio keniodendron* and *Senecio brassica*, and *Alchemilla argyrophylla*.

Although there are glaciers on the peak of Mount Kenya, pioneering plant species such as alpine plants from Asteraceae (e.g., *Senecio kenioophytum*) and Brassicaceae (e.g., *Arabis alpine*) can be found immediately below the peak, and their distributions are increasing with the retreat of the glaciers. On the relatively stable slopes below, large woody rosette plants such as *Senecio keniodendron* and *Lobelia telekii* are found. These plants are characteristic of tropical alpine landscapes where daily temperature fluctuations are high.

*Senecio keniodendron* is also identified as *Dendrosenecio keniodendron*, when woody *Senecio* is considered as a subgenus of *Senecio*; this book adopts the term *Senecio keniodendron*.

### 3 Recent Climate Changes: Glacial Retreat and Landform Development

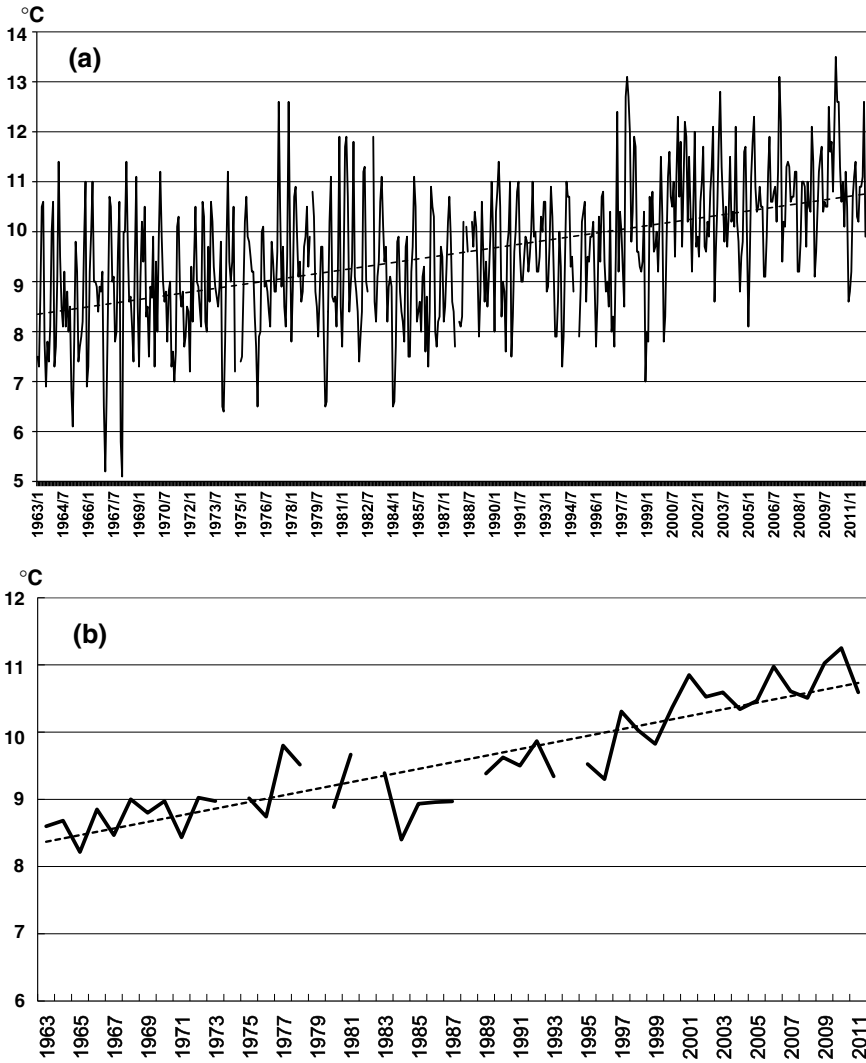
The temperature at Nanyuki Meteorological Station (0.03°N, 37.02°E), located at an elevation of 1890 m on the western foothills on Mount Kenya, has increased by more than 2 °C in 48 years from 1963 to 2011 (Fig. 1). In contrast, no notable decrease in precipitation at the same location has been recorded from 1956 to 2011.

Based on temperature data at Mount Kenya Global Atmosphere Watch (GAW) Station (0.06°N, 37.30°E), which is situated at a higher elevation of 3678 m, it was inferred that the rate of temperature decrease in Mount Kenya was 0.63 °C/100 m. Based on this rate, the temperature of the glacier terminus located at an elevation of 4500 m was calculated.

There was a significant relationship between the changes in the monthly mean minimum temperature at an elevation of 4500 m and the glacial retreat process ( $y = 5.882x + 45.427$ ,  $R^2 = 0.6625$ ;  $P = 0.0085$ ) (Mizuno and Fujita 2014). Therefore, we can suggest that the glacial retreat at Mount Kenya is mainly caused by climate change (warming).

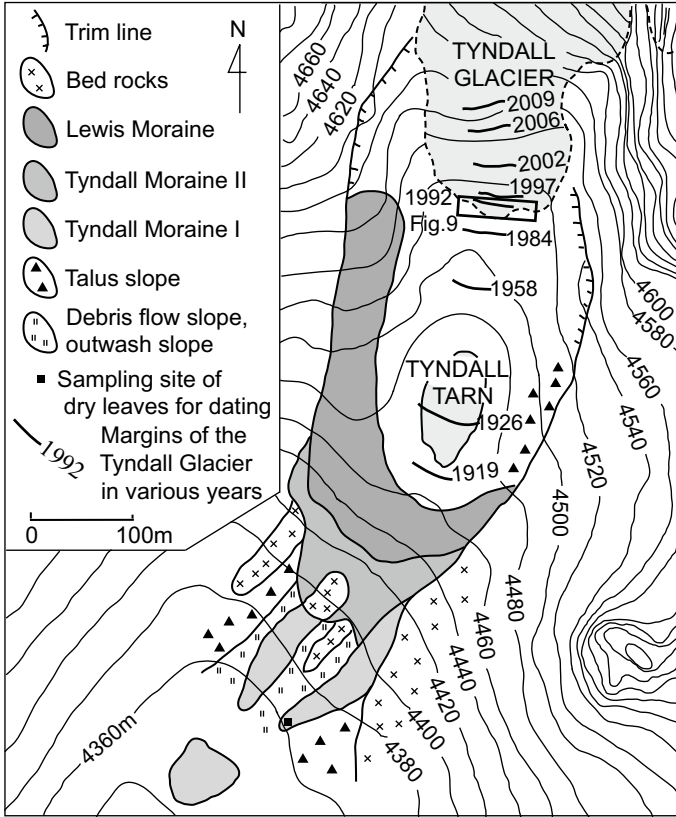
Figure 2 shows the terminus of Tyndall Glacier and its surrounding landforms. Around Tyndall Glacier, Lewis Moraine is found, which is estimated to have formed approximately 100 years BP (100 years before 1950). On the lower slope, Tyndall Moraine was estimated to have formed at approximately 900 years BP (Fig. 3) (Mahaney 1989, 1990; Mizuno 1998; Mizuno 2005a). The location of Tyndall Glacier terminus shown in Fig. 2 reflects that the glacier has continuously retreated in the past 150 years. Therefore, it is evinced that no moraine was formed in this location during the past 150 years.

On the eastern side of Tyndall Tarn, talus is found, which is a sedimentary landform where weathering debris from the surrounding cliff accumulates at the base. Since talus forms an unstable slope consisting of debris, it is difficult for plants to get established in this location. On the lower slope of moraines lies the outwash fan, which is a landform created by sediments that were carried and deposited by debris flow and outwash (glacial meltwater flow).



**Fig. 1** Temperature variations between 1963 and 2011 in the foothills of Mount Kenya situated at an elevation of 1890 m. **a** Monthly mean minimum temperature, **b** annual mean minimum temperature (data obtained from Kenya Meteorological Department)

During the 1997 survey, I discovered the remains of a leopard, half of which were protruding from the ice at the terminus of Tyndall Glacier (Fig. 4). The remains were subjected to radiocarbon dating using an accelerator mass spectrometer, and it was found that the remains were 900–1000 years old (Mizuno 2005a, b). This timing was associated with climate shift from warm period to cold period, which is consistent with cold climate until the 19th century.



**Fig. 2** Geomorphological map of Tyndall Glacier on Mount Kenya (Mizuno and Fujita 2014). Location of the terminus of Tyndall Glacier in the respective years was obtained from the following studies: 1919 and 1926: Hastenrath (1984); 1958: Charnley (1959) and Coe (1967); 1984: Spence (1989); 1992–2009: Mizuno and Fujita (2014). Names of Lewis Moraine (Lewis Till) and Tyndall Moraine (Tyndall Till) are based on Mahaney (1984, 1989) and Mahaney and Spence (1989). The map is prepared by Kazuharu Mizuno based on the contour map of Hastenrath et al. (1989)

## 4 Reactions of Each Species to Recent Glacial Retreat

### 4.1 Glacial Retreat and Plant Succession

Several studies have been conducted on the dynamics of glaciers on Mount Kenya (Hastenrath 2005, 2008). The relationship between glacier dynamics and sediments has been also examined (Mahaney 1990). Tyndall Glacier rapidly retreated between 1992 and 2019 (Fig. 5), and the rate of retreat was approximately 3 m/year between 1958 and 1996, 10 m/year between 1997 and 2002, 15 m/year between 2002 and 2006, 8 m/year between 2006 and 2011, and 9–18 m/year between 2011 and 2019.

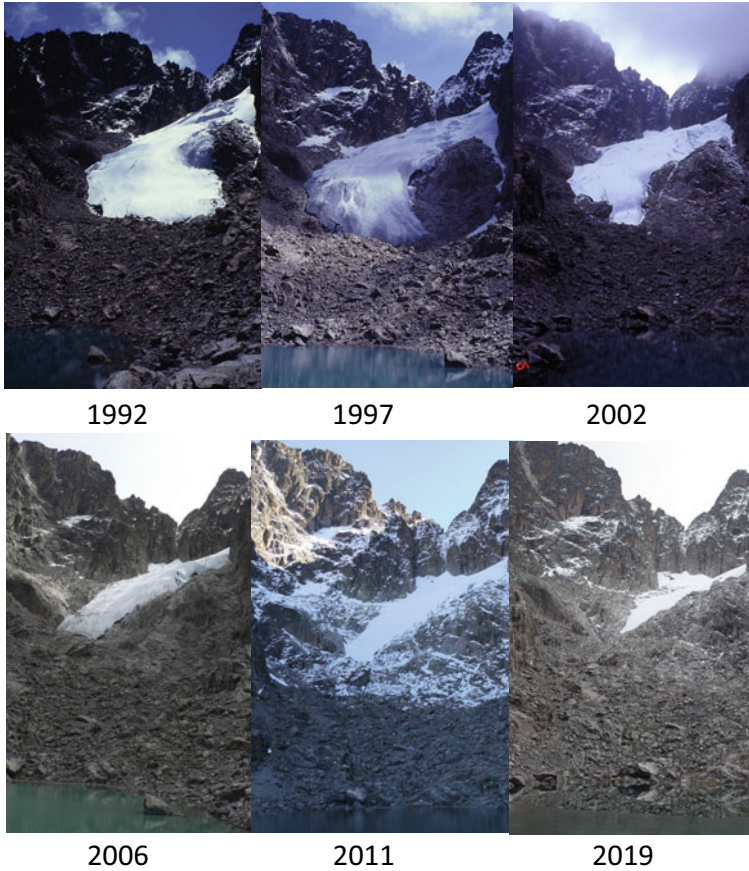




**Fig. 3** Main peak of Mount Kenya, Batian peak (5199 m). The glacier on the left is Tyndall Glacier in 1992. The moraine in the front is Lewis Moraine



**Fig. 4** The remains of a leopard discovered in Tyndall Glacier in 1997. The remains were dated back to 900–1000 years via radiocarbon dating



**Fig. 5** Tyndall Glacier in 1992, 1997, 2002, 2006, 2011, and 2019

It was observed that four pioneering plant species have advanced their respective fronts to uphill following the retreat of the glacier. Specifically, *Senecio keniophytum* (Fig. 6), the primary pioneering species that grows in areas where glaciers have melted, was found to have advanced at the same pace as the glacial retreat (Fig. 7). The rate of glacial retreat was significantly correlated with the migration of *Senecio keniophytum* ( $y = 0.8635x + 1.5631$ ,  $R^2 = 0.7205$ ;  $P = 0.0047$ ). Other pioneering plant species such as *Arabis alpina*, *Agrostis trachyphylla*, bryophytes, and lichens have also advanced at an increasing rate since 1997 (Fig. 7).

*Carex monostachya* and *Agrostis trachyphylla* have advanced faster in recent years; between 2015 and 2019, they advanced especially faster, at 37 m/year and 27 m/year, respectively. For a long time, the first species to appear after the disappearance of glacier was *Senecio keniophytum*; however, in 2016 and 2017, a species of lichen, *Rhizocarpon geocumum*, appeared as the first pioneering plant species closest to the glacial terminus (Fig. 7).





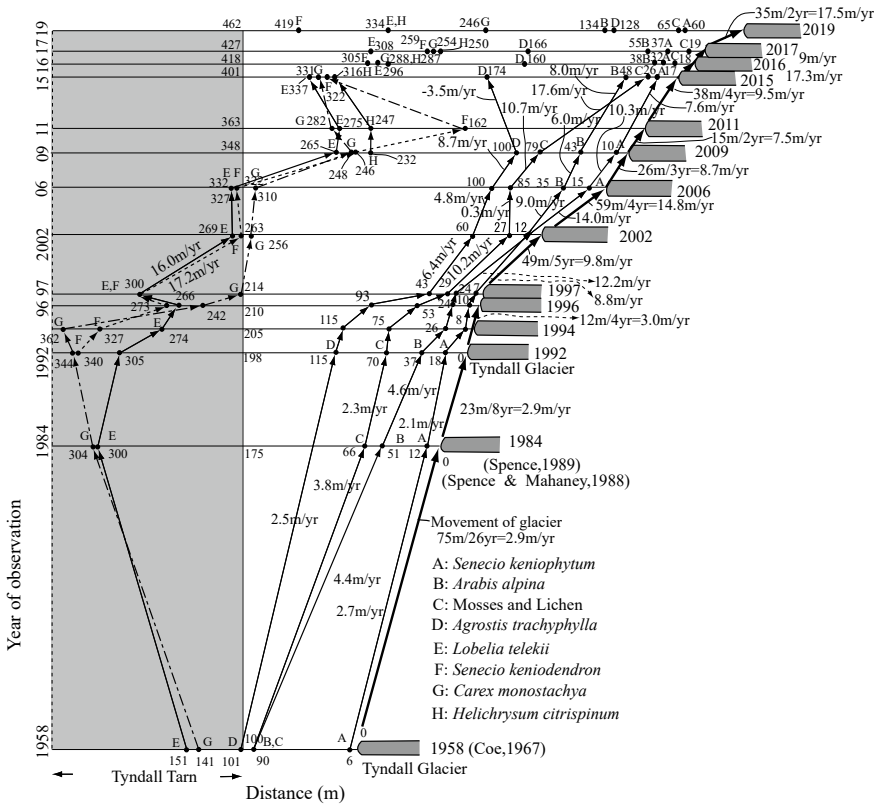
**Fig. 6** First pioneering species, *Senecio keniophytum*, that appeared after the disappearance of the glacier

Seeds of *Senecio keniophytum* (3 mm) and *Arabis alpina* (1–1.4 mm) are extremely small. Therefore, these species can spread their seeds over relatively wider areas. Dispersal capacity of seeds varies between species, which has an impact on the composition of plant communities (Fuller and del Moral 2003). The characteristics of seed dispersion might be related to invasion by pioneering species in those areas that were recently vacated by glaciers.

The changes in the front of large woody rosette species, *Lobelia telekii* and *Senecio keniodendron* (Fig. 8) appeared unrelated with glacial retreat until 1997; these species have been advancing ever since (Fig. 7).

#### **4.2 Succession at a Permanent Plot in the Cirque Bottom**

A survey of the distribution of plants was initiated in 1996 in a permanent plot (80 m × 20 m) located at the terminus of the glacier in the cirque bottom (Fig. 2). The survey demonstrated that the population and cover of *Senecio keniophytum* has significantly increased in 15 years after 2011 (Fig. 9). In these 15 years, the average number of individual plants per sampling quadrat (2.5 m × 2.0 m) increased by 14 times, while the average cover (the ratio of ground surface covered by plants) per sampling quadrat increased by 183 times (Mizuno and Fujita 2014). In 1996, only *Senecio keniophytum* grew in the plot; however, in 2011, three additional species appeared although *Senecio keniophytum* was still predominant. In areas that were recently vacated by glaciers, the number of individual plants and cover had increased

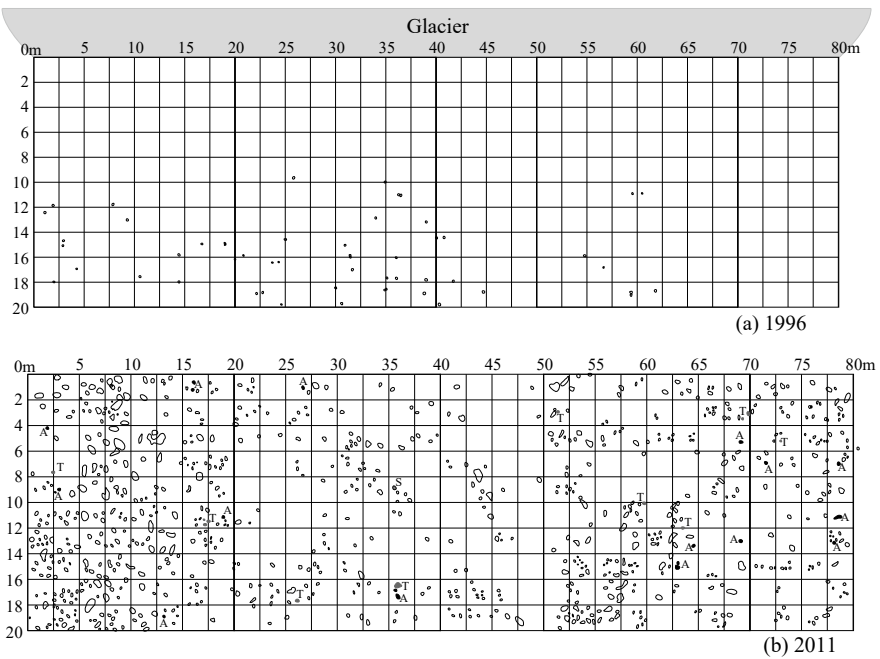


**Fig. 7** Fluctuations of Tyndall Glacier and the succession of alpine plants. Horizontal axis: Distance (m) from Tyndall Glacier terminus to the leading edge (upper distribution limit) of each plant species. Vertical axis: Years of observation, whereby the length of the vertical axis indicates years. The arrows indicate the movement of Tyndall Glacier terminus (thick line) and changes in the leading edge of each plant species. The inclination of arrows shows the speed of movement

at a distance of 16–18 m from the glacier terminus; however, this trend disappeared after some years. Within five to six years of the disappearance of glacier, several seedlings of *Senecio keniophyllum* grew (Mizuno and Fujita 2014).



**Fig. 8** Large woody rosette plants, *Senecio keniodendron* (center) and *Lobelia telekii*



**Fig. 9** Distribution of *Senecio kenioophytum* in **a** 1996 and **b** 2011 in the permanent plot (80 m × 20 m) established in 1996 adjacent to the glacier terminus (Fig. 2) (Mizuno and Fujita 2014). A: *Arabis alpina*; T: *Agrostis trachyphylla*; S: *Senecio keniodendron*

## 5 Environmental Parameters in Relation to the Distribution and Succession of Plants

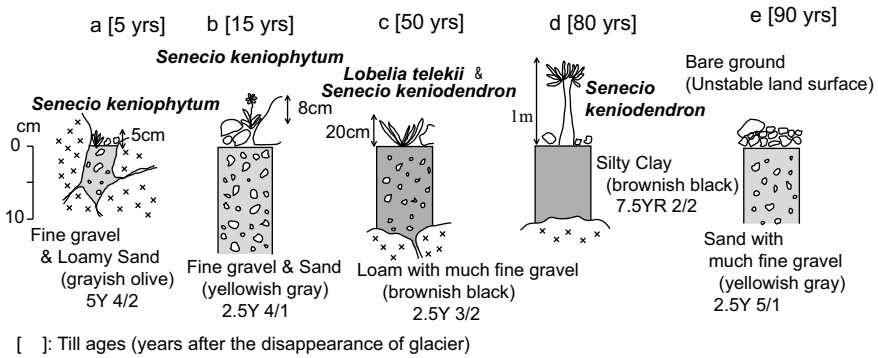
### 5.1 *Plant Distribution Based on Moisture Conditions and Slope Stability of Landforms and Sediment*

It was observed that near the glacier terminus, *Senecio kenioophytum* tends to grow on ridge-shaped convex slopes in the cirque bottom. It grows within the cracks in bedrocks and in gaps between rocks because finer particles tend to collect in cracks and gaps. In Fig. 9, the areas that are densely populated with plants correspond roughly to such ridge-shaped convex slopes. When seeds fall in these areas, they receive sufficient moisture retained by fine particles, and as they grow, roots stabilize these particles. Stable bedrocks and boulders play an important role in stabilizing the habitats as the ground surface is not easily mobilized.

I examined the environment in the habitat of large woody rosette plants, *Senecio keniodendron* (giant *Senecio*) and *Lobelia telekii* (giant *Lobelia*) in a wider area including cirque bottom, moraine, talus slope, debris slope, and outwash slope (Fig. 2). I found that *Lobelia telekii* is mostly found on debris flow and outwash slopes, while *Senecio keniodendron* is found on moraines (Mizuno 2005b) (Fig. 8). The inflorescence of *Lobelia telekii* withered every year (for several years); however, that of *Senecio keniodendron* did not wither for decades. Their stalks grew upwards, and new rosette leaves grew on the top of the stalk. The difference in the specific characteristics of these plants likely led to their adaptation in different sites, such as debris flow, outwash slope, and moraines. In other words, the present debris flows and outwashes inhibited the growth of plants on concave debris flow and outwash slopes. However, their landform indicated that soil moisture was high, which made it suitable for *Lobelia telekii* to grow. In contrast, convex slopes, such as that of Tyndall Moraine I, do not often experience impact of debris flow or outwash after formation, and owing its stable surface, *Senecio keniodendron* was able to grow for years to reach their large size. The locations like Tyndall Moraine I, where large boulders accumulate, are the perfect habitat for *Senecio keniodendron*. This is because the rocks become warm during daytime, and the increased heat favors the growth of *Senecio keniodendron*. In addition, seedlings and saplings can use water dripping through rocks, while being sheltered from snow and rain.

### 5.2 *Development of Soil and Plant Succession Associated with Glacial Retreat*

In areas where soil conditions make it difficult for the general plants to grow, only pioneering plant species can invade. *Senecio kenioophytum* can grow in those locations that were freed from glacier 5–15 years back. In such areas, the soil was coarse, and



**Fig. 10** Typical soil profiles at the survey sites (Mizuno 1998; Mizuno and Fujita 2014). Number in bracket is the age of till (years after the disappearance of the glacier). Age of till (years) was estimated based on the distance from the glacier terminus and from the following rate of glacial retreat: 3.8 m/years [–1958] (Charnley 1959); 2.9 m/years [1958–1997]; 9.8 m/years [1997–2002]; 14.8 m/years [2002–2006]; and 8.7 m/years [2006–2009]. Soil profiles were drawn based on the soil profile data observed between 1992 and 2009

consisted of grayish olive and yellowish gray colored loamy sand with small gravels. Gray color was observed owing to low humus content (Mizuno 1998; Mizuno and Fujita 2014) (Fig. 10). After many years since the disappearance of the glacier, gravels became weathered, soil particles became finer, and soils were developed that were relatively rich in nutrients due to accumulation of humus from pioneering species. In locations where the glacier disappeared nearly 50 years back, enough humus was accumulated from pioneering plant species, and soil became black and turned into brownish black loam with a finer grain size. Seedlings of large woody rosette plants, *Senecio keniodendron* and *Lobelia telekii*, began to grow, which changed the environment in such a way that it became suitable for several other plant species. In locations where the glacier disappeared 80 years previously, the height of *Senecio keniodendron* reached 1 m, and the soil became fine silty clay with brownish black color due to the accumulation of humus.

### 5.3 Vegetation and Land Surface Stability

After 100 years since the disappearance of glacier, if the ground surface remains covered in fine gravels and if it undergoes movement, plant invasion and establishment become difficult, which leaves the site bare (Fig. 10). In August 1994, I drew a 1 m line on the bare ground surface with 27° slope of Lewis Moraine using yellow paint to evaluate the changes in the line. During two years, from August 1994 to August 1996, the line moved to a maximum of 6.1 m, and subsequently, it moved to a maximum of 32 m over eight years between August 1994 and August 2002 (Mizuno 2005a, b). During the dry season, freezing of land surface in the morning and thawing



in the afternoon was observed along the slope. The solifluction of the thawed layer with oversaturation in the dry season was also monitored, and the results indicated that the gravels moved due to the freeze-thaw actions and solifluction.

In tropical alpine areas, diurnal temperature fluctuation was large, which could be 10 °C or more around glaciers on Mount Kenya. Mount Kenya has a snow season of approximately five months and a dry season of approximately seven months. Therefore, the diurnal temperature of air and soil fluctuated between above and below 0 °C during the dry season, leading to notable freeze-thaw actions and solifluction on the ground surface. Soil in such locations was underdeveloped, similar to locations that have remained free from glacier only for a short period of time. As such, the development of soil was impacted by the establishment of plants associated with the number of years elapsed since the disappearance of glacier and establishment of plants due to the stabilization of the ground surface, i.e., without any movement of surficial materials.

## 6 Relationship Between Climate Change and Plant Succession

### 6.1 Growth of Large Woody Rosette Plant and the Climatic Environment

Giant *Senecio* has a stalk of 1–6 m. It has large rosette-shaped evergreen leaves at the top of the stalk, avoiding colder temperature at the ground surface (Fig. 8). While aging, instead of falling down, their leaves droop, wrap around the stalk, and turn woody, which creates a heat insulation layer. Rosette-shaped leaves open during the day and close at night. As giant *Senecio* does not have tree rings, the relationship between its height and age has remained unknown. Thus, the growth rate of giant *Senecio* was examined using dried leaves on stalk. In 2019, dry leaves were collected from three places on each of the stalks of two giant *Senecio* (*Senecio keniodendron*) plants on Tyndall Moraine I (Fig. 2). The age of six samples was determined through radiocarbon dating (<sup>14</sup>C, AMS: accelerator mass spectrometer) (Table 1). The average rate of growth was found to be 3 cm/year for *Senecio keniodendron* A, which had a height of 283 cm (208 cm for the stalk and 75 cm for the crown). Its date of germination and age were estimated to be 1940 and approximately 80 years, respectively. The average growth rate was 4.5 cm/year for *Senecio keniodendron* B, which had a height of 337 cm (241 cm for the stalk and 96 cm for the crown). Its date of germination and age were estimated to be 1950 and approximately 70 years, respectively. It is likely that the age of giant *Senecio*, whose height exceeds 5 m, is 100 years or more (Fig. 8).

The giant *Lobelia*, *Lobelia telekii*, has stalk height of 2–3 m. Its structure is like a hollow cylinder with a diameter of 5–8 cm that is filled with liquid up to approximately 1 m from the ground surface. The outer surface of the stalk is covered

**Table 1** Dates obtained through radiocarbon dating (<sup>14</sup>C, AMS) of three dry leaf samples collected from two *Senecio keniodendron* plants in Tyndall Moraine I (Fig. 2)

Sampling height from the ground (cm)	Date ( <sup>14</sup> C, AMS)	Beta ID
<i>Senecio keniodendron</i> A (height 283 cm; 208 cm stalk and 75 cm crown)		
48	1958–1960	537356
118	1978–1981	537357
168	1996–2000	537358
<i>Senecio keniodendron</i> B (height 337 cm; 241 cm stalk and 96 cm crown)		
20	1959–1960	537359
120	1984–1987	537369
200	1999–2002	537361

with hairy buds. It was found that the liquid in the stalk began to freeze at night when the temperature reached 0 °C or lower, which released latent heat and warmed the air in the upper stalk through convection (Krog et al. 1979). In this manner, these large woody rosette plants adapted themselves to the large diurnal temperature changes, which are typical of tropical alpine areas.

## 6.2 Climate Changes and Plant Succession on Mount Kenya

Although most pioneer species advanced according to the glacial retreat from 1958 to 2019 (Fig. 7), *Helichrysum citrispinum*, *Lobelia telekii*, and *Senecio keniodendron* did not undergo such migration.

*Helichrysum citrispinum* (Fig. 11) was not present on the upper slope north of Tyndall Tan until 2006; however, 32 plants were found on a lateral moraine located above the northern edge of Tyndall Tarn in 2009. This species did not advance according to the glacial retreat; however, it is likely to have advanced towards higher elevation with increasing temperatures (Mizuno and Fujita 2014). As the temperature between March and September 2009 was more than 1 °C higher than the average of 2007 to 2011, its habitat range increased rapidly up the slope.

The large woody rosette plants, *Lobelia telekii* and *Senecio keniodendron* did not migrate up the slope between 1958 and 1997, however, they moved up the slope between 1997 and 2011 (Fig. 7). For this species, their succession was not directly related to the glacial retreat; however, the improvements in soil conditions through upslope advancement of pioneering species, warm climate, and changes in the environment of the habitat resulted in the upslope migration of these plant species.



**Fig. 11** *Helichrysum citrispinum*, also called the everlasting flower

## 7 Conclusions

1. Tyndall Glacier on Mount Kenya is retreating rapidly every year. The retreat of this glacier is influenced by warm climate owing to climate change.
2. Along with the glacial retreat, four pioneering plant species expanded their front upslope. The first pioneering species that appeared in areas vacated by the melting glacier, *Senecio keniophytum*, advanced at almost similar speed as that of the glacial retreat. In 2016 and 2017, a species of lichen appeared close to glacier terminus as the first pioneering plant species.
3. In a permanent plot adjacent to glacial terminus in 1996, the number and cover of *Senecio keniophytum* significantly increased in 2011. Near the glacier terminus, where the glacier had recently disappeared, the number of plants and its cover increased drastically; however, such increasing trend slowed after the passage of 10 years since the disappearance of the glacier.
4. *Senecio keniophytum* tended to grow on relatively stable slopes, while *Senecio keniodendron* grew on stable moraines. In contrast, *Lobelia telekii* grew on debris flow and outwash slopes, where soil moisture content was high. As such, the difference in sediments, moisture conditions, and surficial stabilities of landforms impacted the distribution of the pioneering plants.
5. *Helichrysum citrispinum* was not observed near the glacier terminus earlier; however, its growth was first confirmed on a lateral moraine at an elevation of 4470 m in 2009. It is likely that the increase in its distribution is not directly related to glacial retreat, rather it might be related to increasing temperature.

6. Areas that have been free of glaciers for 10 years or less have coarse soil with small, gray gravels due to limited humus. Over time, the gravels progressively weathered, soil particles became finer, and humus from pioneering species accumulated, which led to the development of nutrient rich soil. In places where 50 years or more have elapsed since the disappearance of glacier, humus was accumulated, which created finer blackish brown soil.

Due to the strong freeze-thaw actions and solifluction on the ground surface of Mount Kenya, it was difficult for plants to get established in areas composed of fine gravels due to movements of the ground surficial materials, which in turn did not allow soil to develop. Thus, we can suggest that the development of soil is influenced by the number of years elapsed since the glacier disappeared and the degree of plant establishment associated with the movements of the ground surficial materials.

7. Changes in the front of large woody rosette plants, *Senecio keniodendron* and *Lobelia telekii*, appeared to be unrelated to the glacial retreat until 1997. Since then, however, the distribution of these plant species has been advancing. The increasing distribution of these species was influenced by the transition from unstable to stable slope and the maturing of soil through the accumulation of humus from the pioneering plant species. Radiocarbon dating of dry leaves showed that the growth rate of two *Senecio keniodendron* plants were 3 cm/year and 4.5 cm/year, respectively. The age of *Senecio keniodendron*, which has a height of 5 m, is likely to be 100 years or more.

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