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# Climate change-driven forest fires marginalize the impact of ice cap wasting on Kilimanjaro

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**Abstract**

**The disappearing glaciers of Kilimanjaro are attracting broad interest. Less conspicuous but ecologically far more significant is the associated increase of frequency and intensity of fires on the slopes of Kilimanjaro, which leads to a downward shift of the upper forest line by several hundred meters as a result of a drier (warmer) climate since the last century. In contrast to common belief, global warming does not necessarily cause upward migration of plants and animals. Here, it is shown that on Kilimanjaro the opposite trend is under way, with consequences more harmful than those due to the loss of the showy ice cap of Africa's highest mountain.**

*Keywords:* alpine vegetation, climate change, East Africa, Erica, forest fires, montane and subalpine cloud forest, vegetation change, vegetation zones

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## Introduction

The shrinking ice cap of Kilimanjaro is a well-known phenomenon since over 100 years (Meyer, 1900; Jaeger, 1909; Klute, 1920). Compared with the 1912 glacier map (Klute, 1920), Kilimanjaro's ice cap lost 82% of its area during the last 90 years (Thompson *et al.*, 2002). At the same time, the number and intensity of wild fires in the montane forest belt have increased, presumably driven by the same climatic changes. The globally synchronous fluctuations of mountain glaciers in modern times lead to the assumption that their causes are also of a global scale (Kaser, 1999). On the one hand, the worldwide retreat of tropical glaciers is consistent with and referred to a recent warming of the tropical middle troposphere (Hastenrath & Kruss, 1992; Diaz & Graham, 1996; Kaser, 1999; Gaffen *et al.*, 2000; Thompson, 2000; Irion, 2001). On the other, a pronounced decrease of precipitation and air humidity is considered to be the main cause for the glacier retreat on Kilimanjaro since 1880 (Kaser *et al.*, 2004). Both these climatic changes also cause fires to become more aggressive on the higher slopes, impacting the Kilimanjaro ecosystem to a far greater extent than the melting of its glaciers. Although most of these fires are lit accidentally (e.g. by honey collectors or poachers; Hemp & Beck, 2001), they would not be so devastating had the climate not become so much drier.

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## Study area, materials and methods

### Study area

*Location and topography.* Mt Kilimanjaro is located 300 km south of the equator in Tanzania on the border with Kenya between 2°45′ and 3°25′ South and 37°0′ and 37°43′ East. It represents an eroded relic of an ancient volcano with three peaks (Shira, Mawenzi and Kibo) rising from the savanna plains at 700 m elevation to a snow- and ice-clad summit of 5895 m altitude. Its diameter from north-west to south-east is about 90 km.

*Climate.* Mt Kilimanjaro is characterized by a typical equatorial daytime climate. The distribution of precipitation over the year follows the intertropical convergence zone and is modified by the respective elevations. Because of its equatorial location, two distinct rainy seasons occur in the study area: the long rains from March to May, and the short rains around November. The driest period is from August to October, while April and May are the wettest months. According to the climate classification system of Köppen and Troll/Pfaffen (in Müller, 1983), Mt Kilimanjaro belongs to the zone of a seasonal dry tropical climate. However, rainfall and temperature vary with altitude and exposure to the dominant wind from the Indian Ocean. The northern slopes, on the lee side of the mountain, receive much less annual rainfall than the southern slopes. The mean annual temperature decreases linearly upslope with a lapse rate of 0.56 °C per 100 m (Hemp, in press a) starting with 23.4 °C at the foothills in Moshi (813 m; Walter *et al.*, 1975), and decreasing to −7.1 °C at the top of Kibo (Thompson *et al.*, 2002). The annual precipitation reaches its maximum in the midmontane zone, between 1800 and 2400 m, where ca. 2700 mm were recorded at 2200 m. At higher elevation, precipitation declines, reaching 80% of the maximum at 2400 m, 70% at 2700 m, 50% near the upper forest border at 3000 m and only 20% at 4000 m (Hemp, 2001, in press a).

*Actual vegetation.* Several bioclimatic belts can be distinguished along the slopes of Mt Kilimanjaro (Fig. 1). A dry and hot colline savanna zone surrounds the mountain base between 700 and 1000 m a.s.l. (mostly farmland, and some intact savanna grassland left around Lake Chala and Ngare Nairobi). The submontane belt between 1000 and 1800 m has been converted to coffee–banana plantations. Montane forests cover an area of about 1000 km$^2$ on Mt Kilimanjaro. In the lower parts of the southern slope, these forests are characterized by *Ocotea usambarensis*. The cloud forest zone is dominated by *Podocarpus latifolius*, *Hagenia abyssinica* and *Erica excelsa*. On the drier northern slope, the lower montane belt is

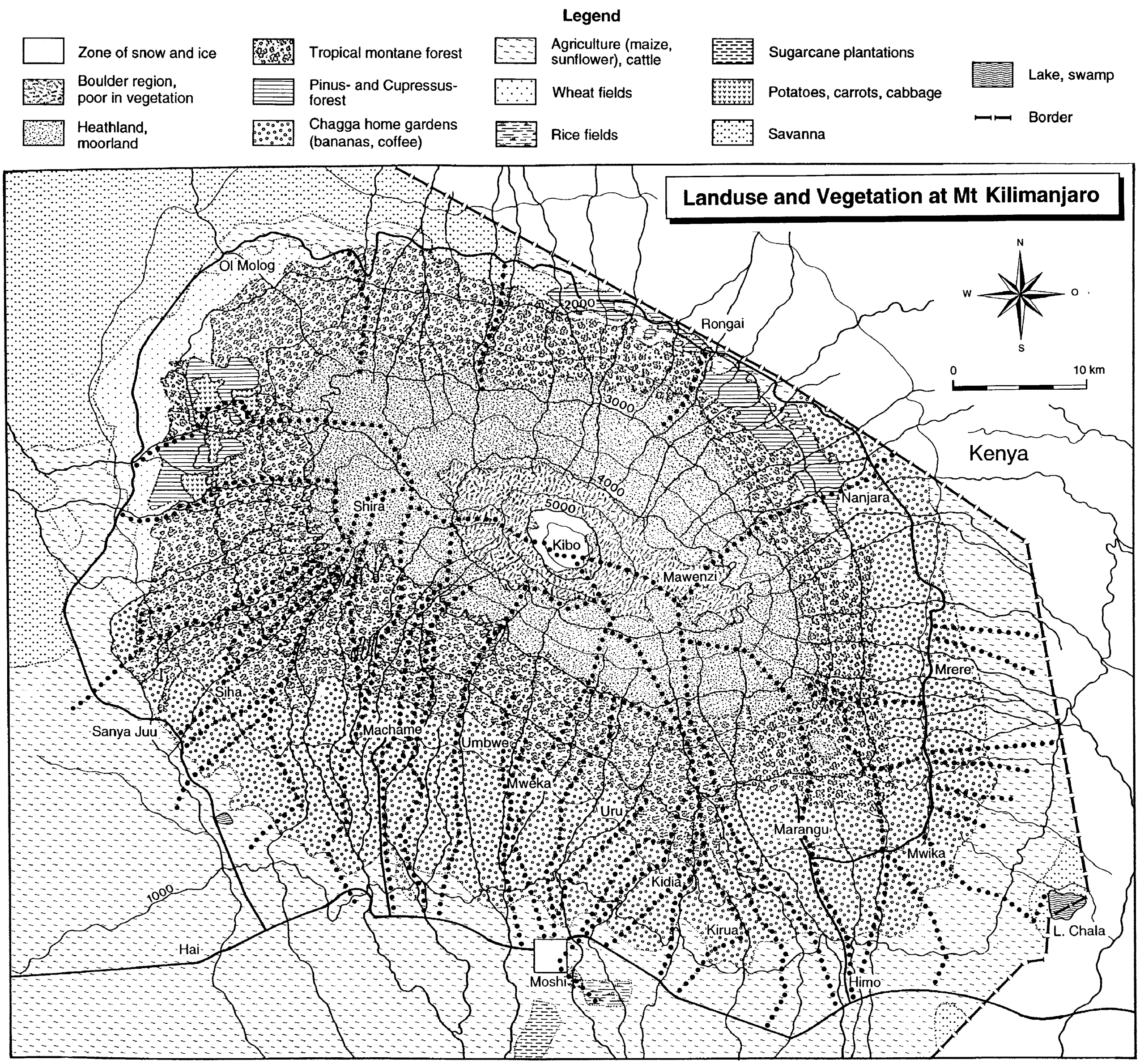

**Fig. 1** Land use and vegetation on Mt Kilimanjaro. Dotted lines represent transects.

dominated by *Croton–Calodendrum* forests, midaltitudes are dominated by *Cassipourea* forests and *Juniperus* characterizes the higher altitudes. Above ca. 3100 m, these forests have been replaced by *Erica* bush in recent decades (*E. arborea* and *E. trimera*, *Protea caffra* and *Euryops dacrydioides*). Around 3900 m elevation, the *Erica* bush grades into *Helichrysum* cushion vegetation with *H. newii* and *H. citrispinum* reaching ca. 4500 m. Higher altitudes are poorly vegetated. For a more detailed description of these vegetation types, see Hemp (2001, in press b) and Hemp & Hemp (2003).

## *Materials and methods*

*Vegetation analysis.* Between 1996 and 2004, over 1400 plots were examined along 34 elevational transects using the method of Braun-Blanquet (1964) (Fig. 1). Based on these plant species inventories and a classification of a Landsat ETM image from 2000 (IDRISI 3.2 software), a vegetation map was produced (in Lambrechts *et al*., 2002), which was compared with a Landsat MSS image from 1976.

The low-stature and open *Erica* woodland of the subalpine zone, the composition of which strongly differs from tall closed forest, is not regarded as forest but as 'bush' (cp. Hemp, 2001; Hemp & Beck, 2001). The term 'subalpine' is applied to the transition zone between the montane forest and the alpine *Helichrysum* scrub vegetation (the treeline–ecotone sensu Körner, 2003). It corresponds closely to the 'ericaceous belt' of Hedberg (1951), who identified three main vegetation belts on East African mountains, each with several subzones: the montane forest belt, the ericaceous belt and the alpine belt.

*Climate analysis.* Beginning in 1997, rainfall was recorded across four elevational gradients using dipping bucket rain gauges (one until 2000, two until 2001, nine until 2002, 16 thereafter). Three transects were situated on the southern slope above Machame, Kibosho and Kidia (Old Moshi) between 1400 and 4000 m a.s.l., and one was established above Rongai on the northern slope. The instruments were accurate within $\pm 1$ mm and were checked two to three times per year. As a proxy for mean annual temperature, soil temperature was measured occasionally at 30 cm depth (cp. Hemp, in press a).

Long-term rainfall trends were analyzed using data of the three oldest and permanent weather stations on the mountain (provided by the Tanzania Meterological Agency) using linear regressions (Fig. 2).

*Water balance.* Based on the vegetation map, the altitudinal forest zonation and rainfall data, the Kilimanjaro forest belt was divided into 10 ecoclimatic zones. For each of these zones, annual rainwater input was compiled. Evapotranspiration (ET) was estimated for altitudes between 1300 and 2500 m based on data from East African mountains presented by Bruijnzeel (1990). For the upper montane zone, between 2500 and 2800 m, an amount of 980 mm derived by Steinhardt (1979) for a cloud forest site at 2300 m in Venezuela with a similar annual rainfall of 1575 mm was assumed. In a subalpine cloud forest at 3500 m in Costa Rica, Dohrenwend (1979) estimated an ET of 390 mm. This amount was assumed for the subalpine zone between 3200 and 3500 m, and a value of 680 mm was extrapolated for the 2800–3200 m interval (cp. Table 2).

No data of fog water deposition exist for East Africa. In other tropical areas, fog stripping accounts for 4–35% of ordinary rainfall (i.e. between 100 and over 800 mm/year; Bruijnzeel & Proctor, 1995; Bruijnzeel, 2001). As strong winds are rare on Kilimanjaro, fogwater deposition is likely to be lower, probably not exceeding 10% of rainfall. Based on observations of fog frequency on Kilimanjaro and the distribution of certain epiphytes (e.g. filmy ferns, lichens, moss balls; Hemp, 2001), fogwater input was estimated to be zero in the ecoclimatic zones 1, 5 and 6 between 1300 and 2200 m a.s.l. (Table 2), as 5% in the zones 2 and 7 between 2000 and 2500 m a.s.l. and 10% ($\leq 200$ mm) in the remaining zones above 2500 m a.s.l., which are commonly enveloped by fog during most of the day.

Given the average thickness of 30 m (according to ice core data by Thompson *et al*. (2002) and own observations), the still existing 2.6 $km^2$ of glaciated area represent a water volume of about 72 million cubic meters. Losses are largely a result of sublimation and evaporation of melting water (Kaser *et al*., 2004; Mölg & Hardy, 2004). In the horizontal part of the ice field (about half of the glaciated area), the meltwater refreezes within the ice body (Mölg & Hardy, 2004) and does not contribute to discharge. Unpublished data by Mölg on the 'Kersten' part of the Kilimanjaro ice cap suggest an annual runoff from the remaining 1.3 $km^2$ of the glacier of approximately 1 million cubic meters.

## Results

### *Evaluation of long-term rainfall data*

Figure 2 shows the mean annual precipitation from three different stations located on the southern slope of Kilimanjaro. The gap in Fig. 2a indicates the time of World War I and the following years, after which the (formerly German) station was operated on the same locality by the British. Therefore, the differences in measured rainfall before and after this period may be partly because of different sampling methods.

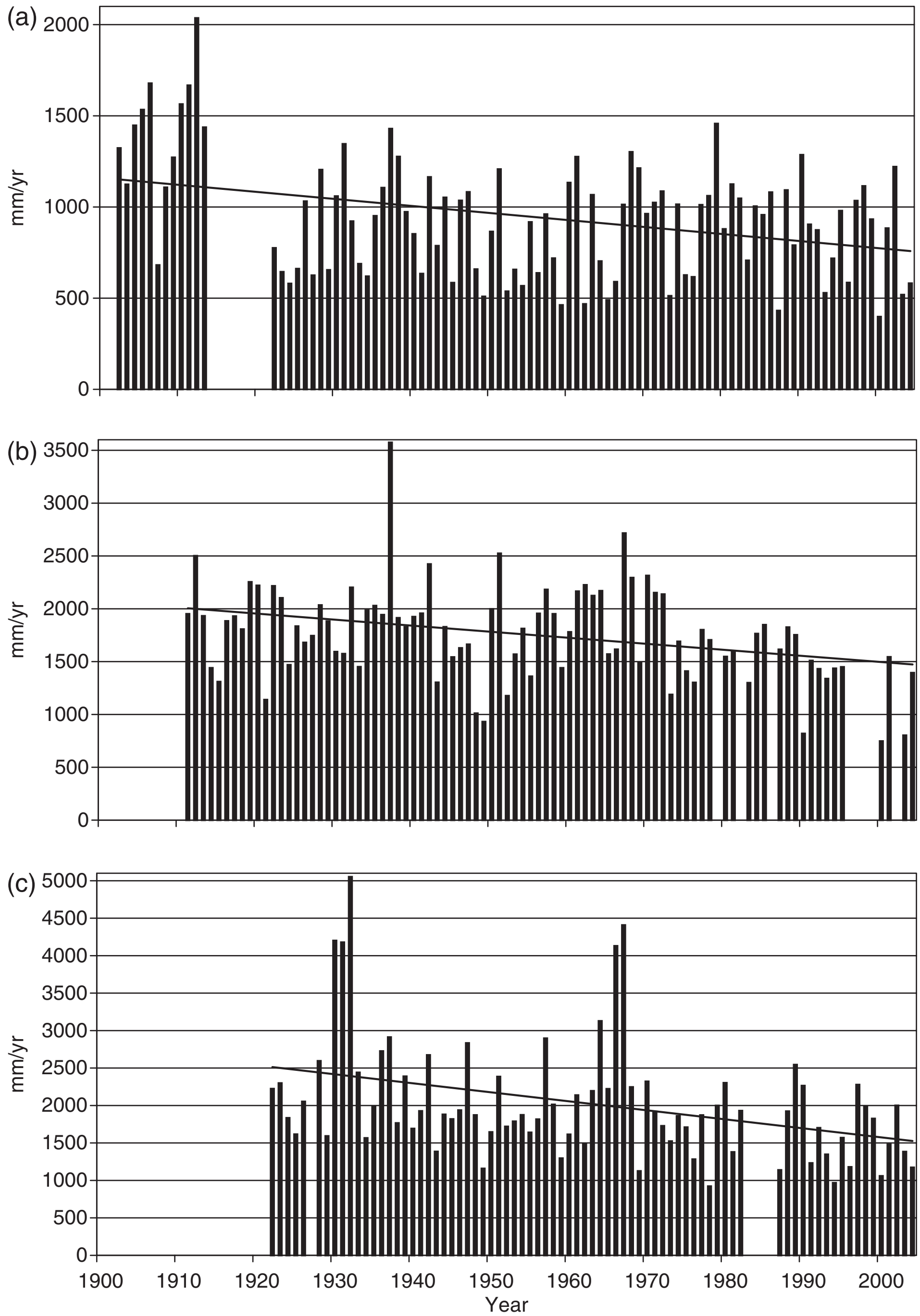


**Fig. 2** Annual precipitation at (a) Moshi Meteorological Station, 830 m a.s.l., (b) Kilema Mission, 1430 m a.s.l. and (c) Kibosho Mission 1430 m a.s.l. on the southern slope of Kilimanjaro. Data source: Tanzania Meteorological Agency, Kibosho and Kilema Mission.

However, no interruptions occurred during this time in the other station (Fig. 2b), which belongs to a Mission, and the data from this station show a similar trend. Using a linear regression, rainfall of the three stations decreased by 34%, 27% and 39% (i.e. by 392, 532 and 986 mm $a^{-1}$) for the periods 1902–2004, 1911–2004 and 1922–2004, respectively (Fig. 2).

### *Impact of fire on the upper vegetation zones*

Induced by the elevational drop of precipitation above the major cloud zone, fire causes a natural sharp discontinuity in the composition and structure of the tall (20–30 m high) subalpine *Hagenia–Podocarpus* forests at 2800–3000 m a.s.l. The giant heather *E. excelsa* becomes dominant at this altitude, forming dense monospecific stands of about 10 m height (Fig. 3) (Hemp & Beck, 2001). The occurrence of an *Erica* forest is an obvious fire sign. During long periods of dry climate with recurrent fires, the *Erica* forest boundary moves downslope and advances upslope during wet periods. The presence of *Erica* enhances the fire risk, as even fresh *Erica* wood burns well, which in turn prevents the *Podocarpus* forest from re-establishing. At high fire frequency, the closed *E. excelsa* forest degrades into open bushland of ca. 1.5 m height, dominated by *E. trimera* and *E. arborea* between 3200 and 4000 m a.s.l. (the potential treeline). Continuously high frequency of fires even destroys this bush, resulting in *Helichrysum* cushion vegetation (Fig. 4), which is the climatic climax vegetation at altitudes above 4000 m (Figs 5 and 6).

The comparison of 1976 and 2000 Landsat images reveals enormous changes in the upper vegetation zones of Kilimanjaro during the last 24 years (Figs 5 and 6; Table 1). In 1976, the *E. trimera* bush – currently depressed below 3800 m – reached 4100 m, in part forming a continuous belt in areas that have become

**Fig. 3** Subalpine *Erica* forests at 3100 m on the southern slope of Kilimanjaro. These cloud forests have a high potential of collecting cloud water and fog.

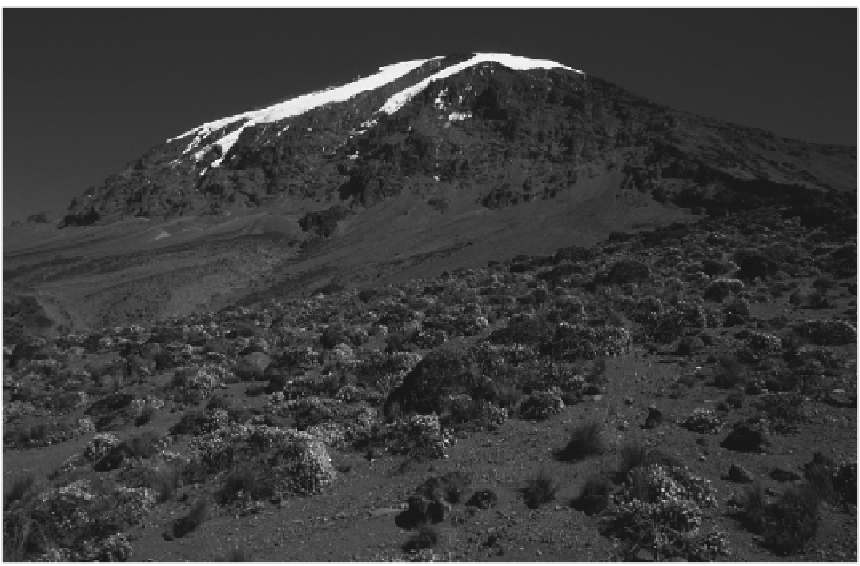

**Fig. 4** *Helichrysum* cushion vegetation at 4200 m. Because of its sparse vegetation cover, this vegetation type is not affected by fires.

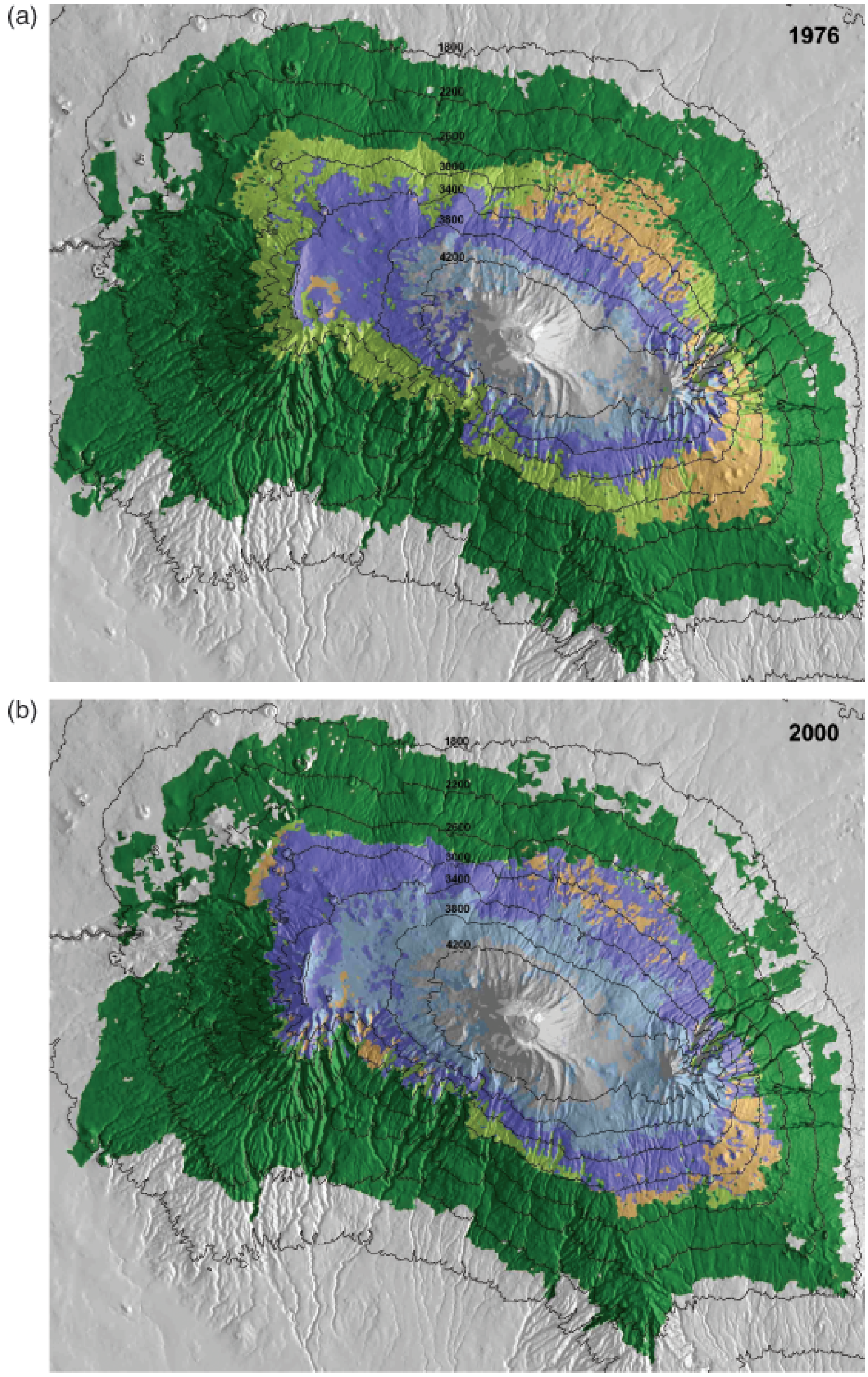


**Fig. 5** Changes in vegetation cover in the montane and alpine zones on Mt Kilimanjaro. The maps are a result of a supervised classification of Landsat MSS images taken on January 24, 1976 and Landsat ETM images taken on January 29 and February 21, 2000 (source: USGS/UNEP-GRID-Sioux Falls) using the software IDRISI 3.2; (a) situation in the year 1976, (b) situation in the year 2000. The whole subalpine ericaceous belt was shifted downslope and became replaced by *Helichrysum* cushion vegetation. Closed *Erica excelsa* forests were reduced to 17% of the land cover in 1976.

covered by *Helichrysum* cushion vegetation since then. That *Helichrysum* shrub is too sparse and low in biomass to fuel the spreading of fires (Fig. 4) and increased its area more than three times between 1976 and 2000. In 1976, closed *Erica* forests (*sensu* Hemp & Beck) covered nearly six times the present-day area (187

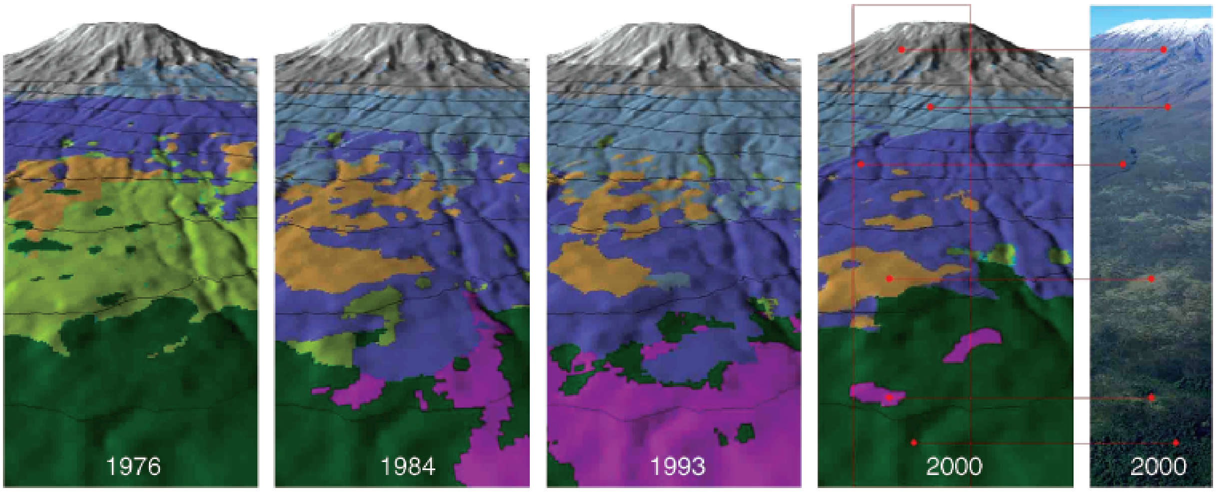


**Fig. 6** Landcover changes on North Kilimanjaro (location and legend see Fig. 5, red color: forest clearings after logging) shown in a time series based on different Landsat images. In 1976, subalpine *Erica* forests covered large areas. After fires, these forests were replaced in 1984 by *Erica* bush and grasslands, and *Helichrysum* cushion vegetation moved downslope into areas of burnt *Erica* bush. At this time, logging of East African Cedar (*Juniperus procera*) had started in the montane forest belt and in 1993 most of the Cedar forest was cut, indicated by the red color. After the ban of commercial logging, the forest had started to regenerate in 2000 as did the *Erica* bush. However, compared with the situation in 1976, (sub-)alpine vegetation and the closed forest line in this area moved downslope by several hundred meters. Three-dimensional model and photo by C. Lambrechts and Janet Akinyi Ong'injo.'

**Table 1** Landcover changes in the upper regions of Kilimanjaro

| Vegetation type | Area 1976 ($km^2$) | Area 2000 ($km^2$) | Change (%) |
|---|---|---|---|
| Montane forest | 1066 | 974 | −9 |
| Subalpine *Erica* forest | 187 | 32 | −83 |
| *Erica* bush | 202 | 257 | 27 |
| *Helichrysum* cushion vegetation | 69 | 218 | 216 |
| Grassland | 90 | 44 | −51 |

instead of 32 $km^2$), extending up to 3800 m in many places. This means that nearly 15% of Kilimanjaro's forest cover was destroyed by fire since 1976 and was replaced by *Erica* bush which extended its total area by 5 $km^2$ (mainly downslope).

### *Impacts of increasing fires and melting glaciers on the water balance*

The forests of Kilimanjaro above 1300 m a.s.l. receive nearly 1600 million cubic meters water annually, 95% by rainfall and ca. 5% by fog interception ('Rain' and 'Fogwater,' respectively, in Table 2). About 500 million cubic meters of water (31%) percolate into the groundwater or into streams ('Water outflow' in Table 2).

If one assumes that fog precipitation is close to zero once the forest is destroyed, the loss of 150 $km^2$ of subalpine forests since 1976 (100 $km^2$ in the ecoclimatic forest zone 4 and 50 $km^2$ in zone 10, Table 2) corresponds to an estimated loss of 20 million cubic meters of fogwater deposition per year. This is more than a quarter of the estimated annual fogwater yield of the whole forest belt or equivalent to the annual water demand of the 1 million inhabitants on Kilimanjaro (according to numbers given by United Republic of Tanzania and CES, 2002). In contrast, the average annual water output of the 2.6 $km^2$ of glaciers can be estimated at only 1 million cubic meters (5%).

## Discussion

### *Evidence for climate change linked with fire activity and glacier retreat*

Long-term rainfall data from three different stations located on the southern slope of Kilimanjaro show a clear decrease in annual precipitation during the last century (Fig. 2). Temperature data, since 1976, from Amboseli on the northern foothills of Kilimanjaro, reveal a drastic increase of mean daily maximum temperature at a rate of over 2 K per decade (Altmann *et al*., 2002). Increases were greatest during the hottest months, February and March. According to the climate trends in the Kilimanjaro area presented by Hay *et al*. (2002) for 1941–1995, temperatures rose between 1951 and 1960, and between 1981 and 1995, but were stable or decreased slightly during the remaining intervals.

**Table 2** Ecoclimatic forest zones on Mt. Kilimanjaro and their water regime

| Ecoclimatic zone | Landscape characteristics: Vegetation | Altitudinal zone* | Altitude (m a.s.l.)* | Location | Climatic features: Area ($km^2$)[†] | Rain (mm)[‡] | ET (mm) | Fog (%)[§] | Water balance (million $m^3$), Input: Rain | Input: Fog-water | Output: ET | Output: Water outflow | Water outflow/($km^2$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | *Ocotea–Agauria* forest, *Ocotea–Syzygium* forest, consisting of *Ocotea usambarensis* associated with *Agauria salicifolia*, *Syzygium guineense*, *Macaranga kilimandscharica* and *Polyscias fulva* | Lower montane | 1800–2200 | South/south-east | 153 | 2400 | 1280[¶] | 0 | 367 | 0 | 196 | 171 | 1.1 |
| 2 | *Ocotea–Podocarpus* forest, consisting of *O.usambarensis* associated with *Podocarpus latifolius* and the tree fern *Cyathea manniana* | Middle montane | 2200–2500 | South/south-east | 108 | 2500 | 1280[¶] | 5 | 270 | 14 | 139 | 145 | 1.3 |
| 3 | *Podocarpus–Ocotea* forest with prevailing *P. latifolius* | Upper montane | 2500–2800 | South/south-east | 99 | 2000 | 980[‖] | 10 | 198 | 20 | 97 | 121 | 1.2 |
| 4 | *Hagenia–Podocarpus* forest with *P. latifolius*, *Hagenia abyssinica* and *Prunus africana; Erica excelsa* forest | Subalpine | 2800–3200 | South/south-east | 66 | 1450 | 680** | 10 | 96 | 10 | 45 | 61 | 0.9 |
| 5 | *Croton–Calodendrum* forest with *Olea europaea* ssp. *africana*, *Croton megalocarpus*, *Calodendrum capense* and *Diospyros abyssinica* | Submontane | 1300–1600<br>1600–2000 | West<br>North | 81 | 1000 | 1280[¶] | 0 | 81 | 0 | 104 | −23 | −0.3 |
| 6 | *Cassipourea* forest with *Cassipourea malosana*, | Lower montane | 1600–2100 | West | 93 | 1100 | 1280[¶] | 0 | 102 | 0 | 119 | −17 | −0.2 |
| 7 | *Teclea simplicifolia*, *Fagaropsis angolensis* and *Olea capensis* | Middle montane | 2000–2500 | North | 192 | 1200 | 1280[¶] | 5 | 230 | 12 | 246 | −4 | 0.0 |
| 8 | *Juniperus–Podocarpus* forest with *Juniperus procera*, *Podocarpus latifolius* and | Upper montane | 2500–2800 | North | 117 | 1100 | 980[‖] | 10 | 129 | 13 | 115 | 27 | 0.2 |
| 9 | *H. abyssinica*<br>Destroyed forest types since 1976 | Subalpine | 2800–3100 | North | 36 | 1000 | 680** | 10 | 36 | 4 | 24 | 16 | 0.4 |
| 10 | *Erica* and *Hagenia* forest | Subalpine | 3200–3500 | Around the mountain | 50 | 950 | 390** | 10 | 48 | 5 | 20 | 33 | 0.7 |
| 4 | *Hagenia–Podocarpus* forest with *P. latifolius*, *H. abyssinica* and *Prunus africana; Erica excelsa* forest | Subalpine | 2800–3200 | South/south-east | 100 | 1450 | 680** | 10 | 145 | 15 | 68 | 92 | 0.9 |

*According to Hemp (in press a).
[†]Based on the vegetation map.
[‡]Mean annual rainfall, based on own measurements.
[§]Fogwater interception in relation to rainfall, estimation based on measured data presented by Bruijnzeel (1990) and L.A.Bruijnzeel (personal communication).
[¶]Evapotranspiration according to data for East Africa given by Bruijnzeel (1990).
[‖]According to data by Steinhardt (1979).
**According to data by Dohrenwend (1979).

Prior to 1900, only few sporadic rainfall data were available from Kilimanjaro. Hence, the historical fluctuations must be reconstructed using proxy indicators, such as lake levels. Over the past millennium, equatorial east Africa has alternated between contrasting climate conditions, with significantly drier climate than today during the 'Medieval Warm Period' ( $\sim$ AD 1000–1270) and a relatively wet climate during the so-called 'Little Ice Age' ( $\sim$ AD 1270–1850; Verschuren *et al*., 2000). Enhanced solar radiation because of diminished cloud cover, accompanied by reduced precipitation during the last two decades of the 19th century, caused a drop of lake levels and glacier recession (Hastenrath, 1984, 2001; Nicholson, 2000; Verschuren *et al*., 2000; Nicholson & Yin, 2001). The drastic drop of the water level of Lake Victoria between 1880 and 1900 had been attributed to the reduction in annual precipitation by about 150–200 mm (Hastenrath, 1984). The wasting of Lewis Glacier on Mt Kenya during this period was explained by this drop in precipitation and the associated increase in insolation (reduced cloudiness); the retreat during the early part of the 20th century seems to have been enforced by climate warming (Kruss, 1983). During the last century, the mean annual precipitation on Kilimanjaro decreased by about 400–1000 mm (Fig. 2), and compared with the situation before 1880, the drop amounts to 600–1200 mm $a^{-1}$. Consistent with the pronounced decrease of precipitation at the end of the 19th century, fires in subalpine forests had already been reported by the first Europeans on the mountain (e.g. Meyer, 1890, 1900; Volkens, 1897; Jaeger, 1909), and in parallel, the glaciers started to recede (Kaser *et al*., 2004) but then entered a few decades of more stable conditions (Kaser, 1999). Since 1976, the warming effect became more significant (Altmann *et al*., 2002) and also led to a second phase of rapid melting and strongly enhanced fire activity.

### *Impact of fire on the upper treeline*

Fire not only transforms land cover, it also maintains certain land cover types (Eva & Lambin, 2000) and influences species diversity and vegetation structure in the different altitudinal zones on Kilimanjaro in various ways (Hemp, 2001, 2002, in press c; Hemp & Beck, 2001). Here, I assessed the destructive role of fires in the upper forest and shrub belt. From field observations and historical descriptions (Jaeger, 1909; Klute, 1920), it can be assumed that different tall subalpine forest types extended up to 3600 m in many areas of Kilimanjaro at the beginning of the 20th century and even until 1996, and small remnants of closed *Erica* forests still exist at altitudes as high as 4000 m. The fires of the years 1996 and 1997 destroyed vast areas of old *Erica* forest, which became replaced by low-stature *Erica* bush and moved the upper closed forest line downslope by about 400 m of altitude (Hemp & Beck, 2001). Thus, fire effects overrun otherwise positive effects of climatic changes in the upper forest belt.

### *Fire and movements of vegetation belts*

Pollen diagrams of East African mountains show that the treeline has never been stable. They indicate a dry climate between 25 000 and 12 500 BP (Lind & Morrison, 1974), with charcoal horizons in today's lower montane forests on Kilimanjaro, suggesting an extent of ericaceous forest 1000 m below its current lower limit (Hemp & Beck, 2001).

While alpine vegetation has been found to migrate upslope because of rising temperatures and enrichment of atmospheric $CO_2$ and nitrogen in temperate zone mountains in the case of pioneer species (Grabherr & Pauli, 1994), or remain more or less stable in the case of late successional communities (Körner, 2003), alpine vegetation on Kilimanjaro also migrates downslope, replacing subalpine forests. This is because of a typical feature of high mountains in Africa: the vast ericaceous belt. This plant formation is very inflammable and becomes more sensitive to fire in a warmer climate.

These findings contrast those by Shugart *et al*. (2001), who reported an upslope movement of vegetation zones on Mt Kilimanjaro, stressing the above-mentioned atmospheric and climatic factors and comparing two satellite images from 1984 and 1993. It seems that they only considered too small sites (only two), and they were not aware of the fact that the vegetation in the subalpine zone of Mt Kilimanjaro is a mosaic of fire-induced regeneration stages. One can always find places in such a mosaic where vegetation is recovering as can be seen in Fig. 6. Extensive ground surveys are needed to 'calibrate' such remote-sensing data. A full coverage of the upper forest belt by satellite and ground data leaves no doubt about the massive decline of forest cover because of fires.

In addition to the losses of upper montane and subalpine forests by fire, losses because of clear cutting of lower elevation forests amount to 450 $km^2$ since 1929, bringing the total loss to ca. 600 $km^2$ (i.e. Kilimanjaro has lost a third of its forests; Hemp *et al*., in press). This sum does not account for the massive logging inside the still existing forest belt as documented during an aerial survey in 2001, when about 8000 newly cut trunks had been counted (Lambrechts *et al*., 2002).

### *Impact on the water balance*

Cloud forests are of great importance for watersheds in East Africa (Pócs, 1976). In addition to the function of filtering and storing water, the upper montane and subalpine cloud forests have a high potential of collecting cloud water (cp. e.g. Cavelier & Goldstein, 1989; Juvik & Nullet, 1993; Cavelier *et al.*, 1996; Bruijnzeel, 2001). Fog interception increases with altitude, and so does its contribution to water yielding (Table 2). Thus, the loss of cloud forests because of climate-induced fires as well as the loss of montane forest because of clearing causes a considerable reduction and enhanced variability of water yields of the Kilimanjaro catchments, affecting over 1 million people living on the mountain, by far exceeding the hydrological consequences of the loss of the glaciers.

## Conclusions

Global warming combined with increasing levels of carbon dioxide and nitrogen, is expected to lead to an upslope shift of the various vegetation zones. On Mt Kilimanjaro, however, climate change-induced fires had an over-riding impact, leading to a downslope shift of the (sub-)alpine vegetation belts within a few decades. During the last 70 years, Kilimanjaro has lost nearly a third of its forest cover. Compared with these landscape changes, the hydrological significance of the melting of the glaciers is almost negligible. However, the disappearance of the glaciers is an alarming indicator of the substantial changes in the Kilimanjaro environment. At current rates of incidence, fires will have made most of Kilimanjaro's high-altitude forests extinct within the next few years, and with this, the mountain will have lost its most effective water source in the fog interception zone. With its glaciers, Kilimanjaro will lose a part of its beauty and an important archive of paleoclimatic records (Thompson, 2000); with its forests, it loses its major ecosystem service to a water-demanding society.

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