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Author(s): Siri A. Abihudi, Hugo J. de Boer and Anna C. Treydte

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RESEARCH ARTICLE

Conservation status revision and communities' perceptions of 22 *Aloe* species in Tanzania

Siri A. Abihudi[1,2,*], Hugo J. de Boer[3] & Anna C. Treydte[1,4]

[1]Department of Biodiversity Conservation and Ecosystem Management, Nelson Mandela African Institution for Science and Technology (NM-AIST), Arusha, Tanzania
[2]Department of Agronomy, Medical Botany and Plant Breeding, Institute of Traditional Medicine, Muhimbili University of Health and Allied Sciences, Dar es Salaam, Tanzania
[3]Natural History Museum, University of Oslo, Oslo, Norway
[4]Department of Physical Geography, Stockholm University, Stockholm, Sweden
*Corresponding author: abihudis@nm-aist.ac.tz

Background and aims – Many *Aloe* species are globally threatened due to overharvesting for trade and habitat destruction. CITES regulates their international trade. In Tanzania, 50% of all existing *Aloe* species had previously been assessed, though some of these assessments were Data Deficient. For those with sufficient data, an update is required as the rate of decline has rapidly increased over the last years.
Material and methods – We estimated Area of Occupancy (AOO), Extent of Occurrence (EOO), and number of locations for 22 Tanzanian *Aloe* species using the Geospatial Conservation Assessment software (GeoCAT). We assessed the reasons leading to their decline based on direct field observations and community perceptions.
Key results – We revised the conservation status of 22 *Aloe* species; two were assessed as Critically Endangered, ten as Endangered, five as Vulnerable, and five as Least Concern. We re-discovered the Critically Endangered *Aloe boscawenii*, which had not been seen in Tanzania for more than six decades. We propose to downgrade the endemic *Aloe dorotheae*, *Aloe leptosiphon*, and *Aloe flexilifolia* from Critically Endangered to a lower threat level. The community perception on *Aloe* species availability did not accurately reflect their categorisation based on the IUCN criteria B. We identified agricultural activities and climate change effects as the two main threats to Tanzanian *Aloe* species.
Conclusion – We conclude that overall numbers are declining for 22 *Aloe* species in Tanzania, mainly due to human activities. We recommend the implementation of laws and policies to protect their natural habitats.

Keywords – Area of occupancy; community surveys; distribution; Eastern Africa; extent of occurrence; interviews; IUCN category; threatened.

INTRODUCTION

The genus *Aloe* L. contains over 500 species of succulent flowering plants (Veríssimo 2016). *Aloe* species are known for their medicinal, cosmetic, and ornamental uses (Newton & Vaughan 1996; Grace et al. 2009), where *Aloe vera* (L.) Burm.f. is the most widely known species (Basmatker et al. 2011; Mugambi 2015). The genus occurs mainly in continental Africa, Madagascar, the Arabian peninsula, and islands in the Indian Ocean (Cousins & Witkowski 2012; Grace et al. 2015). *Aloe* species occupy a wide range of habitats, from forests to exposed rock surfaces and cliff faces, across a considerable altitudinal range, from sea level (e.g. *A. boscawenii* Christian, *A. kilifiensis* Christian)

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to about 3,500 meters above sea level (e.g. *A. ankoberensis* M.G.Gilbert & Sebsebe, *A. steudneri* Schweinf.) (Newton 2004). In East Africa, almost a third of the species have limited distributions and are locally threatened (Carter 1994; Wabuyele 2006). There are 52 known *Aloe* taxa in Tanzania, 24 of which are endemic (Newton 2004; Wabuyele 2006). The Eastern Arc Mountains and Coastal Forests CEPF Plant Assessment Project assessed the threat level for 19 *Aloe* species in the Eastern Arc Mountains and Coastal Forests, two of Tanzania's biodiversity hotspots (Eastern Arc Mountains & Coastal Forests CEPF Plant Assessment Project Participants 2009a, 2009b, 2009c, 2009d, 2009e, 2009f, 2009g, 2009h, 2009i, 2009j, 2009k, 2009l, 2009m, 2009n, 2009o, 2009p, 2009q, 2009r, 2009s). However, some Tanzanian *Aloe* species have never been assessed for the IUCN Red List (Not Evaluated), and some species listed as assessed do not have enough available data to be certain about their status such as *A. niensiensis* L.E.Newton (Richart 2019d).

The present rate of global biodiversity loss resulting from human activities is 100 times higher than losses resulting from natural extinction incidences (Djoghalf 2007). In Madagascar alone, three *Aloe* species were reported to be extinct in the wild in 2014 (Rakotoarisoa et al. 2014). Numerous other *Aloe* species are globally extinct due to overharvesting and habitat destruction (Rakotoarisoa et al. 2014; CITES 2016). Particularly Tanzanian *Aloe* species are rapidly declining in numbers, with five species currently categorised as Critically Endangered (Eastern Arc Mountains & Coastal Forests CEPF Plant Assessment Project Participants 2009b, 2009h, 2009i, 2009m, 2009o). These species are threatened with extinction due to their naturally occurring limited distribution and small population size. These factors make them particularly vulnerable to human activities (Eastern Arc Mountains & Coastal Forests CEPF Plant Assessment Project Participants 2009b, 2009h, 2009m, 2009o).

One Critically Endangered species, *Aloe boscawenii*, is endemic to Tanzania and had occurred along the coast of the Indian Ocean in Boma ward, Tanga region, up to the 1950s. *Aloe boscawenii* was last sighted in the wild in 1953 and had been thought to be nearly extinct. The other Critically Endangered *Aloe* species in the previous IUCN Red List included *A. dorotheae* A.Berger, *A. leptosiphon* A.Berger, *A. pembana* L.E.Newton, and *A. flexilifolia* Christian, which are present in limited numbers in specific geographical regions in Tanzania (Eastern Arc Mountains & Coastal Forests CEPF Plant Assessment Project Participants 2009h, 2009m, 2009o).

A frequent update of conservation assessments is essential for making informed conservation decisions (Schatz 2009), particularly for *Aloe* species occurring in areas that are strongly affected by increasing human activities or by the effects of climate change (Syfert et al. 2014). In many parts of the world, species selection is one of the most challenging aspects when setting conservation priorities (Myers 1990). In the past, conservation priority was given to biodiversity-rich areas, depending on the level of threat and endemism (Myers 1990; Myers et al. 2000). However, the very limited geographical areas, in which some *Aloe* species are found (Newton 2004; Wabuyele et al. 2006; Wabuyele & Kyalo 2008; Grace et al. 2015), as well as the unusually high levels of human activities that threaten their population levels (Cousins & Witkowski 2012; Grace et al. 2015), call for their conservation prioritisation. The Convention on International Trade in Endangered species of Fauna and Flora (CITES) tries to ensure that international trade in both flora and fauna does not threaten their survival. The global trade for *Aloe* species is regulated by Appendices I (21 species listed) and II (all remaining), with an exception for the widely cultivated *Aloe vera* (CITES 2019).

Our study uses the Geospatial Conservation Assessment Tool (GeoCAT) software, an online species assessment tool that utilizes information on a species' Extent of Occurrence (EOO) and Area of Occupancy (AOO) (Bachman et al. 2011). We re-assess 22 *Aloe* species present in high biodiversity regions across Tanzania using the IUCN Red List criteria. Some of these species were previously assessed and published in the IUCN Red List of threatened species (table 1). Of the remaining 30 Tanzanian *Aloe* species not evaluated in this study, only 37% has previously been assessed by the IUCN Red List. We re-examine the conservation status using IUCN Red List criterion B since it enables objective assessment of all 22 species, and discuss the factors leading to their decline based on direct observations and community perceptions. We used field-generated coordinates, site visits, and interviews with local communities to assess individual species threat level and conservation status. Our conservation re-assessments provide a basis for updating the IUCN Red List status for these 22 Tanzanian *Aloe* species.

MATERIAL AND METHODS

Survey

From December 2017 to November 2018, we visited regions with known high *Aloe* species diversity in Tanzania, including the Kilimanjaro, Tanga, Mara (Serengeti district), Katavi, and Rukwa regions, and other regions where specific *Aloe* species had been reported in literature (fig. 1) (Carter 1994). To understand the distribution of different *Aloe* species, we surveyed a total of 28 districts in a stratified random meander survey (Huebner 2007; McCaffrey et al. 2014). The respective district authorities gave their permission to conduct this study. For species with a known and consistent distribution in the landscape, such as those growing along water bodies, a systematic search was conducted within that particular habitat (Bonar et al. 2011; McCaffrey et al. 2014).

Data collection

We collected the coordinates and elevation for the Tanzanian specimens of different *Aloe* species and used ArcGIS v.10.1 (Yan et al. 2020) to map their distribution and diversity across the study sites. Local (DSM, NHT) and international (AAU, BR, DES, FR, K, MO, S, WAG) herbarium databases complemented this mapping. We collected duplicate voucher specimens and deposited them at the local herbaria ITMH, DSM, and NHT (table 2). Community interviews supplemented the distribution mapping to evaluate the communities' view on what threatened local *Aloe* species.

Table 1 – The conservation status of 22 assessed *Aloe* species in Tanzania, including, their scientific names, endemism, current global IUCN status, estimated number of locations for the national assessment, and the category B1 (EOO) and B2 (AOO) in Tanzania. The description of the IUCN Red List status: CR = Critically Endangered, EN = Endangered, VU = Vulnerable, LC = Least Concern, NT = Near Threatened, and NE = Not Evaluated.

Scientific name	Endemic	Current IUCN status (all global)	Estimated # of locations	EOO (km²)	AOO (km²)	Tanzania newly proposed status	Threat
Aloe ballyi Reynolds	No	EN B2ab(iii) (Eastern Arc Mountains & Coastal Forests CEPF Plant Assessment Project Participants 2009a)	3	6,156	32	EN B2ab(iii) (National assessment)	Overharvesting, land for road and agriculture
Aloe bicomitum L.C.Leach	No	NE	2	6,490	16	EN B2ab(iii) (National assessment)	Overharvesting
Aloe boscawenii Christian	Yes	CR D (Eastern Arc Mountains & Coastal Forests CEPF Plant Assessment Project Participants 2009b)	2	43	16	CR B1b(iii)c(iii)	Restricted population and human activities
Aloe chabaudii Schönland	No	NE	3	45,607	20	EN B2ab(iii) (National assessment)	Land for agriculture
Aloe christianii Reynolds	No	NE	5	82,927	68	EN B2ab(iii) (National assessment)	Land for agriculture
Aloe confusa Engl.	No	NE	2	1,265	20	EN B1ab(iv)+2ab(iv) (National assessment)	Restricted population and floods (at Kifaru river)
Aloe deserti A.Berger	No	NT (Eastern Arc Mountains & Coastal Forests CEPF Plant Assessment Project Participants 2009g)	5	22,561	52	EN B2ab(iii) (National assessment)	Land for agriculture
Aloe dorotheae A.Berger	Yes	CR B2ab(v) (Eastern Arc Mountains & Coastal Forests CEPF Plant Assessment Project Participants 2009h)	7	4,109	76	VU B1ab(iii,v)+2ab(iii,v)	Fire from clearing agricultural land and grazing
Aloe duckeri Christian	No	LC (Richart 2019a)	> 15	167,960	108	LC (National assessment)	Land for agriculture and grazing
Aloe fibrosa Lavranos & L.E.Newton	No	NE	1	65	12	CR B1ab(iv)+2ab(iv) (National assessment)	Restricted population
Aloe flexilifolia Christian	Yes	CR B1ab(v) (Eastern Arc Mountains & Coastal Forests CEPF Plant Assessment Project Participants 2009i)	4	112	36	EN B2ab(iii)	Overharvest for trade products
Aloe lateritia Engl.	No	LC (Weber 2013)	>15	624,760	320	LC (National assessment)	Fire and land for agriculture
Aloe leptosiphon A.Berger	Yes	CR B1ab(v) (Eastern Arc Mountains & Coastal Forests CEPF Plant Assessment Project Participants 2009m)	4	62	32	EN B1ab(iii)+2ab(iii)	Restricted population
Aloe macrosiphon Baker	No	NE	8	114,191	80	VU B2ab(iii) (National assessment)	Land for agriculture
Aloe massawana Reynolds	No	VU B1ab(iii)+2ab(iii) (Eastern Arc Mountains & Coastal Forests CEPF Plant Assessment Project Participants 2009n)	6	13,087	112	VU B1ab(iii)+2ab(iii) (National assessment)	Urbanization

Table 1 (continued) – The conservation status of 22 assessed *Aloe* species in Tanzania, including, their scientific names, endemism, current global IUCN status, estimated number of locations for the national assessment, and the category B1 (EOO) and B2 (AOO) in Tanzania. The description of the IUCN Red List status: CR = Critically Endangered, EN = Endangered, VU = Vulnerable, LC = Least Concern and NE = Not Evaluated.

Scientific name	Endemic	Current IUCN status (all global)	Tanzania				
			Estimated # of locations	EOO (km^2)	AOO (km^2)	Newly proposed status	Threat
Aloe mzimbana Christian	No	NE	6	26,339	40	VU B2ab(iii) (National assessment)	Pumice mining and road construction
Aloe myriacantha (Haw.) Schult. & Schult.f.	No	LC (Richart 2019b)	10	350,683	68	LC (National assessment)	Fire from clearing agricultural land
Aloe nuttii Baker	No	LC (Richart 2019c)	6	66,150	32	VU B2ab(iii) (National assessment)	Fire from clearing agricultural land
Aloe parvidens M.G.Gilbert & Sebsebe	No	LC (Weber & Demissew 2013a)	2	206	12	EN B1ab(iii)+2ab(iii) (National assessment)	Land for agriculture
Aloe rabaiensis Rendle	No	LC (Eastern Arc Mountains & Coastal Forests CEPF Plant Assessment Project Participants 2009p)	4	201	28	EN B1ab+2ab (National assessment)	Land for agriculture
Aloe secundiflora Engl.	No	LC (Weber & Demissew 2013b)	> 15	215,938	216	LC (National assessment)	Overharvest for trade and wrong harvesting method
Aloe volkensii Engl.	No	LC (Eastern Arc Mountains & Coastal Forests CEPF Plant Assessment Project Participants 2009r)	> 15	174,244	152	LC (National assessment)	Overharvesting and land for agriculture

Extensive in-depth interviews on *Aloe* species' abundance and threats were assessed using questionnaires in 22 villages across Tanzania (Abihudi et al. 2019). A total of 236 respondents were interviewed (56 in Kilimanjaro, 67 in Katavi-Rukwa, 22 in Mara (Serengeti district), and 91 in the Tanga region) about their knowledge on different *Aloe* species that we had previously published upon (Abihudi et al. 2019). The respondents were randomly chosen to obtain a broad range in age, gender, ethnicity, and occupation. We included questions on whether the *Aloe* species were declining, the species' current availability, and asked respondents to list potential threat factors and levels. Direct field observations and photographs complemented the interviews.

Red List assessments

We assigned Red List categories to *Aloe* species following guidelines set by the IUCN-SSC (IUCN Standards and Petitions Committee 2019). Our Red List assessments apply at the national and international level for *Aloe* species endemic to Tanzania. However, they only apply at the national level in Tanzania for *Aloe* species that also occur in other countries besides Tanzania. We used GeoCAT to analyse geospatial information based on criteria B, which includes information on the Restricted Geographical range, the Extent of Occurrence (EOO), the Area of Occupancy (AOO) (Bachman et al. 2011), and the number of locations. The number of locations is estimated to be an indicator for significant possible threat(s) that could decrease or wipe out the population (IUCN Standards and Petitions Committee 2019). We were not able to use criteria C and D because we lacked population data, and for criteria A, there was no estimate on the population reduction in comparison to the past population.

Aloe species were categorised according to their conservation status based on the IUCN Red List category (IUCN Standards and Petitions Committee 2019), i.e. Critically Endangered, Endangered, Vulnerable, Near Threatened, or Least Concern. For the species under the threatened category, i.e. Critically Endangered, Endangered, and Vulnerable, two of the following sub-criteria, i.e. Severely Fragmented or Number of locations, Continuing Decline and Extreme Fluctuations, were added in the assessment. Species were mapped and the current or potential threat factors for the species were determined within their EOO and AOO. Descriptive statistics were produced using SPSS Statistics v.20 (Awang et al. 2018) determine the threat level and conservation practices for *Aloe* species in each region. Pearson correlation analysis was used to determine the correlation between elevation and diversity of *Aloe* species.

RESULTS

We evaluated the conservation status of 22 *Aloe* species in Tanzania and found that 77% of these species are threatened. A distribution map of all collections is provided in fig. 1 and locality maps of each species are provided in supplementary file 1. We assessed two species as Critically Endangered, ten as Endangered, five as Vulnerable, and five as Least Concern (table 1) using the Extent of Occurrence and Area of Occupancy criteria. Forty percent of the studied *Aloe* species were present at high elevations (> 1,500 m a.s.l.), while 30% were present each at moderate (1,000–1,500 m a.s.l.) and low (< 1,000 m a.s.l.) elevations. There was no significant correlation between *Aloe* species diversity and elevation ($F_{1,8} = 0.12$, $p = 0.738$, $R^2 = 0.015$). We found the Critically Endangered *Aloe boscawenii* at low elevation only. Of the 22 species studied, the highest species diversity was found in the Eastern Arc Mountains, followed by the Katavi-Rukwa ecosystem, Arusha, and the Coastal Forest and Serengeti ecosystem (fig. 1). Most of the studied *Aloe* species (55%) were found in rocky areas, 74% in clumped distributions, while 26% were randomly distributed (n = 22). Most of the studied endemic *Aloe* species had higher threat categories than non-endemic species.

More than 74% of our respondents (total n = 236) perceived *Aloe* species to be accessible or intermittently available (fig. 4). On the other hand, when we asked

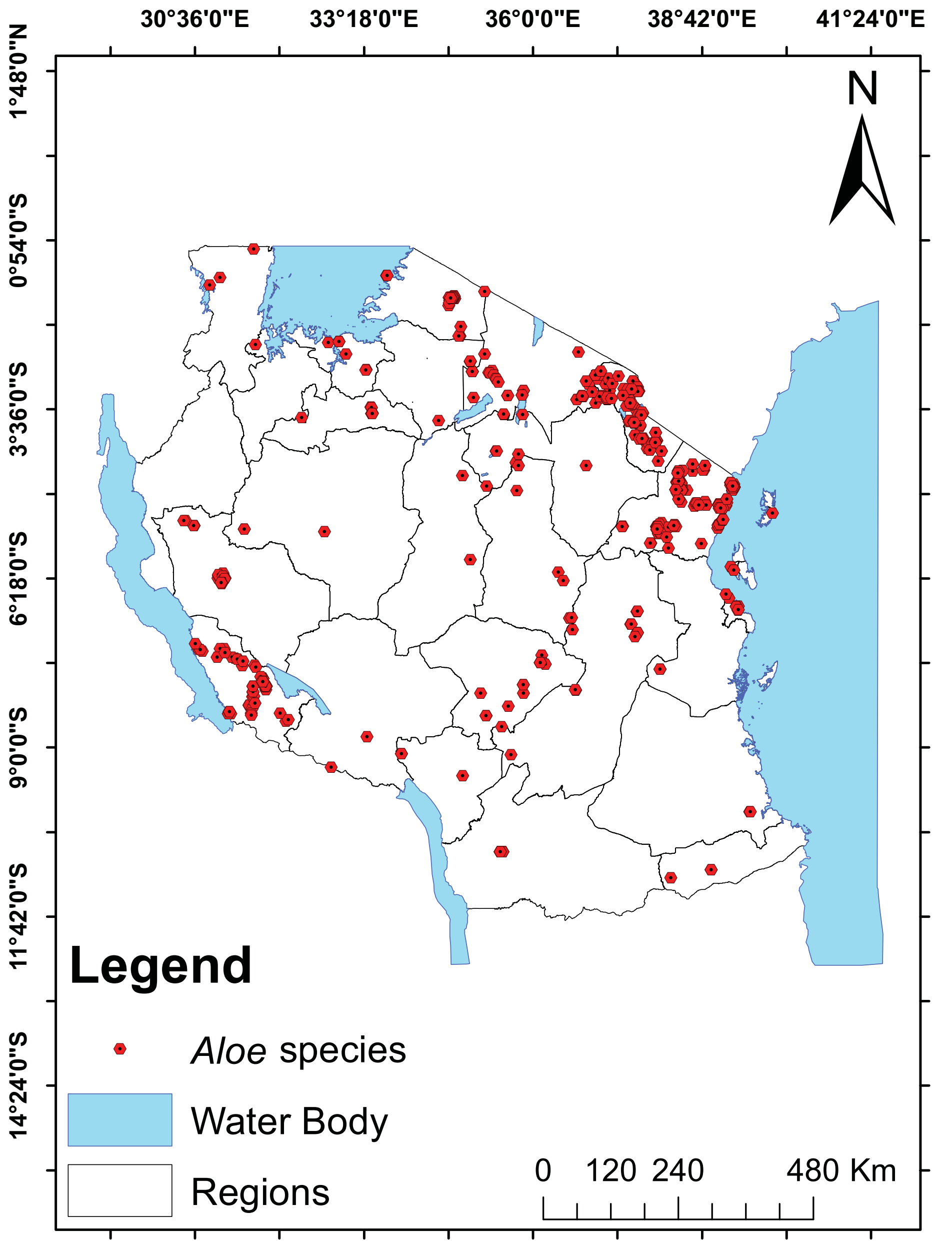

Figure 1 – Distribution of the 22 studied Tanzaniana *Aloe* species. Map created using ArcGIS v.10.1 (https://www.arcgis.com, © Esri and its licensors, all rights reserved), layer data from the Tanzania National Bureau of Statistics.

Table 2 – Studied material of the 22 studied *Aloe* species, detailing material collected by S. Abihudi: collection number (NHT, DSM, and ITMH), year of collection, region, and locality, as well as the number of internationally available specimens (specimens in Western herbaria, with number of specimens in parentheses).

Scientific name	Collector	Collection number	Year	Region	Locality	Specimens
A. ballyi	S.Abihudi	SA-172, 180	2018	Kilimanjaro	Lembeni ward in Mwanga district and Mamba ward in Same district	K (3), MO (2)
A. bicomitum	S.Abihudi	SA-137, 145	2018	Rukwa	Kasanga, Muzi, and Namanyele	MO (1), S (1)
A. boscawenii	S.Abihudi	SA- 99, 100, 101, 102	2018	Tanga	Manza, Moa, and Boma	
A. chabaudii	S.Abihudi	SA-105, 107, 109	2018	Katavi	Tanganyika district	MO (2)
A. christianii	S.Abihudi	SA-106, 108, 110, 112, 113, 125, 132, 133, 138	2018	Katavi and Rukwa	Tanganyika, Mchakamchaka, Msanzi, Muze, Kasanga, Namanyele, and Mpanda	MO (1)
A. confusa	S.Abihudi	SAA-153	2018	Kilimanjaro	Lake Chala	K (6)
A. deserti	S.Abihudi	SA-181	2018	Kilimanjaro	Lembeni wards in Mwanga district and Kisiwani ward in Same district	K (7), MO (3)
A. dorotheae	S.Abihudi	SA-47, 48, 49, 69, 76	2018	Tanga	Bangu, Kideleko, Kilimamzinga, Kwamkono, Msasa, Kwamagome, and Hoza	DES (2), MO (2)
A. duckeri	S.Abihudi A.Chawala	SA-114, 116, 117, 118, 122, 124, 126, 128, 129, 131, 134, 140, 142, 148	2018, 2019	Katavi, Rukwa, Iringa, and Njombe	Msukumilo, Matai, Msanzi, Laela, Namanyele, Mpanda, Njombe, Mufindi, and Ugala River	MO (3)
A. fibrosa	S.Abihudi	SAA-165	2018	Kilimanjaro	Simba farm in Engarenairobi ward	K (3)
A. flexilifolia	S.Abihudi	SA-34, 37	2018	Tanga	Soni and Kisiwani village	MO (4)
A. lateritia	S.Abihudi	SA-28, 29, 31, 39, 42, 44, 46, 67, 73, 74, 77, 82, 85, 88, 155	2018	Mara, Kilimanjaro, and Tanga	Kisangula, Pongwe, Handei, Magamba, Kwematungutu, Migulu, Shukilai, Migambo, Kifulilo, Kifungiro, Masange, Gale, Kisangula, Handei, Bangu, Kwamkono, Kwamagome, Golani, Handeni, Mbamba, Hoza,Kwafivi, Mshizii, Kwamsononi, Soni, Lushoto, Bomole hill, Amani, Rombo, Dodoma, and Mbulu	K (51), MO (6)
A. leptosiphon	S.Abihudi	SA-20, 21, 22, 23, 30, 32, 33, 35, 36, 41	2018	Tanga	Soni, Kishewa, Magila, Kwamsononi, Mgombelwa, and Mlalo	MO (4)
A. macrosiphon	S.Abihudi	SA-51, 57, 59, 62	2018	Mara	Serengeti NP	K (1), MO (7)
A. massawana	S.Abihudi	SA-27, 83, 90, 92, 98, 163	2018	Tanga, Dar es Salaam, and Pemba	Pongwe, Moa, Boma, Manza, Mwera, Dar es Salaam near sea cliff hotel, Masange village, and Pemba	MO (7)
A. mzimbana	S.Abihudi	SA-120, 127,130	2018	Rukwa	Mtai, Msanzi, Laela, Namanyele, Ugala River, and Tunduma	FR (9)
A. myriacantha	S.Abihudi	SAA-187, 188	2018	Arusha and Rukwa	Lake Duluti and Sopa Chala	K (14), MO (2)
A. nuttii	S.Abihudi	SAA-149	2018	Rukwa	Muzi	MO (2), WAG (2)
A. parvidens	S.Abihudi	SA-171, 174	2018	Kilimanjaro	Kiverenge and Lembeni	
A. rabaiensis	S.Abihudi	SA-176, 179, 182, 183	2018	Kilimanjaro	Jipe and Lembeni	MO (1)
A. secundiflora	S.Abihudi	SA-150, 152, 169, 184	2017, 2018	Mara, Kilimanjaro, Arusha, Manyara, and Dodoma	Serengeti NP, Kisangula, Engarenairobi, Siha, Ngarenanyuki, Jipe, Kisiwani, Stelingi, Mwembe, Sanya juu, Chemka, close to lake Chala, Himo, Kiverenge, Lembeni, Holili and Mwika, Arumeru, Mbulu, and Kongwa	AAU (1), BR (1), DES (3), MO (2), WAG (2)
A. volkensii	S.Abihudi	SA-24, 68, 84, 89, 91, 94, 96, 160, 161, 162, 166, 168, 175, 185, 186	2017, 2018	Mara, Manyara, Kilimanjaro, Arusha, and Tanga	Karatu, Mwembe, Mbaga, Bangu, Mwika, Handei, Pongwe, Serengeti NP, Kisangula, Kisiwani, Same, Himo, Siha, Tongoni, Lushoto, Marangu, Lembeni, Kiverenge, Arusha, Arumeru, Golani, Kifulilo, Mtindili, Mamba, Ngoni village, and Nkwisha	AAU (1), K (8), MO (9)

respondents how the availability had changed over the last five years, 78% reported a declining availability. Most of the reported *Aloe* species were harvested from the wild, except for *Aloe massawana* Reynolds and *A. volkensii* Engl., which were mainly cultivated in the respondents' gardens and farms (fig. 2).

Respondents additionally answered questions on how their communities utilized *Aloe*. Respondents across all regions reported that *Aloe* leaves were a primary source of medicine (fig. 3). In the Kilimanjaro region, stems from the tall *Aloe* species, *Aloe ballyi* Reynolds, and *A. volkensii*, were used for local beer brewing. Moreover, respondents

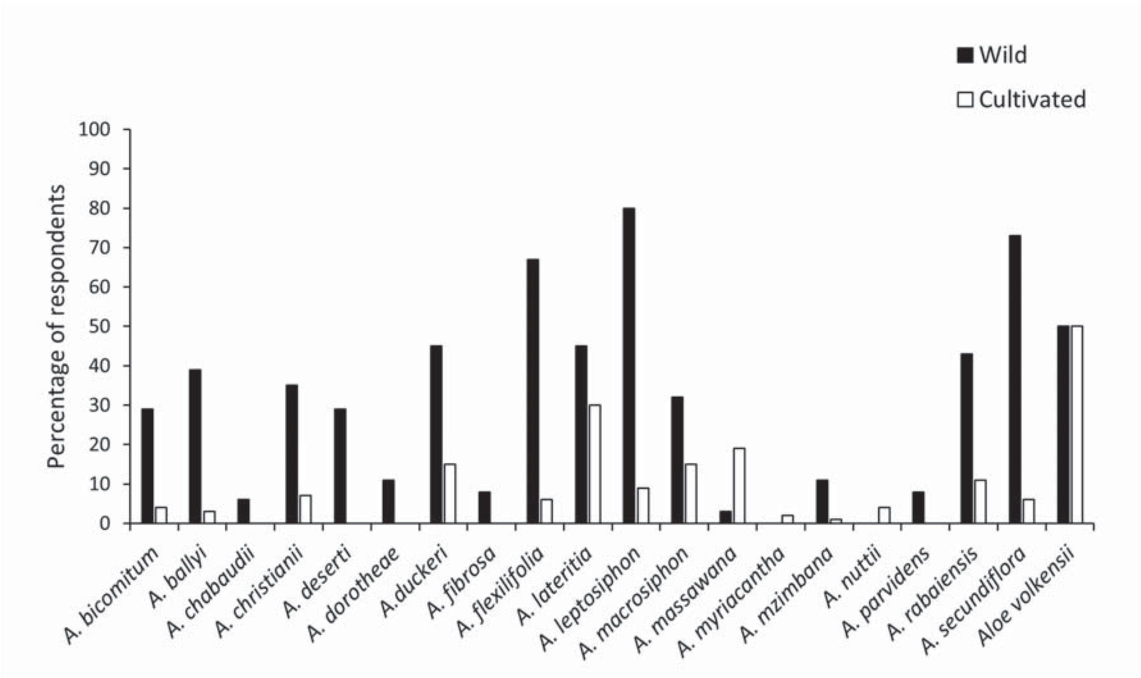

Figure 2 – Use of the 22 studied *Aloe* species by 236 respondents accross 22 districts of Tanzania distinguishing between use of wild and cultivated plant material.

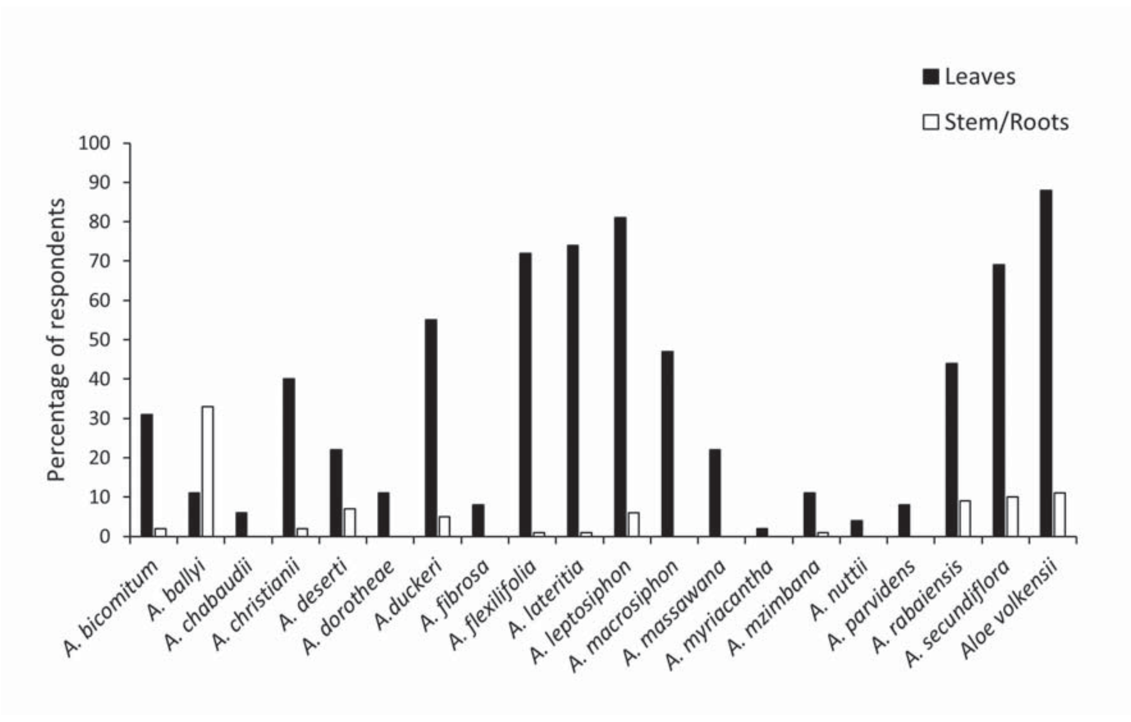

Figure 3 – Preferred plant parts for utilization for the 22 studied *Aloe* species in Tanzania based on interviews conducted across 22 districts in Tanzania in the year 2017–2018. Leaves are the most commonly used part, except for *A. ballyi*. n = 236.

harvested roots from *A. deserti* A.Berger (24%, n = 29; % = percentage of respondents using this species; n = number of the individual species-uses mentioned by respondents), *A. rabaiensis* Rendle (17%, n = 53), *A. mzimbana* Christian (8%, n = 29), and *A. leptosiphon* (7%, n = 87), which might have negatively affected their conservation status.

For the species with the highest EOO (*Aloe duckeri*, 70%, n = 60, and *A. lateritia* Engl., 64%, n = 75), we found a correlation between the reported number of uses and whether the species were perceived to be threatened. We additionally found that community myths and beliefs might contribute to *A. lateritia* conservation in the Moa ward and Lushoto district. This is because *A. lateritia* is only found in the sacred forests where only the Washana Clan are allowed to enter. Respondent answers also suggested that the *A. duckeri* population levels are affected by agriculture and grazing activities in Nkasi district, while *A. lateritia* is affected by agriculture and fires when farmers prepare the land for the rainy season. Respondents additionally reported that a particular company was overharvesting the widespread *A. secundiflora* Engl. for trade in the Same district, and that an incorrect harvesting method resulted in their widespread death. The three short *Aloe* species in the Mwanga district (*A. deserti*, *A. parvidens* M.G.Gilbert & Sebsebe, and *A. rabaiensis*) had been affected by the increased human population and the need for agricultural areas, but were also intermittently utilised for beer brewing. In contrast, *A. fibrosa* was unknown to most respondents (79%, n = 38) in the Engarenairobi ward, except for a few people in the Simba farm area (21%, n = 10). Accordingly, it was not utilized as often as other more available species such as *A. secundiflora*, and *A. volkensii.* Moreover, respondents perceived *A. chabaudii* Schönland (100%, n = 6) in the Katavi region and *A. macrosiphon* Baker (65%, n = 43) in the Serengeti district to still be available.

Respondents additionally thought that *Aloe mzimbana* (59%, n = 29), *A. myriacantha* (Haw.) Schult. & Schult.f. (87%, n = 40), and *A. nuttii* Baker (100%, n = 10) were rare (fig. 4). They believed road construction had a negative impact on the *A. mzimbana* population in the Kalambo district, while the fires used for farm preparation negatively affected *A. myriacantha* populations in the Nkasi district. In contrast to these perceptions, we found in our survey that *A. mzimbana* was plentiful in the Chala Hills in the Nkasi district in the Rukwa region.

Similarly, 77% of respondents (n = 29) in the Pongwe ward, Tanga region believed that *A. massawana* was rare in the wild, which they attributed to urbanisation and the demand for agricultural land. To counteract this perceived rarity, most respondents in Pongwe ward and Pangani district, Tanga region have planted *A. massawana* in their home gardens. Likewise, 79% of respondents thought that *A. christianii* Reynolds was threatened. They attributed the decline to a demand for agricultural land and to road construction in the Kalambo district.

Only four respondents, three of whom were fishermen, knew about *Aloe boscawenii* at the Boma ward. No respondents at Lake Chala knew about *A. confusa*. Farmers along the Kifaru river had previously seen *A. confusa* at the river banks, though more frequent flooding due to climate change was believed to have washed it away. Although respondents thought that *A. flexilifolia* was available, two

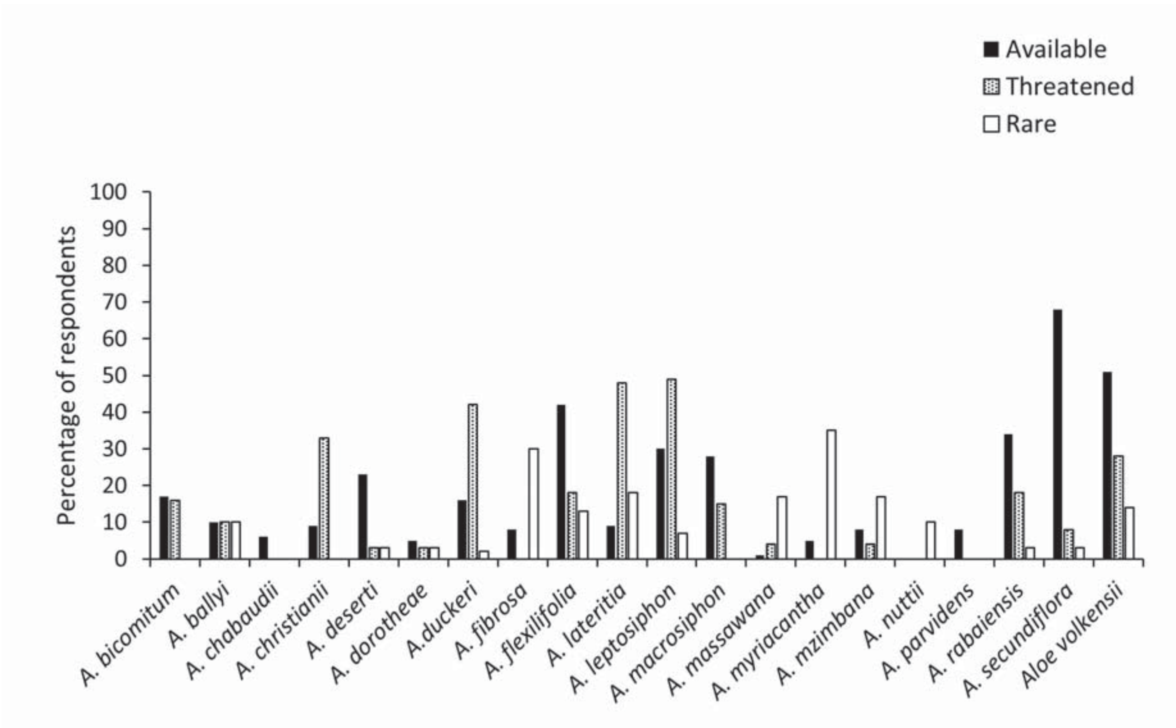

Figure 4 – Local perceptions of availability and rarity of the 22 studied *Aloe* species across 22 districts of Tanzania in the year 2017–2018. n = 236.

respondents mentioned it was over-harvested for commercial detergents. The respondents (43%) believed *A. bicomitum* L.C.Leach was threatened by overharvesting because it was harvested from the wild and planted at hotels along Lake Tanganyika. Based on our survey, human activities, including primary agriculture, and climate change are the two leading causes of *Aloe* species' population declines. Other threats to *Aloe* species based on respondents included using it as feed for livestock and converting their habitat into human settlements. The tall *Aloe* species (*A. ballyi* and *A. volkensii*) were also impacted by overharvesting for beer brewing and road construction, particularly in Same district, Kilimanjaro.

DISCUSSION

Natural habitats of threatened *Aloe* species

In this study, we reassessed 22 *Aloe* species present in Tanzania using EOO and AOO criteria to determine their threat level. We upgraded 18% of the studied *Aloe* species (*Aloe deserti*, *A. nuttii*, *A. parvidens*, and *A. rabaiensis*), downgraded 14% (*A. dorotheae*, *A. flexilifolia*, and *A. leptosiphon*), while 39% (*A. ballyi*, *A. boscawenii*, *A. duckeri*, *A. lateritia*, *A. massawana*, *A. myriacantha*, *A. secundiflora*, and *A. volkensii*) retained their current IUCN Red List status in Tanzania. The remaining species were assessed for the first time (*A. bicomitum*, *A. chabaudii*, *A. christianii*, *A. confusa*, *A. fibrosa*, *A. macrosiphon*, and *A. mzimbana*). It is important to note that EOO calculations mostly downgrade the threat status if the AOO and locations are not considered. This had previously been done for the *Aloe* species in Kenya (Wabuyele et al. 2006). Our inclusion of the AOO and number of locations into the analysis gives a more accurate representation of highly distributed species (Solano & Feria 2007), since the AOO analysis also takes the physically occupied area into account.

All four previously assessed Critically Endangered *Aloe* species remained threatened; one retained its Critically Endangered status (*Aloe boscawenii*), two were categorised as Endangered (*A. flexilifolia* and *A. leptosiphon*), and one as Vulnerable (*A. dorotheae*). This is not surprising since rare and endemic species are often at a competitive disadvantage, compared to Least Concern species, when competing for space (Murray et al. 2002). *Aloe confusa*, which was re-assessed as an Endangered species in Tanzania, was found in only two locations along Lake Chala that could not be reached by the local community. During our survey, *A. boscawenii*, which had last been observed in 1953 (Eastern Arc Mountains & Coastal Forests CEPF Plant Assessment Project Participants 2009b), was re-discovered in the coastal area of the Boma ward in Tanga region. *Aloe boscawenii* had four sub-populations along the coasts of Boma, Manza, and Moa, with two of them in Manza being adjacent to commercially active salt mines, posing a hazard if more ponds are built, while the two sub-populations in Moa and Boma were adjacent to the ocean, hence vulnerable to flooding. As a result, sub-populations in Boma and Moa were considered as a single location and the two in Manza were considered to be a single location, hence we consider two locations for *A. boscawenii.* One villager stated that *A. boscawenii* was available along the coast of Mombasa, Kenya, as previously reported (Eastern Arc Mountains & Coastal Forests CEPF Plant Assessment Project Participants 2009b). We also identified five locations for *A. flexilifolia* and *A. leptosiphon*. The previous IUCN Red List assessment only identified two locations for both species. In our previous article (Abihudi et al. 2020), we found that both the Critically Endangered (*A. boscawenii*) and Least Concern (*A. lateritia*, *A. secundiflora*, and *A. volkensii*) *Aloe* species responded to different environmental parameters according to their IUCN Red List status. In this experimental study (Abihudi et al. 2020), we found that *A. boscawenii* had a limited distribution within Tanzania, and it did not germinate well under different environmental conditions while the commonly spread Least Concern *Aloe* species germinated well under a wide range of environmental conditions.

Our assessment resulted in a downgrade for most *Aloe* species that had previously been categorised as Critically Endangered. For example, the Critically Endangered *Aloe flexilifolia* and *A. leptosiphon* were assessed as Endangered and *A. dorotheae* as Vulnerable. The downgrade of these species was due to the identification of new locations that had not been reported in the previous assessment. *Aloe dorotheae* was found in previously undocumented areas beyond the Handeni district, resulting in an increased EOO of 4,109 km^2.

It is important to note that a species' rarity does not necessarily mean it is highly endangered if human activities and natural processes do not negatively impact its natural population levels (Oredsson 1997). In our study, the existence of the Endangered *A. confusa* was not known to the people living around Lake Chala in Rombo district, Kilimanjaro region. Such unawareness might help its conservation in the wild, as has been suggested in previous studies. For instance, Oredsson (1997) argues that the presence of a rare plant species in two poorly visited localities in Sweden helped maintain its population.

On the other hand, a community's familiarity with a species can also lead to ex situ conservation, which can eventually aid rehabilitating and reintroducing threatened species into the wild (Cochrane et al. 2007; Abeli et al. 2020). Similarly, a lack of observation does not mean a species is absent (Alberta Native Plant Council (ANPC) 2012). We recorded the first sighting of *A. boscawenii* in six decades along the coast of the Boma ward in the Tanga region. Nevertheless, we still categorised *A. boscawenii* as Critically Endangered, and several coastal human activities threaten its existence according to our findings.

We found most *Aloe* species to be patchily distributed in rocky areas, i.e. *Aloe ballyi*, *A. bicomitum*, *A. confusa*, *A. dorotheae*, *A. fibrosa*, *A. flexilifolia*, *A. lateritia* (Lushoto district), *A. leptosiphon*, *A. mzimbana*, *A. myriacantha*, *A. nuttii*, and *A. volkensii*. Rocks are sheltering ground away from human disturbance and threats like fires (Larson et al. 2005; Arena et al. 2015). However, the inherently barren environments such as rocky outcrops and cliffs, do not generally support high plant growth and contribute to low population densities (Larson et al. 2005). Furthermore, a narrow habitat range increases a species' vulnerability to natural disasters and human activities as was found for various Tanzanian *Aloe* species (Abihudi et al. 2020). Thus, we recommend that human activities should be restricted or prohibited in those rocky areas and cliffs where *Aloe* species are present.

We found that most threatened *Aloe* species were present in high elevation areas that are also considered fertile by the local communities and, thus, more favourable for agricultural activities than moderate and low elevation areas (Hall et al. 2009; Winowiecki et al. 2016). This increases the risk of human activities that can threaten *Aloe* species in these areas. Lowlands, in our case defined as coastal areas and the land close to freshwater bodies, are mostly urbanised with a high concentration of economic activities such as fishing, salt making, tourism, and recreation. These activities also threaten the locally available *Aloe* species habitat. The *Aloe* species along the shorelines are further at risk due to dynamic and unpredictable weather conditions such as hurricanes and floods (Ouborg et al. 2006). Therefore, we recommend a more concerted effort to locate remaining populations and update the *A. confusa* assessment since we did not find any plants along Kifaru river. Moreover, our study calls for more in situ conservation efforts of riparian ecosystems to protect *Aloe* and other species.

We found the highest number of threatened *Aloe* species within our study group in the Eastern Arc Mountains (EAM, South and North Pare, East and West Usambara), Coastal Forests, and the Katavi-Rukwa ecosystem. The EAM has been documented to be very rich in endemic species compared to other Eastern Africa areas (Howell et al. 2006; Hall et al. 2009). There are different land use categories in Tanzania and 7,000 km^2 are in a protected area made up of national parks, nature reserves, and forest reserves (Burgess & Kilahama 2005). We found most of the threatened *Aloe* species within these protected areas. We believe this is because *Aloe* populations are diminishing in less strongly protected areas due to over-exploitation, land-use change, and poaching in the EAM (Kideghesho & Msuya 2010; Tabor et al. 2010), coastal forests (Tabor et al. 2010; Godoy et al. 2011), and the Katavi-Rukwa ecosystem (Wilfred et al. 2019). More research on *Aloe* species distribution and threats is needed in other areas of the EAM, including North and South Nguru, Uluguru, Ukaguru, Rubeho, Malundwe, Udzungwa, Mahenge, and Uvidunda Mountains.

Threats towards and conservation of *Aloe* species

We previously reported no strong correlation between high utilization of *Aloe* species and its threat level (Abihudi et al. 2019). Moreover, the most-utilized *Aloe* species, *Aloe duckeri*, *A. lateritia*, and *A. secundiflora*, are non-endemic, widely distributed and categorised as Least Concern. In the present re-assessment, all three *Aloe* species were assessed as Least Concern in Tanzania, as they are considered worldwide in the IUCN Red List (Weber 2013; Weber & Demissew 2013b; Richart 2019a). The high number of locations and EOO explains this, although our survey was limited to Tanzania only. In Kenya, the EOO was above 20,000 km^2 for *A. deserti*, *A. lateritia* var. *lateritia*, *A. secundiflora*, and *A. volkensii*. In contrast to the situation in Tanzania (table 1), in Kenya these species are, therefore, not considered threatened with the exception of *A. lateritia* var. *graminicola* (Reynolds) S.Carter, which was categorised as Vulnerable (Wabuyele 2006).

Although interviewees reported moderate use levels for *Aloe flexilifolia* and *A. leptosiphon*, they were categorised as Endangered. For both species, previous assessments (Eastern Arc Mountains & Coastal Forests CEPF Plant Assessment Project Participants 2009i, 2009m) mentioned that they could be impacted by collectors. For *A. flexilifolia*, two respondents in our study also observed this. This is likely one reason for their current threat category. However, despite these examples to the contrary, we hypothesize that the current threat level for most *Aloe* species is due to their restricted distribution range and not to human use, i.e. *A. confusa* and *A. fibrosa*.

We did not always find agreement between the species-specific folk perception on the availability of *Aloe* species and the threat level that we assigned using number of locations, EOO and AOO. While we assigned 77% of the studied *Aloe* species as threatened, the majority of respondents viewed 45% of the species to be available in the wild. This difference between local community perceptions and scientists is well-known (Sajem et al. 2008). For example, here a community perceived the Least Concern and widespread *Aloe duckeri*, *A. lateritia*, and *A. myriacantha* to be threatened. Even though *A. lateritia* has a large EOO (624,760 km^2), it was scarcely available compared to other species at the village level. This is because communities tend to look at a species' local status when defining its availability, while scientists more commonly use larger geographical areas.

The conservation status of the Critically Endangered *Aloe boscawenii* and *A. fibrosa* is in agreement with the community perception of its availability. The endangered status of *A. boscawenii* is attributed to its restricted distribution range (Eastern Arc Mountains & Coastal Forests CEPF Plant Assessment Project Participants 2009b). We also observed human activities along the coast that likely affect *A. boscawenii* population levels, including salt harvesting adjacent to one location which was also reported in the previous assessment (Eastern Arc Mountains & Coastal Forests CEPF Plant Assessment Project Participants 2009b), recreational activities and trampling by fishermen as they hide their fishing gear. Seven of the *Aloe* species that we categorized as Endangered (*A. bicomitum*, *A. chabaudii*, *A. deserti*, *A. flexilifolia*, *A. parvidens*, *A. rabaiensis*, and *A. volkensii*) in our study, and two that were assessed as Vulnerable (*A. dorotheae* and *A. macrosiphon*) were perceived by the local communities as available.

Despite some disagreements, involving locals in plant species assessments is often essential due to their in-depth knowledge on how to find and use them (Biró et al. 2014). This was also reported in Benin, where traditional knowledge of woody plant species was essential in identifying the highly threatened ones, i.e. *Afzelia africana* Pers., *Khaya senegalensis* (Desv.) A.Juss., *Milicia excelsa* (Welw.) C.C.Berg, and *Pterocarpus erinaceus* Poir. (Agbani et al. 2018). Traditional knowledge is also often relevant for managing natural resources for conservation purposes

(Liu et al. 2002). Thus, we recommend taking communities' perceptions on availability and threat factors into account when considering conservation policies for *Aloe* species.

A major contributing factor towards declining levels of natural vegetation worldwide is land-use changes (Maundu et al. 2006). We found that our studied *Aloe* species were affected by agricultural activities encroaching in natural habitats, urbanisation such as roads and buildings, overharvesting, and land clearing. We also found that fire for land preparation had affected *A. dorotheae*, which usually grows in rocky areas far away from agricultural fields. *Aloe* species have developed different adaptation mechanisms to withstand fires, including changes in their succulent nature (Cousins & Witkowski 2012), increased insulation resulting from attached dead leaves (Bond 1983) and refuge on rocky areas (Pfab & Witkowski 1999; Larson et al. 2005). However, these adaptations can negatively affect pollination rate, seed set, and seedling survival, which in turn reduces next-generation population levels (Cousins & Witkowski 2012). Additionally, livestock and wild animals have also been reported to damage *Aloe* species (Newton 2004; Cousins & Witkowski 2012; Abihudi et al. 2019). Policy makers can use our present study as an aid in deciding which threatened species to prioritise in conservation efforts. Since the number of species threatened with extinction outweighs the resources available for conservation, making informed decisions on which species to prioritize is essential (Myers et al. 2000). We suggest the protection of existing habitat as well as restoring and reintroducing *Aloe* species into sites that had previously been occupied. Botanical gardens are used worldwide as sanctuaries for threatened species (Powledge 2011) and play an essential role in *Aloe* species ex situ conservation. We recommend that botanical gardens should be utilised for the reintroduction of threatened *Aloe* species into the wild as was already successfully done with *Cypripedium macranthos* Sw. (Orchidaceae) from Beijing Botanical Gardens in China (Seaton et al. 2010). Additionally, there is a need for greater understanding of the ecology and biology of *Aloe* species. This information is necessary to maintain the genetic integrity of threatened *Aloe* species and to mimic their natural habitat in botanical gardens (Chen et al. 2014).

We further argue that the Tanzanian national laws governing natural resource collection should be more strictly enforced to control the commercial harvest of *Aloe* species. Communities should be empowered with conservation techniques, including cultivation and sustainable harvesting, to improve their livelihoods and reduce pressure on wild populations. Education and intervention to combat overharvesting of tall *Aloe* from the wild for beer brewing is in particular necessary to halt the current population decline.

CONCLUSIONS

We established that most of the 22 Tanzanian *Aloe* species studied are declining based on our quantitative assessment and our qualitative informants' perceptions survey. We observed ubiquitous threats to *Aloe* species in high and low elevations, from the Eastern Arc Mountains to the Coastal Forests. *Aloe* species that cluster together and those that find refuge in rocky areas were frequently assessed as Threatened due to their greater vulnerability to human activities including agriculture, fire, overharvesting, and climate change. We conclude that there is a need to update the conservation assessments of *Aloe* species continuously as their available habitat changes. Most of the *Aloe* species we surveyed were threatened, which demonstrates that even in protected areas, such the Eastern Arc Mountains and Katavi-Rukwa ecosystems, the fate of the species is precarious. This calls for greater implementation of laws and policies to protect natural resources, including *Aloe* species, as the rate of their decline is higher than what had previously been assumed.

SUPPLEMENTARY FILE

Supplementary file 1 – Species locality maps of the 22 studied *Aloe* species in Tanzania. Maps created using ArcGIS v.10.1 (https://www.arcgis.com, © Esri and its licensors, all rights reserved), layer data from the Tanzania National Bureau of Statistics.

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