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A potential feedback between landuse and climate in the Rungwe tropical highland stresses a critical environmental research challenge

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Characteristic trends in landuse and climate highlight critical challenges in future resource management along the tropical topoclimosequence (TCS) of the Rungwe Volcanic Province (RVP), a major headwater biodiversity and food reservoir of Tanzania. The RVP orography supports a coherent distribution of agroecosystems and livelihoods, from hot irrigated lowlands to endangered afromontane forests above 1500 m.a.s.l. Recent increases in deforestation, land fragmentation and soil denudation/compaction in the densely populated TCS were combined with a strengthened need and consumption of water in the lower, warmer and drier end-member. Consistent with a regional decline of the long rains, a considerable (up to 30%) decrease in annual rainfall and a pervasive decline of the Lake Masoko (LM) aquifer testifies to a strong aridification trend. We suggest here that current landuse and demographic trends likely amplified the hydrological response of the TCS to regional and global warming. Testing such a hypothesis, however, requires improved local monitoring, to allow scaling and quantification of local hydrological budgets associated with landuse impacts, and evaluation of the contribution of trees and agroforestry systems to mitigating the aridification trend.

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Introduction

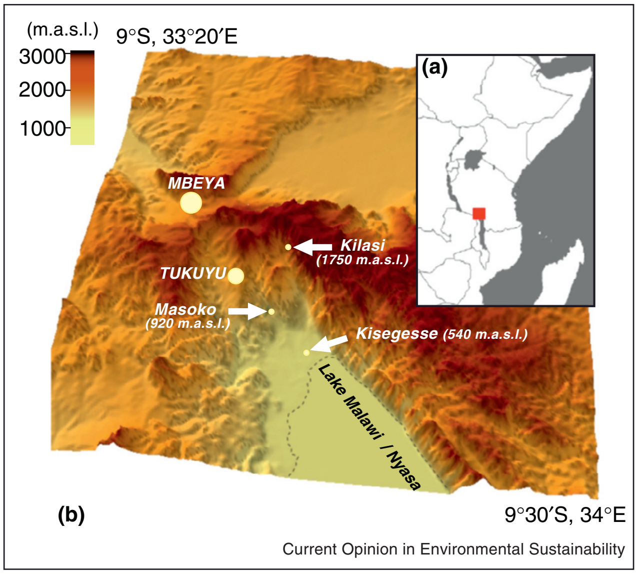
Although highland agroecosystems do provide major biodiversity, water and food resources in more than 35 tropical countries, the biophysical response of tropical highlands to climate variability and to economic and demographic trends remains sparsely documented and understood. This is especially the case in eastern and central Africa, where a complex mosaic of highland landscapes and agro-ecosytems is nested along contrasted geological, climate and socioeconomic gradients, from the southern to the northern summer rainfall zones.

Owing to the availability of long-term hydrological and ecosystem records reconstructed from small lakes, we use here the case of the Rungwe Volcanic Province (RVP, Mbeya region, southern highlands of Tanzania) to address the impact of interacting climate, ecosystem and social drivers over highland resources at larger scale than the instrumental record. We further identify key questions and challenges to improve the sustainable management of natural resources and agroecosystems in the RVP and in other tropical highlands.

A complex hydrological frame

As in most East African highlands, the outstanding diversity and vulnerability of natural resources and ecosystems of the RVP (Figure 1) originates from a long (20 Ma, Neogene) history, linked with the swelling and rifting of East Africa [1], and the formation of internally drained basins [2]. The N–S topography deflects the lower atmospheric circulation from the Indian Ocean, enhancing meridional transport of moisture along this barrier, extending the intertropical convection zone between 25° S and 10° N [3•], and making the climate highly sensitive to monsoon circulation and low-latitude insolation [4,5]. As a result, strong regional aridity gradients and well described 'rain shadow' effects strongly constrain the rainfall patterns and amounts. Along with geological gradients and ecosystem fragmentation related to asynchronous uplift and volcanic activity, the topography has major consequences for the biosphere, shown by the contrasted distributions of C3-photosynthesizing and C4-photosynthesizing plant communities along aridity gradients [6], and by the characteristic elevational changes in tree associations and diversity across afroalpine vegetation belts [7].

Figure 1



Elevation model (SRTM90) of the Rungwe topoclimosequence. **(a)** Map of East Africa showing the study area (red box). **(b)** The Rungwe TCS, north of Lake Malawi (Nyasa), 470–2960 m.a.s.l. (see text for comments).

These features are particularly well observed in the RVP, ~630 km west of the Indian Ocean coast. The rainfall and hydrology of the region is firstly controlled by the ~3000 m elevated SE-NW rift escarpments, and by the topographic 'lock' posed by three main volcanic centres (Rungwe, Poroto and Kiejo) at the triple junction between the Malawi, Rukwa and Usangu rift basins [8]. South of the RVP, the large open water body of Lake Malawi [9] (478 m.a.s.l.) acts both as a reservoir and source of moisture for highlands through land/lake breeze effects and orographic lifting [10].

The soil hydrological properties and the soil fertility also follow the geological and orographic frame. The upper zone of Precambrian escarpment rocks and volcanoes, near the wetter and forested areas, strongly contributes to the recharge of the regional underground aquifer. It is generally covered by young volcanic soils providing a highly fertile and favorable environment for agriculture. The transitional zone consists of older, poorly permeable and cation-depleted weathered materials prone to desiccation (dry season) and flooding (rain season). The lower alluvial plains of Lake Malawi (southern RVP) or Usangu (northern RVP) directly depend on water and sediment inputs from the upper and transitional zones and are intensively cultivated and irrigated.

Millennial to multi-decennial imprints of rainfall seasonality over highland ecosystems

The RVP is located in the summer rainfall area of the southern tropics, with a near-monomodal rainfall season distributed between November and May. As in other tropical topoclimosequences (TCSs) [11••], strong rainfall contrasts are observed between the windward southern RVP and the leeward (drier) northern RVP: for example, the mean annual rainfall reached 2400 mm yr^{-1} in Tukuyu (windward, 1550 m.a.s.l.) and only 900 mm yr^{-1} in Mbeya (leeward, 1720 m.a.s.l.) in the 1990s. Hydrological and ecological imprints of the regional climate are found in present-day eco-system and hydro-system, particularly through the occurrence of small perennial crater lakes indicating positive [P-E] water balances at decennial scale [12], and through the control of the vegetation by annual rainfall, seasonality and temperature [13]. A little rain fall between June and October contributes to maintain relatively wet conditions and the montane, upper montane and bamboo forests above 1500 m.a.s.l. [14]. The five months dry season of the lower zone favors the development of semi-deciduous 'miombo' Zambezian woodlands dominated by Caesalpiniaceae (e.g., *Brachystegia*) [15].

Multi-decennial to millennial climate variability in the RVP is first documented by the sedimentary record of Lake Masoko (LM, 840 m.a.s.l.), where vegetation proxies (pollen and molecular assemblages, microcharcoal) [16••,17,18] and hydrological proxies (diatom assemblages, magnetic proxies of deposition) [19,20] provide a still unique continuous paleoclimate record covering the last 45 ka in the region. Several lessons are learned from this work and its comparison with other paleorecords. The critical impact of the dry season over the RVP hydrology and vegetation is clearly evidenced, consistent with present-day biome patterns [21] and with other paleorecords from Lakes Malawi [22•], Tanganyika [23] and Challa [24]. Taken together, these paleorecords indicate a dominant control of the Intertropical Convergence Zone activity and radiative forcing over rainfall seasonality, constrained either by multimillennial orbital frequencies [25] or by sea surface temperature (SST) patterns in the Indian Ocean [26], the latter occurring at shorter (millennial to decennial scales). Peculiarly, the development of drought-intolerant vegetation during cold intervals (e.g., Last Glacial Maximum, Younger Dryas, Maunder Minimum) in the Rungwe [27] contrasts with the opposite development of drought-tolerant trees and arid conditions in the region, which encompasses the large lake catchments of lakes Malawi, Rukwa and southern Tanganyika [22•,28]. Such intervals of opposite climatic trends ('hydrological reversals') point to a strong control of tropical air temperature (and associated shifts of the Intertropical Convergence Zone, ITCZ) over rainfall in highlands located windward of large water bodies, with recurrent wetter (drier) conditions during regionally colder (warmer) intervals, likely as a result of weakened (strengthened) orographic lift.

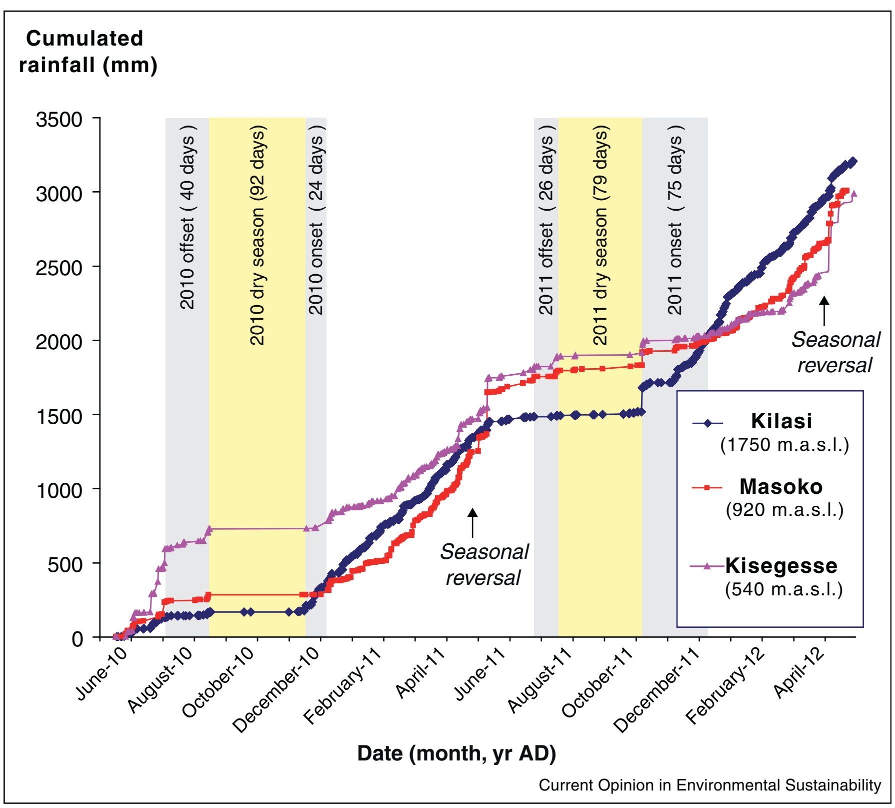
Current intraseasonal and seasonal variability

Hydrological and land use studies undertaken in the Rungwe and in southern Tanzania allow addressing local and regional controls on the Rungwe landscape dynamics [29]. Along with a relatively steep temperature gradient (~7.2 °C km^{-1} in 2011), the seasonal distribution of temperature and rainfall with altitude is well illustrated by manual or automated rainfall measurements carried out in the lower (Kisegesse, 540 m.a.s.l.), mid altitude (Masoko, 920 m.a.s.l.) and high altitude (Kilasi, 1730 m.a.s.l.) zones. These measurements confirm a shorter duration of the rain season and lower annual rainfall amount in the warmer flood plain, where relatively higher rainfall in the austral autumn (in May) (Figure 2) as well as weather observations by local communities strongly support a control of temperature over rainfall patterns along the TCS. Daily monitoring of rainfall and Masoko lake-level for more than ten years by the Rungwe Environmental Science Observatory Network [29] shows a systematic and regular decline of the LM level (around 10 cm yr^{-1}), associated with a delay of the rainfall onset, pointing to a continuous decrease in local water availability (Figure 3). The LM drop corresponds to a trend toward drier conditions, illustrated in altitude (Tukuyu) by an almost ~30% decrease in total rainfall over the last 35 years, along with a longer dry season starting ~25 days earlier (around mid-May) and ending up ~15 days later (end of November) (Figure 4). Albeit considerable, such aridification trend occurs along with a continuous temperature increase in the region [30–32], consistent with the long term history of the Rungwe's sensitivity to regional temperature.

Landuse trends

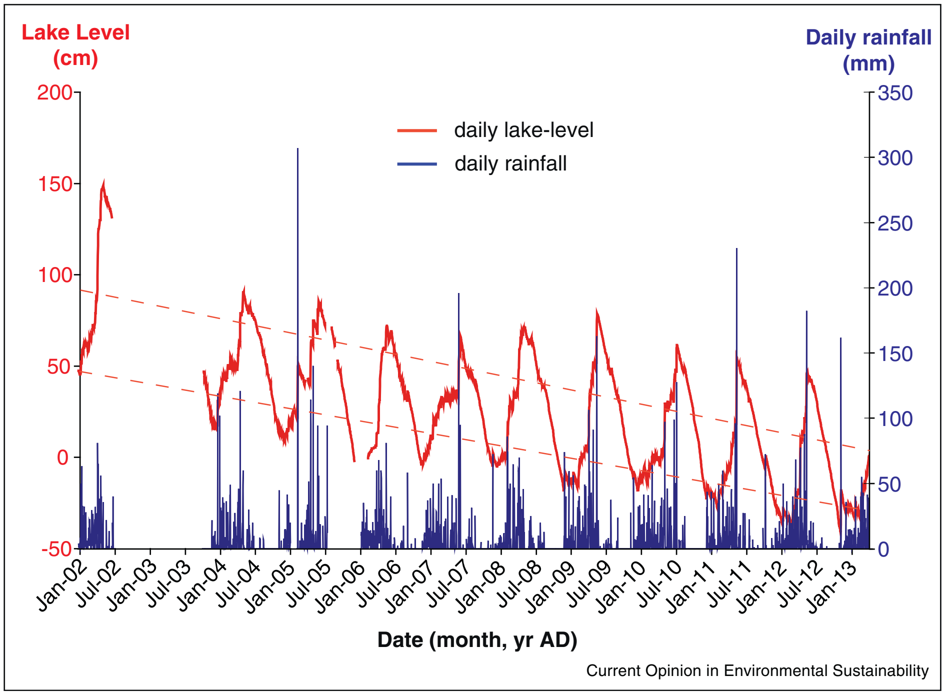
Agriculture is the main socio-economic activity of the Rungwe TCS and its rural population of ~570 000, which increased by ~38% between 1988 and 2012 according to the 1988, 2002 and 2012 population census of the Rungwe and Kyela districts (Bureau of Statistics, United Republic of Tanzania). Cropping is developed from the upper/wet to the lower/dry end members for subsistence and commercial purposes. Decreasing tree cover and increased density of farms have been reported along the entire TCS during the Tanzanian villagization period (1974–1985) and after [33]. It occurs along with the disappearance of initially 4–5 yr fallows and the consecutive loss of soil nutrients and food production [33], with the fragmentation of land through increasing density of the network of paths and tracks, and with the development of livestock

Figure 2



Rainfall patterns across the Rungwe TCS. Cumulative rainfall series (from May 2010 to June 2012) at Kilasi (blue), Masoko, (red) and Kisegesse (purple). The 2010 and 2011 dry seasons (yellow areas) and the rainfall offset and onset intervals (grey areas, see Figure 4 for calculation details) evidence a large seasonal variability over the toposequence. An earlier onset of rains is evidenced in altitude (Kilasi). The intensity of rainfall events is higher in the Masoko and Kisegesse areas. These 'low altitude' heavy rainfall events occur in April–May, at the end of the rainfall season, compensating for an apparent deficit during the warmer November–March interval.

Figure 3

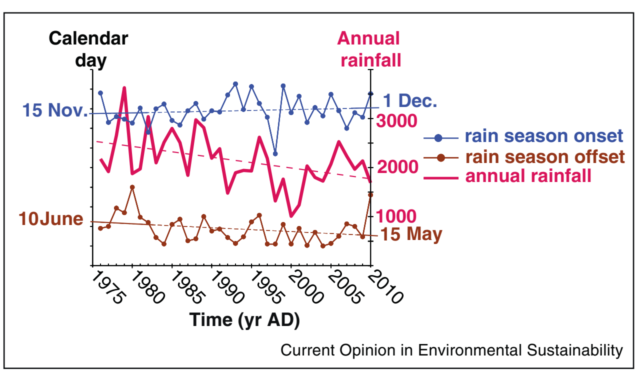


Daily rainfall and lake-level at Masoko. A systematic and regular decline of the lake level of around 10 cm/year from January 2002 to April 2013 is associated with a reduced amount and duration of rains, pointing to a decrease in local water availability.

keeping around lakes, river shores and springs, which increases soil erosion and the risk of schistosomiasis infection.

Potato, wheat, maize, banana–coffee systems and tea estates dominate in the upper zone, between ~1300 and 2000 m.a.s.l. Strong expansions of potato and maize cultivation at the expense of forests located outside conservation zones are a pervasive trend. It is illustrated, for the Rungwe district and between 1997 and 2012, by considerable production increases of 60 000–124 000 t yr^{-1} for maize and 27 000–124 000 t yr^{-1} for potato, respectively. Conversion of forest into cropland is associated with a devastating loss in carbon [34], reducing soil infiltration and increasing runoff, together with soil erosion and landslides on the steeper slopes. Rotational agriculture (maize–bean, maize–groundnut) is a characteristic of the mid zone (~600–1300 m.a.s.l.) where coffee–banana crops and the few remaining tea plantations are progressively abandoned in favor of rainfed rice, cassava, and cocoa (800–4400 t yr^{-1} between 1997 and 2012 in the Rungwe district). Cassava is becoming more frequent due to increasing drought and to the recent cultivation of poorly fertile uphill soils.

Figure 4



Annual rainfall and drought indicators at Tukuyu (1550 m.a.s.l.). The onset and offset dates of the rain season were calculated following crop requirements (onset: 20 mm cumulated rainfall over two days not followed by a drought over the next 15 days, and offset: first dry interval of 15 days). Despite strong interannual variability a ~30% average linear decline in total rainfall is suggested at Tukuyu over the last 35 years, associated with a longer duration of the dry season (from 10 June–15 November in 1975, to 15 May–1 December in 2010).

Over the last four decades, the lower altitude alluvial floodplain of the Rungwe TCS has become an important area of production (and export) of rice (up to three harvests per year) and cocoa, cultivated in the flooded areas and over ridges or ancient river banks, respectively. Tapping of aquifers from the mid altitude zone of the TCS (above 1200 m) is increasingly undertaken to supply the growing demand in irrigation water during the dry season.

A positive feedback loop between landuse and drought?

Taken together, landuse practices and land pressure over the main end-members most likely contribute to the depletion of water resources across the Rungwe climosequence, amplifying a trend toward drier conditions observed in East Africa since the 1990s, driven first by SST changes in the tropical Pacific Ocean [35]. Indeed, the combined impacts of warming (currently ~0.4 °C per decade in the Mbeya region [31]), as well as socio-economic and demographic trends have resulted in a general fragmentation of agroecosystems, associated with a shift toward higher altitudes of the main crops. The latter is especially evidenced by firstly, the replacement, at 800–1200 m.a.s.l., of coffee and banana crops by initially lower altitude cocoa and rice crops, secondly, the development, above 1500 m.a.s.l., of banana, maize and potato at the expense of the upper montane forest.

The surface export of highland water to the hot flood-plain lowlands is amplified by deforestation, land fragmentation and agriculture, which increase runoff and drainage [36,37•], and by the additional capture of aquifers for the irrigation of lowland paddies. As a result, the highland aquifer recharge decreases, while most likely, increased water consumption and evaporation under warmer lowland floodplain environments result in a net deficit of available water in the Rungwe. Recycling of evaporated water into local rainfall is likely to be less efficient, due to the higher altitude of water vapour condensation in a warmer atmosphere, and/or to a limited moisture supply by deforested or compacted soils [38•]. Further, deforested areas in altitude would also decrease the land rugosity, enabling transportation of moisture over regional [11••] or even continental [39] distances. Exportation of moisture would be especially effective in the austral spring and summer, contributing to delay of the onset of the rains and to decrease their total amount and their duration [40].

Conclusion: a scaling and monitoring research challenge to unravel climate and social impacts over resources and food

Given the occurrence of increased deforestation, land and socio-economic pressure, and an aridification trend in the Rungwe TCS, this review stresses critical research issues for sustaining ecosystem resources and food security in tropical highlands. Owing to the near decennial scale of global trends (temperature, demography, market globalization, growth of mature trees, residence time of subsurface aquifers, landscape management.), an improved understanding of local land use, land cover and surface fragmentation impacts over the soil and water budget is urgently required for further integration at the scale of TCSs. Given the poor development of agroforestry practices in the RVP to date, this understanding is especially required to assess the role of trees in soil moisture limitation, evaporative demand and effects of orographic lifting on (local) climate and rainfall [38•] in the future, and their implications in terms of land and natural resource management. An improved quantification of the water budget and its subsurface and groundwater components across the geoclimatic and agroecosystem gradient is especially required for firstly, upscaling the assessment of the environmental impact of local practices to the entire TCS, and secondly estimating the economic value of the different water components of the hydrological cycle [41,42].

Reaching these complementary goals for any TCS, however, is beyond the capacities of the research for development *sensu stricto*: the amount of currently unavailable data required to calibrate satellite observations [43] and to calibrate and validate coupled atmospheric-ecosystem-landuse models of TCSs is indeed considerable. Given the scales and dynamics involved, the latter cannot be effective without the involvement of local rural communities. Hence, new local and sustained strategies of local resource monitoring and scientific partnership with rural communities should be considered. Strong linkages between poverty level and illiteracy in one hand, and land degradation, habitat fragmentation and biodiversity collapse in the other [14,44] would support immediate participatory and educational approaches (e.g., with local schools) aiming at increasing knowledge exchange and capacity building around the long-term observation and measurement of climatic, water and agroecosystem resources. This is stressed as a critical research for development issue.

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