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Research Article

The aftermath of environmental disturbance on the critically endangered *Coffea kihansiensis* in the Southern Udzungwa Mountains, Tanzania

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Abstract

The endemic *Coffea kihansiensis* was monitored in the Kihansi gorge over a three year period following diversion of the Kihansi River underground for hydropower production and its associated catastrophic effect on the gorge biota. We assessed the growth status of the coffee population by measuring, along an altitudinal gradient, the height and diameter of 450 randomly selected coffee stems in 18 sampling plots covering ca 1800 m². We also collected microclimatic data to compare with that collected prior to river diversion. Coffee infestation by parasites was examined by recording the number of stems with signs of infestation. There was no significant change in size of *Coffea kihansiensis* during the study period. However, the size for immature plants differed between the two sites; LWF and UCF. Parasite infestation differed between reproductive age classes and was greater at lower elevation (800 - 850 m a.s.l) than above, suggesting possible effects of altitude and microclimate on coffee infestation. Increasing habitat degradation, parasite infestations, and loss of the species' ecological envelope seriously undermine the species' growth potential with severe consequences for its long-term population survival. Continued monitoring of the species is recommended, with the emphasis on understanding basic species biology, population trends, and the potential role of assisted migration in saving the population from collapse.

Key words: Kihansi gorge, wild coffee, parasite infestation, plant growth, population survival.

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Introduction

The Kihansi wild coffee *Coffea kihansiensis*, described by Davis and Mvungi in 2004, is a recently discovered endemic coffee species in the Kihansi gorge forest, southern Udzungwa Mountains, Tanzania [1]. Due to restricted range size and potential threats from human disturbance, it has been listed as a critically endangered species under the IUCN Red List [2]. The Kihansi gorge forest forms part of the gorge ecosystem, which under natural conditions was maintained by large quantities of spray from Kihansi waterfalls. The spray zone was characterized by lower and more stable temperatures and higher and more stable relative humidity, with a mean spray precipitation of 300 mm per day [3]. The physical structure of the Kihansi River made it suitable for construction of a hydropower plant to generate much-needed electricity for Tanzania. Commencing in 1994 and completed in 1999, the construction was supported financially by the World Bank, the European Investment Bank and the governments of Norway, Sweden and Germany through their development agencies [4]. Power production involved diverting the river (> 90% of flow) from its natural course (the gorge) into an underground tunnel to run the hydropower plant's turbines. This led to a vast reduction in river flow and spray, causing a major part of the gorge habitat to desiccate [5]. As a result, only *ca.* 2 m³ / s of the original natural river flow (16 m³ / s) remains as bypass flow downstream to the gorge. Following this reduction, monitoring of the species most at the risk of decline was initiated in 2001. These species included vertebrate (amphibians, birds, non-human primates) and invertebrate taxa throughout the terrestrial and aquatic systems in Kihansi gorge [4]. In 2005, it was realized that at its current observed range size (17 ha between 775 and 950 m above sea level; [1]), *C. kihansiensis* is highly vulnerable to local extinction due to changes in its semi-aquatic environment, particularly the river spray on which it appears to depend [4]. The species was therefore added to the list of at-risk species for long-term monitoring.

Increasing evidence indicates that a range of animal and plant taxa, and the gorge ecosystem in general, have been severely disrupted by diversion of the river. The after-effects include changes in community composition and structure of birds [6], insects [7], and plants in the gorge wetlands [8]. Disruption of both physical and chemical properties of the impounded river has also been recognized [9]. While these studies concentrated mostly on the impact of the river diversion on the composition and structure of plant and animal communities that were in constant contact with the flowing water, limited information is available on how the river diversion affected growth and health parameters of *C. kihansiensis*. The aim of this study was to understand the subsequent effects of construction of the hydropower-plant, and the reduction both in the flow of river and the spray from the waterfall, on the population of the critically endangered *C. kihansiensis* in Kihansi gorge forest. We tested three hypotheses: (i) Coffee plants would show significant change in height, crown cover and stem diameter at various age classes during the sampling years but these variables would be similar throughout the sampling sites. (ii) Wilting and parasite infestation, as a response to environmental disturbance, would be different between immature and mature plants as well as between the sampling sites across altitudinal gradients. (iii) The gorge micro-climate parameters, i.e. temperature and relative humidity would remain similar prior to and following river diversion.

Methods

Study Site

This study was undertaken in the Kihansi gorge forest (8°35'S; 35°51'E; Fig 1). Three sampling sites within the recorded range of *C. kihansiensis* along the gorge were used: Kihansi forest at Upper camp (coded UCF), the forest near Kihansi research station (KHU), and forest near the Lower spray wetland (LWF). Site UCF is located between 875 and 952 m a.s.l. Prior to reduction of the river flow, the area was wet all year round [4]. It is characterized by stony and shallow soils and increasingly steep slopes

towards the Kihansi River valley. Visibility is more than 50%, as it is covered by open forest with a few canopy trees such as *Rinorea ilicifolia* and *Garcinia semeseii*. KHU stretches between 825 and 850 m a.s.l. and is covered by evergreen forests with dense canopy trees at least 10 m high such as *Euclea nobilis*, and *Filicium decipiens*. This site slopes gently away from the walking trail, and the soil is black indicative of high humus content. LWF lies between 800 and 825 m a.s.l. in an area once reached by spray from the waterfall. It has gentle slopes with stony and shallow soils and is dominated by canopy trees such as *Parinari curatellifolia* and *Uapaca kirkiana*.

The Kihansi gorge receives an average annual rainfall of about 1800 mm, with mean daily minimum and maximum temperatures of approximately 13 °C and 25 °C, respectively [6]. The gorge supports a rich avifaunal community such as insectivore-frugivore (*Andropadus virens*, *A. milanjensis*, *Andropadus masukuensis*). Initial assessment of bird abundance shows declines in the members of some functional groups, especially the insectivore-frugivore community, due to the severe reduction in moisture after river diversion [6].

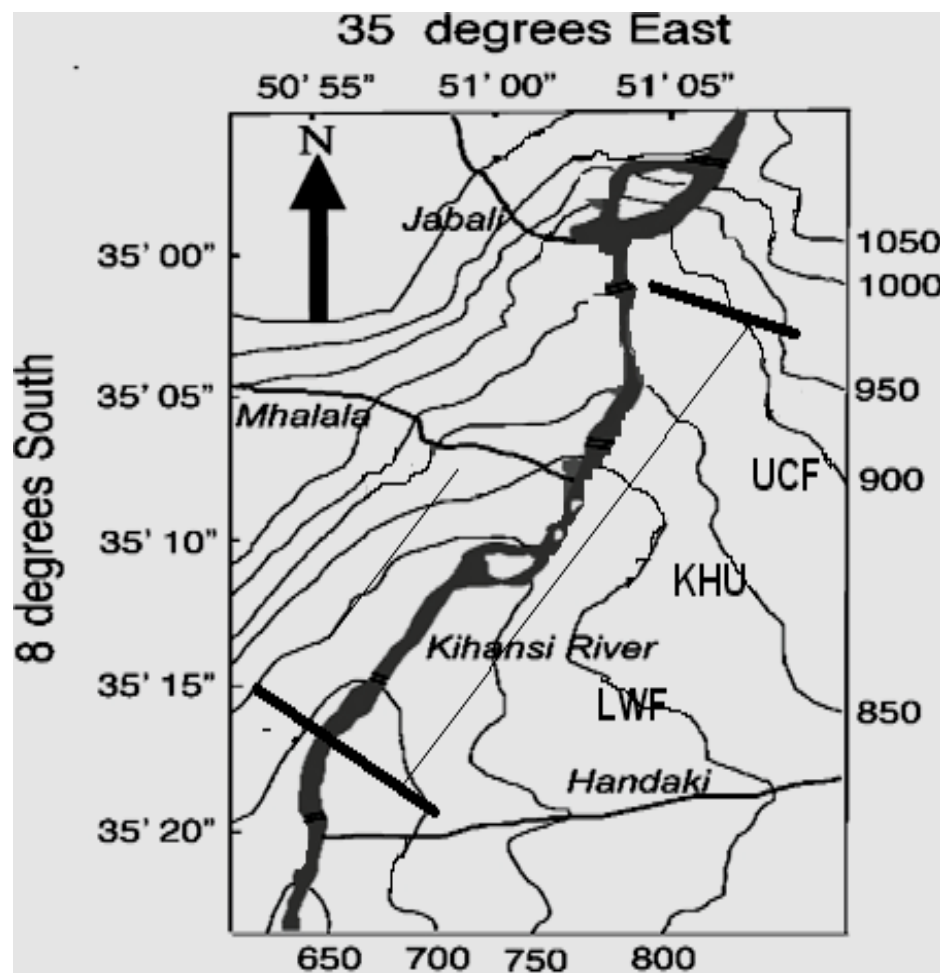


Fig. 1. Map of the Kihansi gorge in Southern Udzungwa Mountains, Tanzania showing location of the study site. Thick short interconnected lines indicate proximate location of our sampling sites (LWF, KHU, and UCF, definition of symbols provided in Appendix 2). Also within the stretch on either side of Kihansi River is where *C.kihansiensis* is mostly distributed between 750-950 m altitudes. Map adapted from Channing et al. 2006.

Sampling and data analysis

Six plots (10 x 10 m) were used within each sampling site. Each site was sampled at least 60 m along an altitudinal gradient between 800-925 m above sea level. A total of 18 plots covering *ca.* 1800 m² were established and these were used throughout the study period. Coffee stems were categorized arbitrarily into four height-based classes i.e. < 25 cm, 25-50 cm, 51-100 cm and > 101 cm. The height classes were translated into two age categories based on phenology: immature (seedlings and saplings) and mature (flowering and fruiting). Aluminium tags indicating the phenological age classes were mounted with strings on the randomly selected coffee stems (n = 450) for monitoring purposes. Twenty five stems were tagged in each of the 18 sampling plots. To understand coffee growth, each year over a three year period we measured the height of the tagged coffee stems from the first lateral root to the stem apex and the basal diameter at 5 cm above the first lateral root. Also, crown diameter was measured across north-south and east-west directions. The sampled coffee plants were only examined for presence of parasitic insects in 2009. Parasites were searched for on the leaves, flower buds, fruits and main stem. The plant status was scored either as healthy or infested. The latter category included all plants with parasites, signs of wilting or totally dry. These characteristics were considered indicators of the effect of habitat disturbance on this species. Neither parasite infection nor wilting had been documented for this species prior to the river diversion [4].

Within each sampling site, four soil samples were collected from the corners of each sampling plot. The samples were collected at depth between 10 and 15 cm and packed in small sealed nylon bags, which were taken to the laboratory at the University of Dar es Salaam for analysis. Levels of potassium, nitrogen and phosphorous were determined using Philip Harris Portable Kit. In addition, we used six electronic data hogs (Skye Instrument Co. Ltd), each powered by six dry cell batteries, positioned at sites that were used in 1997 to record ambient temperature and relative humidity post river diversion. The data were used to compare the microclimatic conditions prior to and after river diversion in 1997. Sampling was done in September each year and was carried out by the same monitoring personnel.

Prior to analyses, data were tested for normality using one-sample Kolmogorov-Smirnov test in SPSS version 16.0. We used analysis of variance to examine if changes in coffee height were different between the sampling periods and sites. A general linear model was used to test whether the increase in coffee diameter was dependent on the age, sites or sampling year. The diameter of immature plants at different sites was compared using the Kruskal Wallis test. The extent of infestation was compared between mature and immature and between healthy and infested plants using the Mann-Whitney test. A correlation test was performed to examine the relationship between heights, diameter and crown cover of the sampled individuals. Means were computed to examine changes in microclimate variables before versus after river diversion.

Results

Growth structure of coffee population over the sampling period

Most of the coffee plants (78%) observed in the sampling sites were flowering during the sampling periods. The mean height and diameter for various age classes during the sampling years are shown in Appendix 1. There was a significant increase in height for immature coffee at LWF and UCF sites (ANOVA $F = 5.76$, $p = 0.048$) but not for mature plants ($F = 0.160$, $df = 2$; $p = 0.852$). Diameter of the saplings significantly varied across altitudinal gradient at all sites (Kruskal Wallis Test $\chi^2 = 6.37$; $df = 2$; $p = 0.041$) but not for mature plants (ANOVA, $F = 1.43$; $df = 2$; $p = 0.777$). As expected, the mean diameter for mature was larger than for immature (Appendix 1). The interactive effects of the sampling year, site and age combined, showed no effects on stem diameter except for the age ($F = 763.367$; $df = 1$; $p = 0.001$).

Further, the mean crown cover was not different between sites (ANOVA, $F = 1.708$, $df = 2$; $p = 0.183$). However, correlations between crown cover and height, and crown cover and diameter, were highly significant (Pearson Correlation, 2-tailed test; $p = 0.001$). The mineral content of the soil in the three sampling sites is indicated in Appendix 2.

Coffee health status and microclimate conditions in Kihansi gorge forest

Sixty five per cent of the sampled coffee plants had parasitic insects on leaves, stems, fruits or flowers. The majority (68.6%) of parasites were aphid, *Aphis*, colonies with smaller proportions of leaf beetles *Coleoptera* (30.3%) and crickets *Orthoptera* (1.1%). Examination of wilting stems (Fig 2) revealed a parasitic larva within the heartwood. Visual signs indicated that the parasite penetrates the plant through the main root, thus killing the plant afterwards. Of the sites impacted by the parasitic larvae, UCF ranked highest with 60.8% of all severe (dried plants) cases ($n = 91$), whereas LWF site showed only 39.2%. Over 75% of the coffee stems at KHU had parasites on the leaves but none showed signs of larval infection. The mean number of the larva-infected and healthy stems was significantly different for pooled data ($t = 5.56$; $df = 15$; $p = 0.001$; Fig 3). Both mature and immature plants were infested by the parasites with no significant difference between age classes (Mann-Whitney $U = 5.50$; $p = 0.486$). The mean temperature and relative humidity in 1997 before diversion of the river were 21.23°C (standard error, 0.22) and 76.64%, (standard error, 1.44) respectively. In 2005, these parameters had changed to 24.08°C (standard error, 0.31) and 68.76% (standard error, 2.25 Fig 4) respectively.



Fig. 2. *C.kihansiensis* healthy (right photo) and infected plants (left photo). Wilting leaves (left photo) indicate signs of habitat disturbance and parasite infection at one of the study sites in Kihansi gorge forest

Discussion

This study suggests that the *C. kihansiensis* population has been negatively affected by the loss of important ecological requirements following reduction of the river flow. There was a stable mean increase in height and stem diameter in all sites during the survey period for mature coffee. This may suggest that growth for the species has leveled off. Over 2460 coffee stems counted within the 17 ha area have been growing on the soil with relatively similar conditions characterized by shallow soils (LWF & UCF) and sandy loam soils (KHU) with the pH ranging from 5.5 to 6.5 (Appendix 2). Coupled with the shallow roots of the coffee species, the reduction in moisture in most parts of the species range following diversion of the river may be crudely linked to the leveling off of growth. Wilting of coffee plants observed immediately near the banks of the Kihansi River, particularly at the lower elevations in LWF site, further suggests that moisture could be a growth-limiting factor for this species. Growth of the immature coffee exhibited marginal variations between sites UCF & LWF (Appendix 3) probably due to elevational influences. On the one hand, site LWF at the foot of the gradient is likely to have less water percolation and hence little water available to plants, while site UCF is likely to benefit more from high relative humidity by virtue of its location high up along the altitudinal gradient.

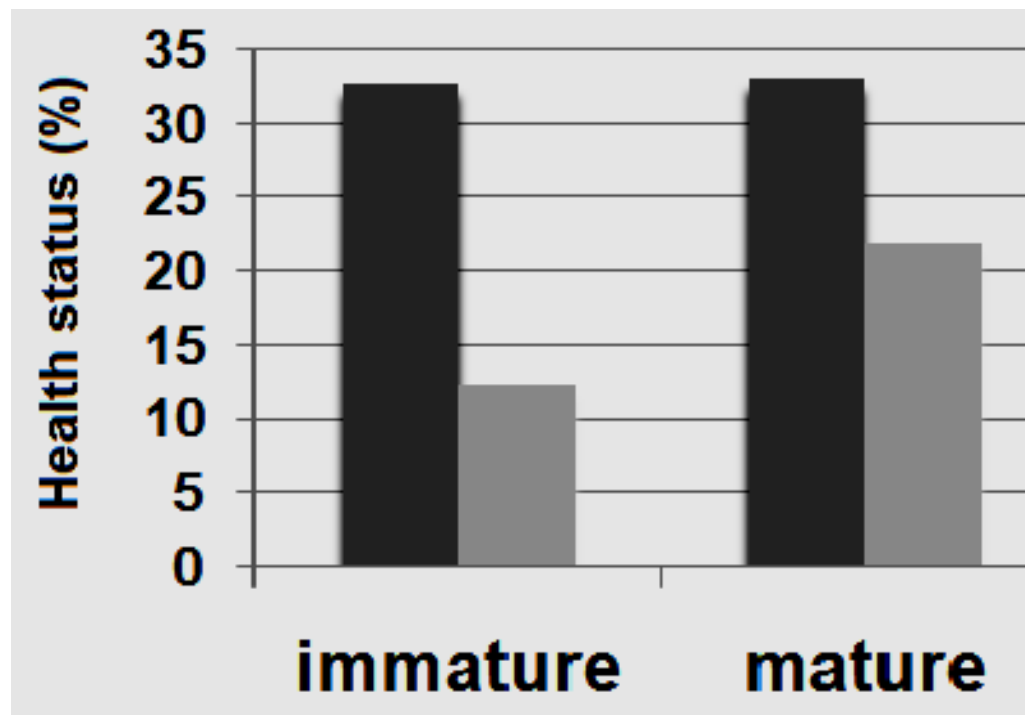


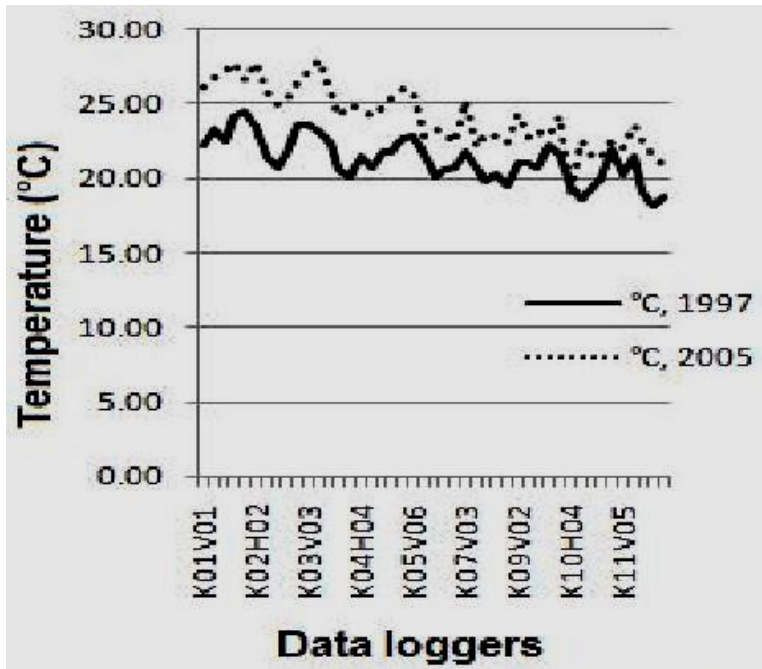
Fig. 3. Status of the sampled coffee plants in Kihansi gorge forest. Dark bars indicate proportion of the healthy coffee stems and grey bars- show infected plants. The sampled population indicates almost equal number of the coffee plants under mature and immature classes, while the infected reproductive plants are twice that of immature plants, a situation potentially dangerous for the species' long-term survival.

Importantly, our study shows that this coffee species is potentially highly threatened by parasites. Almost 50% of the sampled population had either been infested by ectoparasites, mostly on leaves, flowers, stems and fruits, or by endoparasites infecting the stem wood. Further, parasites were observed attacking the species regardless of the age class of the plants. The majority of infestations were observed at UCF with very few at KHU, reflecting the different influences of river flow on these sites. Essentially, the former site is close to the river and had constantly been reached by spray before the river diversion while the latter may have been less influenced by the river as it is located relatively farther away (*ca.* 200 m). This suggests that there were changes in important hydro-ecological parameters that perhaps exposed the coffee population to parasite attack. Also, the gorge microclimate parameters data are slightly higher for temperature and lower relative humidity than they were before habitat perturbation. There were no records of parasite infestations in the early years (2000-2003) immediately after river diversion when intensive field observations for this species were undertaken [1]. This further suggests that the disturbance has exposed the species to parasites. The impact of the aphids includes causing leaves to pucker or to become severely distorted and causing malformed flowers or fruits. Further, the heavily-infested leaves can wilt or turn yellow (Rija, pers. obs.), because excessive sap removal results in reduced rate of photosynthesis and growth structure. This may also predispose victim plants to secondary infection by viruses [10, 11].

The construction of the Lower Kihansi hydropower plant brought about immediate and long-term effects on the various gorge biological communities. Immediate impacts included the rapid population decline and extinction of *Nectophrynoides asperginis* which predominantly depended on the aquatic systems [5, 12]. Birds [6], arthropods [7] and gorge wetland plant communities [8] have changed in composition and structure following the disturbance. Furthermore, the reduced quantity of water via the gorge has seriously affected the chemistry and the quality of the water [9]. However, it is still not clear how soil nutrient dynamics have been affected post river diversion in the areas covered by *C. kihansiensis*, as there were no data collected prior to river diversion. *C. kihansiensis* has been under the indirect and long-term effect of the disturbed hydrological regime of the area and is under great risk of severe population decline. Wilting affects all size classes of the plant, while parasites such as aphids and beetles affect plant leaves and potentially seed formation and maturity [10, 11]. The impacts of habitat loss and parasites on the overall recruitment potential of the coffee are currently unknown. However, elsewhere in Africa wild coffee populations are increasingly threatened. For instance, wild coffee (e.g. *Coffea arabica*) populations in Ethiopia and Uganda are diminishing because the remaining natural habitat is under intense pressure due to unplanned land use and unsustainable resource extraction [13, 14].

Wild coffee species are a potential resource for rural economies because of their role in promoting socio-economic and ecological agendas [14]. For example, there has been effort to harvest Kibale forest wild coffee (*C. arabica*) in Uganda to improve rural livelihoods in communities around Kibale National Park [15]. Wild coffee also could potentially be useful as a genetic resource to improve coffee production, for instance by incorporating disease resistant strains from other species, thus contributing greatly to improved coffee production in rural communities [16]. To date, the use of *C. kihansiensis* as a source of rural income or for improving coffee varieties in Tanzania has not been explored. Advocating it for such use, however, would require prior and more complete knowledge of the species biology and distribution within and beyond its current recorded geographical range. It would also require ecological impact and crop breeding studies, along with monitoring of the current population in Kihansi, to avoid the risks of severe population decline.

4a



4b

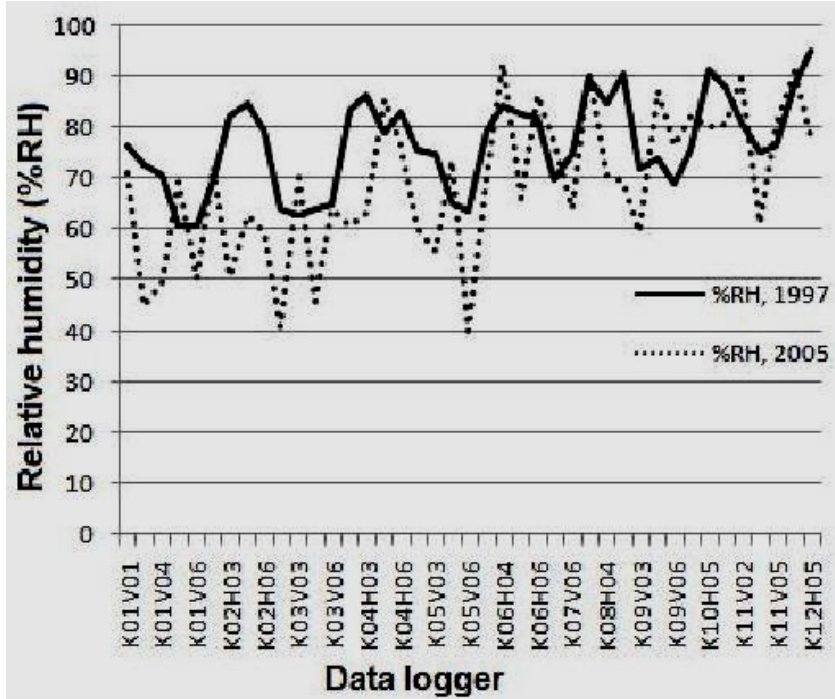


Fig 4 (a). Variation of temperature (°C) and (b) relative humidity (% RH) between 1997 and 2005 after reduction in flow of the river in Kihansi gorge. The values are average daily (24 h) temperature and relative humidity collected at various points (Data loggers-horizontal axis) in the study area.

Implications for conservation

Habitat disturbance has been a major challenge for conservation managers, especially when species are at immediate risks of local extinction. Evidence shows that disturbed areas in the Eastern Arc forests have a lower number of endemic plant species than undisturbed areas [17, 18]. In the southern Udzungwa Mountains, the diversion of the Kihansi River resulted in detrimental effects on most species that depended on the high volume of water flow. In this area the emergence of the chytrid pathogen (*Batrachochytrium dendrobatidis*) that decimated the population of the endemic amphibian, *N. asperginis* has been associated with the change in hydrology and water chemistry following the disturbance [12]. The emergence of the parasitic larva (Fig 5) that is increasingly infesting *C. kihansiensis* is a conservation concern for this critically endangered plant. Furthermore, the decline of some frugivore species such as the Little Greenbul (*A. virens*) in the Kihansi gorge [6] has the potential to adversely affect the natural dispersal ability of *C. kihansiensis* in the area. The combined effects of the loss of the species' ecological envelope, declining natural seed dispersers (frugivorous birds), and increasing parasitism may have highly negative consequences for the reproduction, recruitment and population persistence of this species. This may jeopardize the prospects for this species to contribute to the livelihood of local communities around the Kihansi gorge.



Fig. 5. A parasite larva (enclosed in rectangle) from stem heartwood in one of the *C.kihansiensis* plant showing wilting leaves. The parasite penetrates the plants via main roots, thus causing wilting and death to both young and old coffee stems in the Kihansi Gorge forest.

Given these threats and our limited understanding of the many biological and ecological aspects of this critically endangered species, sound management and conservation options are required to sustain the species in the area. We advance four proposals to encourage the long-term survival of this species:

- i) Continued monitoring of the coffee population with respect to habitat disturbance. This entails regular vegetation assessment throughout and beyond its current range to establish population status in terms of both numbers and distribution.
- ii) Research is highly encouraged to understand basic biological and ecological aspects and the long-term health and fertility effects of parasites on coffee plants. Assessment of potential seed dispersers of *C.kihansiensis* in the frugivore community is also highly recommended in the area.
- iii) As the current threats continue, the managers responsible should seriously consider translocating the species beyond the current known range within the Udzungwa Mountains, using seedlings found *in situ*. Assisted migration is increasingly being used as a tool to save species faced with shrinking ecological envelopes owing to the rapidly changing climate [18 - 21] and is increasingly successful in

plant conservation e.g. [22]. The proposed translocation would involve moving *C. kihansiensis* relatively short distances within its geographic range to avoid unforeseen negative impacts [23]. Such areas could also be within the village land around the Kihansi forest, which would enhance conservation awareness for this species among the local communities.

iv) Establishing seed bank and production of seedlings in nurseries for wide-scale assisted migration of the species should be a priority to ensure perpetuation of the species for potential exploitation at commercial level. Seed banking for threatened or endangered plant taxa is a lasting solution for the species long-term survival [24], and modern standard methods, conforming to Guerrant et al. [25], should be used when preparing seed banks for *C. kihansiensis*.

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Appendix 1. Mean height and diameter (cm) of coffee measured over three years in Kihansi gorge forest (N = 450)

Sampling year									
2007			2008			2009			
Stem Height									
height group(cm)	Minimum	Maximum	Mean+ SD	Minimum	Maximum	Mean+ SD	Minimum	Maximum	Mean+ SD
< 25	9.8	27	18.62 ± 4.55	9.7	29.4	20.11 ± 10.17	4.8	52.2	22.29 ± 10.17
25-50	25.8	49.4	35.71 ± 7.18	4.8	55.8	36.53 ± 9.18	11	61.2	37.23 ± 10.19
51-100	50	97	66.38 ± 14.49	7.6	99.2	68.46 ± 17.47	17.6	102	68.24 ± 17.88
> 101	102	215	130.94 ± 25.79	44.4	213.2	131.94 ± 28.81	25.2	218	130.65 ± 31.00
Stem Diameter									
Age group	Minimum	Maximum	Mean+ SD	Minimum	Maximum	Mean+ SD	Minimum	Maximum	Mean+ SD
Mature	0.6	3.0	1.63 ± 0.66	0.6	3.4	1.67 ± 0.62	0.4	3.4	1.73 ± 0.75
Immature	1.8	9.0	4.57 ± 1.43	2.0	9.6	4.67 ± 1.57	1.2	10.6	4.51 ± 1.56

Appendix 2. Soil physical parameters and levels of nitrogen, phosphorous and potassium in the sampled soil of coffee sampling sites in Kihansi. UCF= upper camp sampling site near Upper spray wetland, KHU= sampling site near Kihansi research station, LWF= Lower camp sampling site near Lower spray wetland

Sampling Site	Altitude (m)	Samples collected	Soil texture, colour	pH range	Mineral content - range (mg/l)		
					Nitrogen	Phosphorous	Potassium
			sandy, dark-				
UCF	875 - 925	18	brown	5.5 - 6.0	5.0 - 15.0	25.0 - 50.0	0.1 - 600.0
LWF	800 - 825	18	Sandy, brown	5.5 - 6.5	20.0 - 35.0	5.0 - 50.0	200.0 - 600.0
			Sandy-loamy,				
KHU	825 - 850	18	dark	6.0 -7.0	45.0 - 70.0	70.0 - 100.0	200.0 - 600.0

Appendix 3. Average height and diameter for the two age classes of the sampled coffee population of the study sites in Kihansi gorge. Definition of LWF, KHU and UCF are given in Appendix 2.

Study	Sampling year/ stem size (cm)					
	2007		2008		2009	
Sites	height	diameter	height	diameter	height	diameter
(i) Immature						
LWF	26.58	1.65	26.33	1.55	26.72	1.89
KHU	26.58	1.65	27.76	1.69	29.43	1.70
UCF	28.34	1.72	31.83	1.94	32.09	2.01
(ii) Mature						
LWF	98.03	4.52	96.59	4.62	97.24	4.68
KHU	98.03	4.52	95.73	4.51	94.81	4.38
UCF	99.93	4.67	99.05	4.82	99.71	4.70