

## APPLIED ECOLOGY

# A third of the tropical African flora is potentially threatened with extinction

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Preserving tropical biodiversity is an urgent challenge when faced with the growing needs of countries. Despite their crucial importance for terrestrial ecosystems, most tropical plant species lack extinction risk assessments, limiting our ability to identify conservation priorities. Using a novel approach aligned with IUCN Red List criteria, we conducted a continental-scale preliminary conservation assessment of 22,036 vascular plant species in tropical Africa. Our results underline the high level of extinction risk of the tropical African flora. Thirty-three percent of the species are potentially threatened with extinction, and another third of species are likely rare, potentially becoming threatened in the near future. Four regions are highlighted with a high proportion (>40%) of potentially threatened species: Ethiopia, West Africa, central Tanzania, and southern Democratic Republic of the Congo. Our approach represents a first step toward data-driven conservation assessments applicable at continental scales providing crucial information for sustainable economic development prioritization.

## INTRODUCTION

Major threats to biodiversity, especially in areas of exceptional plant diversity, primarily in the tropics, are often linked to industrial-scale activities such as timber exploitation or large plantations, mining, and agriculture (1). Article 14 of the United Nations Convention on Biological Diversity ([www.cbd.int/](http://www.cbd.int/)) explicitly indicates that environmental impact assessments (EIAs) should be conducted before implementing these projects. To reduce risks linked to environmental concerns, EIAs should identify adverse impacts on biodiversity by projects and indicate measures to avoid, minimize, and offset impacts. A growing realization that environmental impacts represent risks not only to biodiversity but also to operational, financial, and reputational aspects of projects has led extractive industries, agro-business, financial institutions, governments, and civil society, inter alia, to identify and adopt best practices for managing biodiversity. Threatened species are one of the key elements [e.g., (2)] that may be affected by these proposed projects.

Assessing the “risk of extinction” of a species using the standardized procedure developed by the International Union for Conservation of Nature (IUCN, [www.iucn.org](http://www.iucn.org)) is widely recognized as the most objective and comprehensive approach for identifying conservation priorities and targeting conservation actions (3). The IUCN Red List

of Threatened Species ([www.iucnredlist.org](http://www.iucnredlist.org)) provides information on the taxonomy, distribution, and conservation status of plants, fungi, and animals based on the IUCN Red List Categories and Criteria. The main aim of this procedure is to determine, using a rigorous and objective method, the risk of extinction for a species and thereby identify which species are of highest conservation concern. The IUCN Red List has been widely adopted as a standard for identifying species that require special attention when planning and implementing projects with an environmental impact (3). For example, Red List status represents a key criterion for identifying “critical habitat,” as defined by Performance Standard 6 (PS6) of the International Finance Corporation (IFC) ([www.ifc.org/](http://www.ifc.org/)). PS6 establishes the standards that private company projects are required to adopt regarding biodiversity conservation and sustainable management of living natural resources (4). Failure to explicitly follow PS6 guidelines will compromise IFC funding (5), which amounted to \$23.3 billion invested in 2018 ([www.ifc.org](http://www.ifc.org)). Red List assessments also contribute to meeting Objective 2 of the Global Strategy for Plant Conservation (GSPC), which calls for an assessment of the conservation status of all known plant species by 2020.

Generating IUCN Red List assessments must be done on a species-by-species basis and requires both reliable data and the careful, knowledgeable application of the Red List criteria, a process that takes considerable time. This is reflected by the fact that there are substantial gaps in the Red List ([www.iucnredlist.org](http://www.iucnredlist.org)). While the conservation status of most species in large vertebrate groups has been assessed [e.g., mammals: 5792 of ca. 6500 species (86%) and birds: 11,133 of ca. 18,000 (61%); [www.iucnredlist.org](http://www.iucnredlist.org), accessed 20 June 2019], this is not the case for plants, despite their crucial importance for terrestrial ecosystems. Only 28,114 vascular plant species ([www.iucnredlist.org](http://www.iucnredlist.org), accessed 20 June 2019), representing less than 8% of the estimated 352,000 species worldwide (6) have been assessed to date. This knowledge gap results, in large part, from the very high level of species diversity in plants, making it a time-consuming proposition to evaluate the threats faced by plants, especially in the many tropical areas where the flora is poorly documented (7, 8). Hence, while the IUCN is on track to achieve its target of 38,500 plant species assessments

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on the Red List by 2020 (9), this would only reach 10% of GSPC Target 2, a situation that has led to calls for complementary methods to speed up the process of assessing the conservation status of the world's flora. Various approaches have been suggested [e.g., (10, 11)], none of which are consistent with the IUCN guidelines, significantly limiting their use.

Here, we propose an efficient, complementary approach that is grounded in key elements of the IUCN conservation assessment process and aims to provide useful information on the conservation status of large numbers of species in the form of Preliminary Automated Conservation Assessments (PACA). PACA can facilitate analyses of the level of conservation concern of a large number of species or of the entire flora of a given area and can help identify species that are likely to be threatened and therefore may require additional attention, including full Red List assessments.

To demonstrate the utility and relevance of the PACA approach, we applied it to the flora of tropical Africa based on the recently developed RAINBIO database, which contains more than 600,000 occurrence records of more than 20,000 vascular plant species (8, 12). Tropical Africa is a highly suitable model for undertaking such a study as it is faced with significant and mounting threats resulting from a wide range of activities, including logging, fuelwood collection, and deforestation for agriculture and mining (13, 14). For example, the surface area of agro-industrial concessions has increased exponentially over the last decade in several Central African countries (15). These threats to plants are, in turn, projected to result in losses of diversity in many associated organism groups and decreases in carbon storage (16), trends that are expected to accelerate because of rapid human population growth and continued changes in land use. Last, these ongoing negative effects on biodiversity are projected to be compounded further by climate change by the end of this century (17, 18).

**RESULTS**

**Extinction risk of the tropical African flora**

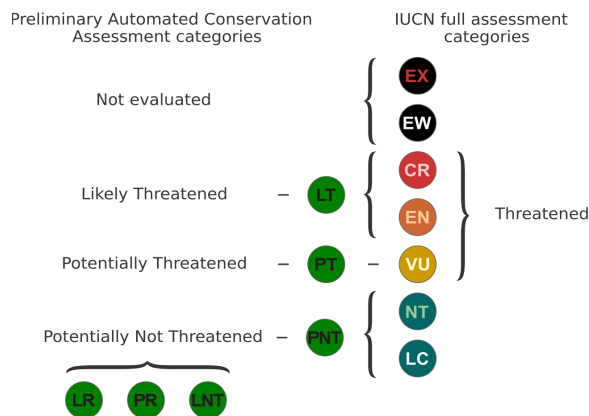
We conduct a preliminary assessment of the conservation status of a total of 22,036 vascular plant species occurring across tropical Africa using PACA. This approach categorizes species into six preliminary conservation status levels (Fig. 1; see Materials and Methods). Three of these [Likely Threatened (LT), Potentially Threatened (PT), and

Potentially Not Threatened (PNT)] are directly linked to five of the IUCN categories, namely, Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), and Least Concern (LC). The PNT category comprises three distinct subcategories not directly linked to categories in the IUCN Red List system, namely, Likely Rare (LR), Potentially Rare (PR), and Likely Not Threatened (LNT). Species falling into the LR and PR categories include those whose distribution, described using IUCN parameters, appears to be limited but for which no projected decline of habitat quality has been detected. Two IUCN criteria, Criterion A based on an estimation of the overall population reduction and Criterion B based on species range, were used for categorizing species into one of these preliminary conservation status levels (see Materials and Methods for details).

When applying IUCN Criterion B (Table 1), more than a fifth of the species (4879 or 22.1%) were assessed either as LT (2803 species, 12.7%) or PT (2076 species, 9.4%). Among the species assessed as PNT, 33.1% (7304 species) were considered LR and 5.3% (1154 species) PR. When applying IUCN Criterion A, a total of 5023 species (22.8%) were assessed as either LT or PT (Table 1). We retrieved a similar portion of species assessed as LT (2652, 12%) and PT (2371, 10.8%) compared to the PACA approach applied using Criterion B (Table 1) and therefore a rather similar number (17,013 species, 77.2%) assessed as PNT. Last, a total of 6990 species (31.7%) were assessed as either LT or PT under both Criteria A and B (Table 1), and 8458 (38.3%) were considered LR (7304, 33.1%) or PR (1154, 5.3%). Overall, 70.1% of the species were placed in one of the Threatened (LT or PT) or Rare (LR or PR) categories.

**Spatial patterns of PT, LT, and Rare species**

We characterized spatial patterns of species that are PT, LT, and Rare at various scales using an adaptive grid size that varied between 0.5° and 8° square (depending on the sampling effort), at the country level and at the ecoregion level. The distribution of the proportion (Fig. 2) and the total number (fig. S1) of LT/PT species are not uniform across tropical Africa. The total number of species assessed as Threatened (LT/PT) under Criterion A (fig. S1) is mostly concentrated

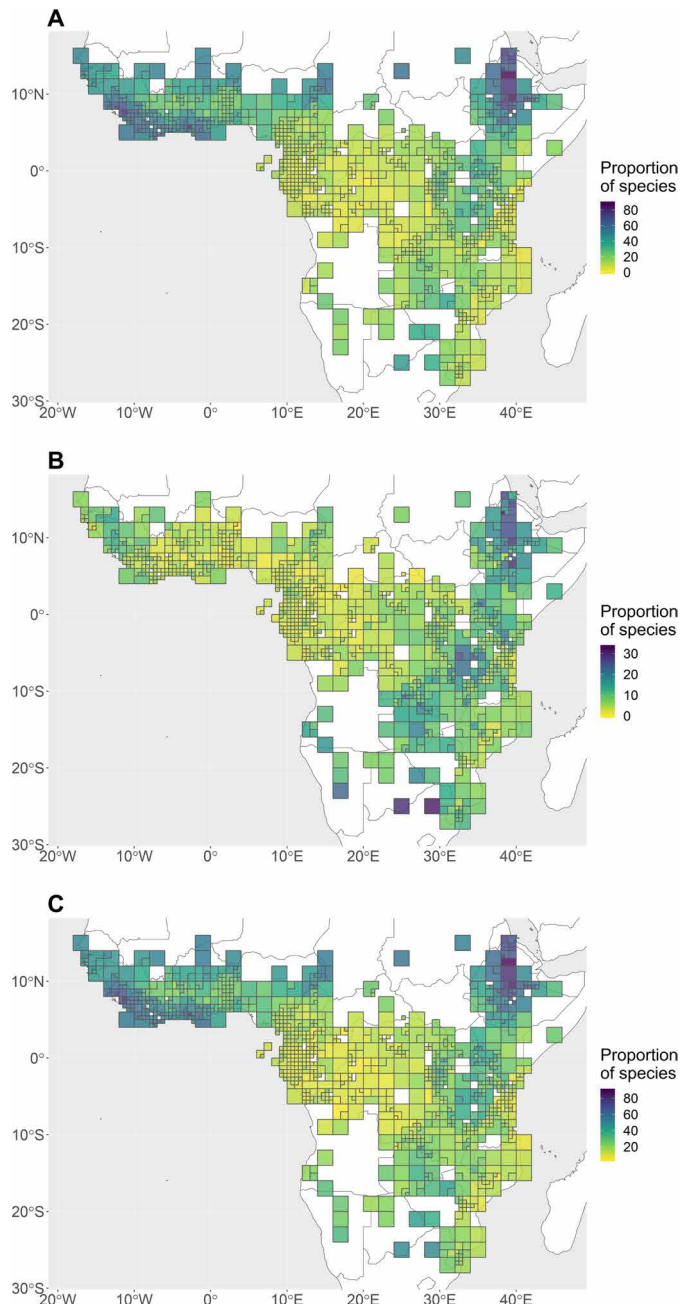


**Fig. 1. Correspondence between categories of the PACA and the IUCN categories.** PACA categories: LT, PT, PNT, LR, PR, and LNT. IUCN categories: EX, extinct; EW, extinct in the wild; CR, EN, VU; NT, and LC.

**Table 1. Number of threatened and nonthreatened plant species for tropical Africa.** Total number and proportion of 22,036 vascular plant species assessed as LT/PT and LNT under our Preliminary Automated Conservation Assessments approach. LR/PR categories include species that meet three subcriteria of IUCN Criterion B [Extent of Occurrence (EOO), Area of Occupancy (AOO), and number of locations] but for which known subpopulations are apparently not exposed to a decline of habitat quality due to land cover conversion.

PACA threat category	Criterion A	Criterion B	Both Criteria
<b>LT/PT</b>	<b>5,023 (22.8%)</b>	<b>4,879 (22.1%)</b>	<b>6,990 (31.7%)</b>
LT	2,652 (12%)	2,803 (12.7%)	3,823 (17.3%)
PT	2,371 (10.8%)	2,076 (9.4%)	3,167 (14.4%)
<b>PNT</b>	<b>17,013 (77.2%)</b>	<b>17,157 (77.9%)</b>	<b>15,046 (68.3%)</b>
LR		7,304 (33.1%)	7,304 (33.2%)
PR		1,154 (5.3%)	1,154 (5.2%)
LNT		8,699 (39.5%)	6,588 (29.9%)

in West Africa, the Ethiopian highlands, and, to a lesser extent, in western Cameroon and Gabon, Katanga [southern Democratic Republic of the Congo (DRC)], and the Albertine rift. The total number of species assessed as Threatened (LT/PT) under Criterion B (fig. S1) is locally greater in Katanga and in southwest Cameroon. Last, high concentrations of species assessed as Rare (LR/PR) are found mainly in several regions of Tanzania and along the Cameroon volcanic line (fig. S2). However, the total numbers of Threatened and Rare species are significantly correlated with sampling effort (Pearson  $R$



**Fig. 2. Spatial distribution of threatened plant species across tropical Africa.** Proportion of species preliminarily assessed as (A) LT or PT following criterion A; (B) LT or PT following criterion B; and (C) LT or PT following both criteria A and B. Values are based on adaptive resolution sampling unit (SU) (for explanation, see text).

coefficients ranging between 0.54 and 0.64), indicating that our inference of threat is partly biased by sampling, unless collectors have tended to visit areas with rare or threatened species, which seems plausible.

To control for the heterogeneous sampling effort, we calculated the proportions of Threatened/Rare species among the total number of species assessed per grid cell, excluding cells with fewer than 100 records. The proportion assessed as LT/PT under either Criterion A or Criterion B highlights different regions (Fig. 2, A and B). For Criterion A, more than 65% of the species in tropical rain forests of West Africa and parts of the Ethiopian highlands were found to be Threatened (Fig. 2A). By contrast, the assessments made under Criterion B highlight Katanga and Zambia as well as parts of Ethiopia, central Tanzania, and Kenya (Fig. 2A). The proportion of Threatened species under Criterion A tends to be much higher than under Criterion B (up to 80% for Criterion A compared to a maximum of 32% for Criterion B). These contrasting ranges of values explain why the map showing the proportion of Threatened species under both criteria (Fig. 2C) is very similar to that under Criterion A (Fig. 2A), mostly highlighting the rain forests of western Africa and the Ethiopian highlands. By contrast, the Central African rain forests, parts of eastern Tanzania, and parts of western DRC display low proportions of LT/PT species (Fig. 2C). The proportion of Rare species (LR/PR) shows a different pattern, reaching 50% of species (Fig. 3), with especially high values in southern Ethiopia and Kenya, Angola, southern DRC, and the islands of São Tomé and Príncipe.

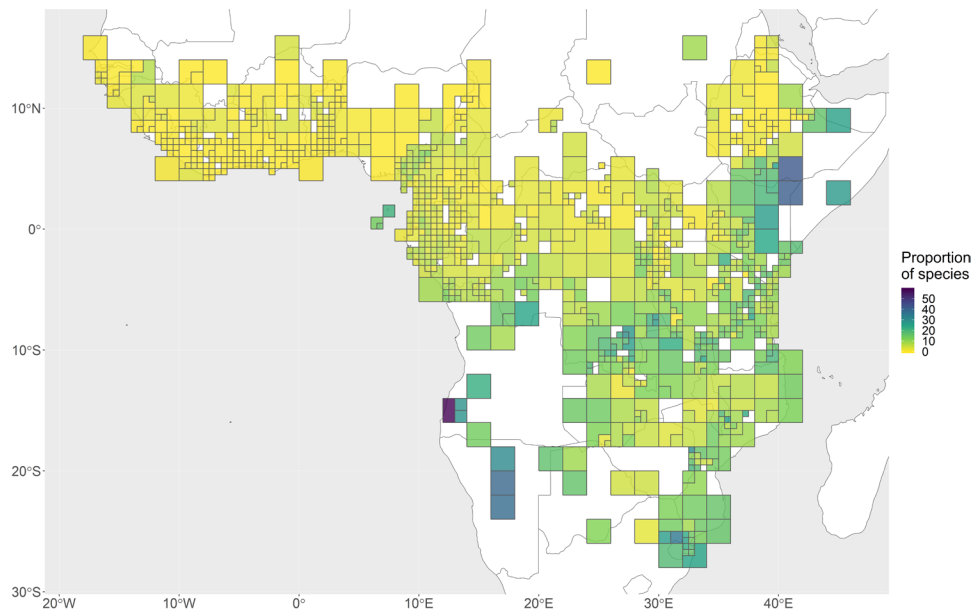
The top 10 countries showing the highest proportion of Threatened species include eight countries from West Africa along with Ethiopia and Uganda (Table 2). Sierra Leone, The Gambia, and Ethiopia have the highest proportions of species assessed as LT/PT under both Criteria A and B, whereas Equatorial Guinea, São Tomé and Príncipe, and the Republic of the Congo have the lowest (table S1). By contrast, Tanzania, DRC, Ethiopia, Cameroon, and Ivory Coast, in decreasing order, have the highest total number of LT/PT species under both Criteria A and B (table S2). At the ecoregion level, more than half of the plant species in Ethiopian montane moorlands, Western Guinean lowland forests, Guinean montane forests, Ethiopian montane grasslands, and woodlands are LT/PT under Criterion A or B (Table 2 and table S3).

### Comparison with published IUCN assessments

To evaluate how well the PACA approach agrees with full IUCN Red List assessments, we retrieved all published assessments available on the Red List website for species in our dataset. We found full assessments for 2856 plant species among those in our study set, of which 600 were published before 2001 or were thus performed using outdated IUCN categories (i.e., LR/NT) (fig. S3). Comparisons were therefore restricted to 2009 species (i.e., 9.1% of the total number of species assessed in our study). The proportions of species categorized on the Red List as either CR or EN (i.e., analogous to LT in the PACA system of categories) and VU (analogous to PT) are 26.1 and 14.7%, respectively, while the PACA approach based on all species provided 17.3 and 14.4%, respectively (Table 1).

We tested how well PACA predicted full IUCN Red List assessments. When considering PNT species (thus including species assessed as Rare; see Fig. 1), the Kappa coefficient, which evaluates the classification agreement between both approaches, was very low (0.01). A total of 446 of the 2009 species considered as Extinct (EX)/CR/EN based on published IUCN assessments were classified as PNT by the





**Fig. 3. Spatial distribution of rare plant species across tropical Africa.** Proportion of species preliminarily assessed as LR/PR following Criterion B. Values are based on adaptive resolution SU (for explanation, see text).

PACA approach (Table 3). When considering LNT species and including species preliminarily assessed as Rare among the Threatened categories, the Kappa coefficient was much higher (0.29). Only 25 species among the 2009 taxa assessed as EX/CR/EN were not identified as LT according to the PACA approach (Table 4). Hence, the sensitivity of the LT category (i.e., the probability of correctly identifying EX/CR/EN species when using the PACA approach) was very good (0.84). On the other hand, the sensitivity of the PT category (i.e., the probability of correctly identifying VU species using PACA) was much lower (0.27).

### Threat estimates across plant habits

The proportion of LT/PT species was estimated for four different habits, namely, tree, shrub, herb, and liana. Overall, the proportion of LT/PT species varied little across habit (Table 4), ranging, for example, from 26.7% for shrubs to 36.8% for herbs under both Criteria A and B. Herbaceous species showed higher levels of threat, while tree species had lower levels (Table 4). Spatial patterns of LT/PT species per habit show some differences (fig. S4). Those of trees and shrubs are similar to the general pattern (Fig. 2) except that risk level is lower in Ethiopia for trees and shrubs. Herbs have a much higher proportion of LT/PT species in Ethiopia and East Africa, while the converse is true for lianas. This indicates that the high overall proportion of LT/PT species in Ethiopia mainly involves herbs.

## DISCUSSION

### High levels of threat to the tropical African flora

By applying our novel PACA approach to a large, taxonomically and geographically verified database of vascular plant occurrences in tropical Africa (12), we conducted the first ever evaluation of the potential conservation status of an entire flora on a continental scale using key criteria used for IUCN Red List assessments. Our results suggest that around one-third (31.7%) of tropical African vascular

plant species are potentially or likely threatened by extinction (17.3% as LT and 14.4% as PT, Table 1). Our study thus provides further evidence that the flora of tropical Africa will be highly vulnerable in the future (17–19). This situation will no doubt be magnified by the effects of climate change, which is one of the most important assumptions influencing extinction risk (20).

Our estimate of 31.7% exceeds the figure of 22.3% of green plant species in tropical Africa assessed as threatened using the Red List criteria (21). The latter value was, however, inferred using the Sampled Red List approach based on full IUCN Red List assessments of a small sample (713) of tropical African plant species (21). In a different study, full IUCN assessments of the entire African palm (*Arecaceae*) flora revealed that just 10% of the 60 species were threatened (22). By contrast, a recent study of extinction risk in the genus *Coffea* (*Rubiaceae*), mainly from tropical Africa and Madagascar, found that 60% of species were threatened with extinction (23). These studies show that significant variability is found when estimating proportions of threatened species, depending on the sampling method used and the taxonomic or geographical scope of the group considered. Unfortunately, identifying the proportion of threatened species in a given area using the IUCN Red List is complicated by the fact that only a small proportion of plant species have been assessed to date (as illustrated by the fact that only 9.1% of the species in our dataset have full post-2001 assessments). Moreover, Red List efforts have often focused primarily or exclusively on narrow-range species, yielding biased results (24) that preclude an accurate estimate of the proportion of threatened species, a situation that justifies the rapid and preliminary conservation assessment batch procedure developed here. In our study, we undertook preliminary assessments for 22,036 vascular plant species, representing around 68% of the tropical African diversity (25). Automated conservation assessment approaches like the one used here were recently shown to perform well in correctly assessing threat categories when compared to full assessments (26). Together, our estimate that one-third of tropical African vascular plant species are threatened thus seems quite accurate.

**Table 2. Number of threatened species per country and ecoregion.** Top 10 countries and ecoregions with the highest proportion of LT/PT species assessed under both Criteria A and B, under Criterion B, and under Criterion A. LT/PT (see Fig. 1).

Country	Area (km <sup>2</sup> )	Number of records	Number of species	LT/PT species under Criteria A and B	LT/PT species under Criterion A	LT/PT species under Criterion B
Sierra Leone	71,576	4,445	1,325	53.4	50.8	13.0
Gambia	10,275	135	97	50.5	48.5	8.2
Ethiopia	1,127,096	24,882	3,810	50.2	44.3	26.4
Liberia	95,252	15,848	2,229	48.9	46.4	11.9
Senegal	196,609	1,867	781	47.6	44.7	9.1
Ivory Coast	320,934	35,915	3,421	43.5	39.7	11.0
Guinea	243,940	9,345	2,189	42.9	39.5	10.5
Ghana	238,559	11,141	2,580	41.6	39.0	7.7
Benin	116,105	20,486	2,371	34.3	30.9	6.5
Uganda	241,474	5,941	1,948	34.0	30.3	10.0
<b>Ecoregions</b>						
Ethiopian montane moorlands	25,049.1	1,135	814	76.5	74.3	30.2
Inner Niger Delta flooded savanna	45,868.1	137	97	67.0	64.9	14.4
Ethiopian montane grasslands and woodlands	244,349.0	11,390	4,200	59.7	56.9	20.9
Ethiopian montane forests	247,734.3	6,841	2,885	53.3	49.1	16.8
Sahelian Acacia savanna	3,042,451.4	2,820	986	52.9	50.1	12.0
Guinean mangroves	23,418.9	1,598	1,159	51.6	50.5	4.6
Western Guinean lowland forests	204,226.3	25,497	2,758	48.3	45.1	14.4
Mandara Plateau mosaic	7,478.5	834	484	47.3	44.8	9.3
Ethiopian xeric grasslands and shrublands	151,868.7	452	265	43.4	36.6	14.3
Guinean montane forests	30,923.5	9,383	3,537	42.8	39.2	9.1

We show a similar percentage of threatened species based on habit (Table 4), ranging from 27.1% in trees to 36.8% in herbs under Criteria A and B (LT and PT), respectively. ter Steege *et al.* (27) speculated that “most tree species of the Old World tropics,” and particularly in Africa, would qualify as globally threatened under Criterion A because of intense deforestation. We show, however, that according to preliminary assessments under Criterion A, this is not validated as only 18.8% of tree species were categorized as threatened in our analysis (Table 4). First, total deforestation across tropical Africa was recently estimated to be lower (13) than that advanced by ter Steege *et al.* (21% instead of 55%). Second, deforestation is not uniform across Africa, with Ethiopia and West Africa being the most severely affected, in contrast to Central Africa, where forest cover has actually increased (13). This is reflected in our analysis, where high proportions of LT/PT tree species under Criteria A and B are mainly found in West Africa but not in Central Africa, and only partly so in Ethiopia

(fig. S4). The fact that trees are not more threatened in Ethiopia than other habits although 99% of the forest has disappeared might be because deforestation had already largely occurred before most plant collections were made, and hence, the original distribution of forest species is not reflected in our data.

For the first time, we have characterized spatial patterns of threat across tropical Africa by mapping the proportion of potentially/likely threatened species (Figs. 2 and 3), which can be estimated when enough records per sampling unit (SU) are available. Our analyses highlight four major regions as containing high proportions of potentially threatened species under Criteria A and B across tropical Africa (Fig. 1C): West Africa, Ethiopia and western Kenya, central Tanzania, and the Katanga region in southern DRC. Some of these regions were highlighted as important for conservation based on the “hotspot” approach, which identifies areas that feature both exceptional concentrations of endemic species and have experienced exceptional habitat loss (28).

Different regions are highlighted as having high proportions of threatened species, depending on the criterion used (Fig. 2, A and B), and these approaches highlight different attributes of the identified regions. Under Criterion B, our analyses mainly identify the Ethiopian highlands, central Tanzania and Katanga, and Sierra Leone/Guinea/Liberia in western Africa (Fig. 1B) as having a high proportion of potentially threatened species. Under Criterion A, we again find not only the Ethiopian highlands but also most of western Africa (Fig. 1B). In our analysis, Criterion A identifies threatened species based on estimated past and future population reduction, as indicated or projected by the percentage of occurrences found within cells classified as human affected and/or as mining areas. This criterion will thus identify regions where human impact is significant. By contrast, Criterion B is based on a species' geographic distribution and will highlight regions with high proportions of narrow-range species. This is indeed what we find. In western Africa, landscapes are highly fragmented and have recently experienced significant losses of suitable habitat (13, 29), whereas regions such as Katanga are known to have numerous narrow-range species endemic to metalliferous substrata (30). We thus suggest that preliminary conservation assessments using Criterion A under the PACA approach should be seen as complementary to those performed using Criterion B.

**Table 3. Comparing PACA versus full IUCN assessments.** Confusion matrices comparing the published full IUCN assessments published after 2001 (columns) and preliminary automated conservation assessments for 2009 species (rows). The matrix above includes Rare categories (LR and PR) within Threatened categories while the matrix below does not.

	EX/CR/EN	VU	NT/LC
Including Rare species into threat categories			
LT/LR	505	180	329
PT/PR	69	107	239
LNT	25	103	452
Excluding Rare species from threat categories			
LT	121	53	136
PT	32	54	189
PNT	446	283	695

Eight of the top 10 countries with the highest proportion of LT/PT species are found in West Africa (Table 2), underlining the high concentration of threatened plant species found in this region. West Africa encompasses several ecoregions with high proportions of threatened species, ranging from 39.2 to 64.9%. These include the Inner Niger Delta savanna, Sahelian *Acacia* savanna, Guinean mangroves, Western Guinean lowland forest, and Guinean montane forests (Table 2). This underlines the fact that a wide range of ecoregions are affected by human impacts (19), all of which should be regarded as important for conservation. Of these ecoregions, the Inner Niger Delta flooded savanna in central Mali in the semiarid Sahelian zone stands out, with more than 64% of species potentially threatened with extinction under Criterion A (but just 14.1% under Criterion B).

Just under half of the species in the Western Guinean lowland forest (45.1%, Table 2) are potentially threatened. By contrast, the lowland rain forests of Central Africa (Lower Guinea and Congolia) show an overall low proportion of threatened species (Fig. 1), and none of the countries it includes are in the top 10 list (Table 2). This is probably linked to the limited amount of deforestation that the region has undergone over the last century compared to West or East Africa (13), or perhaps because the layers used to detect past and future decline are not precise enough (see limits of our study, detailed below). Nevertheless, the Lower Guinea region contains a high percentage of endemic species [24.2%; see (31)], which in part accounts for the fairly low number of narrow-range species identified as Rare but not necessarily threatened (Fig. 3 and fig. S2).

Ethiopia stands out as having one of the highest proportions of LT/PT species across tropical Africa (50.2%; Table 2) under both Criteria A and B, underscoring the importance of this region for conservation (Fig. 1). This is also reflected in the ecoregion-based analyses, in which four of six ecoregions represented in the Ethiopian highlands are in the top 10 most threatened, and all six are within the top 20 (Table 2 and table S4). Together with western Kenya, this region is equivalent to the East African Montane region of Droissart *et al.* (31), where 22.6% of species are endemic. This high level of endemism linked to widespread deforestation and a steady increase of human impact on natural vegetation (13) has resulted in these high values across the region.

The Eastern Arc Mountains and Coastal Forests (EAMCF) of Kenya and Tanzania are together one of the most biologically important regions of Africa (32). When compared to other regions such as Ethiopia

**Table 4. Number of threatened species for four habit types.** Total number and proportion (in %) of species per habit assessed as LT/PT using PACA under Criterion A, Criterion B, and both Criteria A and B. LT species encompass EN and CR IUCN categories, and PT species encompass the VU IUCN category.

Threat category	Tree: Total (proportion)	Shrub: Total (proportion)	Herb: Total (proportion)	Liana: Total (proportion)
<b>LT/PT</b>				
Criterion A	658 (18.8%)	865 (17.7%)	2818 (27.6%)	442 (25.6%)
Criterion B	596 (17%)	945 (19.4%)	2666 (26%)	341 (19.8%)
Criteria A and B	959 (27.4%)	1305 (26.7%)	3761 (36.8%)	605 (35.1%)
<b>PNT</b>				
Criterion A	2843 (81.2%)	4025 (82.3%)	7414 (72.5%)	1281 (74.3%)
Criterion B	1886 (53.9%)	1910 (39.1%)	3623 (35.4%)	973 (56.5%)
Criteria A and B	2542 (72.6%)	3585 (73.4%)	6471 (63.3%)	1118 (64.8%)

or West Africa, our analysis does not highlight the EAMCF as containing a high proportion of potentially threatened species (Fig. 2). The ecoregions (33) that make up part of the EAMCF contain 7.2 to 17.2% (Eastern Arc forests ecoregion) and 9.9 to 19% (Northern Zanzibar-Inhambane coastal forest mosaic ecoregion) LT/PT species, respectively, depending on the criterion used (table S4). Both regions are in fact species rich, with 7629 and 3603 species, respectively, based on our data (table S4). These proportions nevertheless reflect relatively the high levels of overall threatened species across tropical Africa (fig. S1). In addition, our results yield high proportions (Fig. 3) and numbers (fig. S2) of LR/PR species, reflecting the high level of plant endemism in the EAMCF (34, 35). These species were not flagged as threatened either because they are found in protected areas or because the layers used to detect decline are not precise enough areas in this highly fragmented region (see limits of our study, detailed below). However, because of their restricted distribution, these species might quickly become threatened in the near future. Together, our results underline once again the urgent conservation importance of this region of tropical Africa (32, 35).

### Definition of PACA

The rationale behind PACA is fourfold. First, the PACA approach in part follows the IUCN Red List, which is the most recognized and widely used source of information on conservation status (3). While other methods exist, using anything other than the IUCN Red List runs the risk of having limited impact as the resulting assessments are unlikely to be taken into account for conservation planning and policy-making. Second, assessing conservation status for large numbers of taxa using the huge quantities of data available via open access portals [e.g., Global Biodiversity Information Facility (GBIF): [www.gbif.org](http://www.gbif.org) and The Living Atlas of Australia: [www.ala.org.au](http://www.ala.org.au)] or data-mobilization projects [e.g., (12)] by means of a full IUCN Red Listing process would be prohibitively time consuming and expensive. Third, identifying conservation priorities and implementing effective actions are badly needed now and will become increasingly urgent as anthropogenic impacts render threats to biodiversity even more acute in the coming decades, necessitating a “no time to waste” stance. Last, in a highly dynamic world where threats change rapidly, and new information becomes available on a regular basis, assessments will need to be updated on a regular, objective, efficient, and cost-effective basis (36). The PACA approach proposed here addresses each of these points in that it is strictly aligned with two key IUCN Red List criteria and allows rapid batch analyses of thousands of taxa simultaneously using freely available data, thereby greatly accelerating the assessment and reassessment processes at limited costs.

Our assessments do not constitute full Red List assessments and are not intended to serve as a replacement or an alternative for them. In addition to placing species in formally recognized threat categories, full Red List assessments provide detailed information (when available) about a species' threats and level of decline with respect to key parameters. They also provide fundamental information for carrying out species-specific conservation actions that cannot be obtained (nor are intended) from the PACA approach. Full Red List assessments remain the only authoritative measure of the risk of extinction faced by a species.

To avoid any possible confusion with the Red List categories, we have explicitly provided alternative names for the five PACA categories (Fig. 1). These categories should be considered as a “box above” or a “first approximation” of the full IUCN categories and are not

intended to represent new categories themselves. Moreover, two additional categories used by the PACA approach, LR and PR, are not, on first inspection, comparable with any of the IUCN Red List categories. Species identified as LR/PR are not preliminarily assessed as Threatened because they do not meet subcriterion (b) under Criterion B (habitat decline), which, using the PACA approach, relies on the presence of the species within human affected or mining areas. However, most LR and PR species could become quickly threatened in the near future, for example, via the downgrading, downsizing, or degazetting of a protected area (37), agricultural expansion, or illegal logging, or when climate change renders its habitat unsuitable. Our LR category corresponds most closely to the definition of VU under Red List Criterion D2 because it identifies species with a restricted distribution [Area of Occupancy (AOO) less than 20 km<sup>2</sup>; see Materials and Methods] or a number of locations equal to or less than five but for which no immediate threats are inferred from land cover mapping. These species are not currently thought to be threatened but will very likely become so in the near future, and because of their limited distribution, could also quickly become extinct. Application of the Red List Category VU D2 requires that there be a plausible future threat that could rapidly lead to CR status, such as the planned construction of a dam in the case of a riparian species or hotel development for a coastal species.

According to the IUCN Red List guidelines, a species can be categorized as Data Deficient (DD) when “there is inadequate information to make a direct, or indirect, assessment of its risk of extinction based on its distribution and/or population status.” Data deficiency in conservation assessments can be the result of (i) taxonomic uncertainty and/or (ii) insufficient information. In this study, we did not define an equivalent to the DD category because the PACA provided are, by definition, preliminary and because our procedures allow for an assessment of any species with at least one georeferenced occurrence. Full Red List assessments using Criterion B are supposed to be based on knowledge of the current number and locality of subpopulations. For this reason, when using data from herbarium collections, old records are generally excluded or at the very least their (generally approximate) geographic position is compared with available remotely sensed imagery to determine whether the record indicates the presence of a subpopulation that still exists today. We therefore considered all collections as long as data on geographic position were available, and the approach that we adopted, using a grid of degraded habitat, allowed us to take into consideration the current status of the corresponding subpopulation, albeit at a coarse level of resolution. One possible improvement to the PACA approach could thus be to take account of the collection date and the accuracy of georeferencing for identifying likely DD species.

Last, our approach does recognize an equivalent to the “extinct” category, which concerns species for which there is “no reasonable doubt that the last individual has died” ([www.iucnredlist.org](http://www.iucnredlist.org)). Again, one possible improvement of our PACA approach could be implemented by using the age of the last record, the collection density within the region from which it is known, and human-impact layers. For example, if a species was last collected over 50 years ago from an area that has been recently well sampled and where there is significant deforestation, it could be assessed as potentially extinct.

### Robustness and limits of the PACA approach

The robustness of our PACA approach is dependent on four important prerequisites regarding the quality of the available data: (i) accurate



specimen identification based on a reliable species-level taxonomic framework, (ii) reliable and precise georeferencing of specimens, (iii) accurate layers for estimating habitat decline, and (iv) sampling homogeneity and completeness. These are all required to generate precise preliminary assessments [e.g., (12)]. We compared our results with published full IUCN Red List assessments (Table 4), which showed that the PACA approach is conservative in the sense that it has high sensitivity (a large majority of species assessed as EX/CR/EN in the published full assessments were identified as possibly threatened by our approach) but low specificity (a significant number of species identified as not threatened by full assessment were identified as potentially threatened using PACA) (Table 4). This comparison should be interpreted with caution because full assessments and PACA were not conducted on the same dataset. Our result is, however, in line with the findings of Nic Lughadha *et al.* (26), who showed that applying default settings of the ConR R package (38) (hence only applying Criterion B without considering habitat decline, as we have done here) on several plant datasets provided very good sensitivity. As noted by these authors, the conservative nature of ConR (and thus by extension the PACA approach) is desirable to minimize the risk of missing threatened species.

With the recent advent of high volume herbarium digitization efforts, large-scale databases of plant species distributions are now widely available. These databases must, however, be accurately checked and taxonomically verified, as has been done for the database used here, RAINBIO (12). Several other databases have also been published for tropical areas (39). Those that have not been taxonomically verified should be used with caution. The GBIF, the most widely consulted repository of biodiversity distribution data ([www.gbif.org](http://www.gbif.org)), presents an invaluable source for species distribution data. Using GBIF applications such as PACA, however, requires careful screening because it comprises an unverified compilation of information drawn from multiple datasets and thus contains inaccurate identifications as well as duplicate records (8) that may be assigned to different species because of a lack of taxonomic standardization. The quality of the data served by GBIF thus depends solely on the original provider. If used as the first source for PACA analyses, data from GBIF thus require significant initial verification to assess their general quality, remove duplicate records, correct inaccurate identifications, check for taxonomic synonyms, and correct erroneous collection coordinates (40).

The PACA approach includes a method to assess species that is aligned with IUCN Criterion A. The results presented here highlight different regions as having high levels of potentially threatened species compared to those resulting from assessments aligned with Criterion B (Fig. 2). However, applying Criterion A equally across all species, as we have done here, could be problematic for species that are tolerant of human disturbance because they might “wrongly” be assessed as Threatened as many of their recorded occurrences could be from disturbed areas. On the other hand, these species are also likely to be assessed as not Threatened under Criterion B because of their extended ranges resulting from expanding and intensifying human-driven disturbance throughout Africa.

Results obtained from using the approaches aligned with Criteria A and B will also be dependent on the layers indicating the level of human impact used for estimating population decline. Several regions were not highlighted as containing high proportions of potentially threatened species possibly because our layers are not precise enough to detect human affected areas at a fine scale. For example, the country of São Tomé and Príncipe has one of the lowest proportions of LT/PT

species but is known to have a high rate of species endemism (31). The land cover layer that we used clearly is not sufficiently resolved for our purposes because native vegetation is indicated as intact in areas where it is in fact known to be highly fragmented (34, 41). Our comparison with published IUCN assessments (for 2009 species) shows that most species assessed as Rare in our analysis (i.e., LR/PR) were assessed as CR, EN, or EX under the full IUCN Red List criteria (Table 3). This again suggests that the layers that we used for identifying habitat decline must be regarded as providing a first approximation. Alternatively, it is possible that assessments published on the Red List were based on an assumption of future decline for all species, which would have led to a higher number of threatened species than the PACA approach. Nevertheless, the accuracy and reliability of layers of human impact are steadily improving with the increased availability of very-high-resolution remote sensing technology [e.g., (42)], and the accuracy of the PACA approach can thus be expected to improve in parallel.

### Accelerating large-scale conservation assessments

Target 2 of the GSPC (9) calls for assessing the conservation status of all known plant species by 2020. To date, several approaches have been proposed to accelerate the estimation of extinction risks for plant species and to identify areas of importance for conservation [e.g., (10, 11)]. Each of these approaches is valid and important in its own right, but none of them are based on the IUCN Red List guidelines [but see (43)]. Although the GSPC does not explicitly call for conservation assessments following the IUCN procedure, estimation of risk of extinction using the IUCN methodology is widely regarded as the most comprehensive approach for identifying and targeting conservation priorities and actions (3). While it will be difficult to reach this target in full by the end of 2020 (9), the PACA approach makes it possible to estimate the conservation status of thousands of plant species simultaneously when using robust distribution information. It can also be used for preliminary reevaluation of species published on the Red List, which should preferably be carried out every 10 years (36).

Applying the PACA approach constitutes an efficient, rapid tool to identify areas with high concentration of LT/PT species and is therefore useful for studies such as EIAs. While PACA assessments are not substitutes for the full Red List assessments needed when identifying Critical Habitat under the IFC PS6, the PACA approach is nevertheless a valuable and cost-effective method for initially determining whether possible Critical Habitat triggers are present on a project site. In the absence of an official Red List assessment, PS6 guidelines suggest using unofficial assessments following the IUCN guidelines, which is precisely what PACA produces. PACA can also be used to identify areas of High Conservation Value (HCV). Under HCV Criterion 1 (<https://hcvnetwork.org>), areas are recognized as having an HCV when they contain a concentration of endemic species and/or species that are rare, threatened, endangered, or significant, unique or outstanding at global, regional, or national levels. HCV 1 is a key element for efforts being made by the Forest Stewardship Council to promote sustainable forest management and for certification of palm oil producers (Roundtable on Sustainable Palm Oil). Logging, mining, and agricultural companies are therefore potential users of our approach.

### Conclusions

The comparatively small number of species whose risk of extinction has been fully assessed for the IUCN Red List partly reflects difficulties



in accessing reliable specimen information. However, because many datasets have recently become available for such analyses, the primary limiting factor today is the time-consuming nature of conducting full assessments coupled with a lack of well-trained assessors. Using the PACA approach proposed here, we were able to assess more than 22,000 species rapidly (6 to 7 hours) and in a way that is aligned with the IUCN guidelines. On the basis of our experience in conducting full Red List assessments in Madagascar and Continental Africa (36), we estimate that the process of assessing a single species, from data compilation and verification to publication on the Red List, costs between \$30 and \$500 and takes on average one person/day of effort. The actual cost depends, however, on the number of specimens and the quality and quantity of the associated information (i.e., assessing a well-documented timber species could take several days and cost 20 times more than a poorly collected species), in addition to the effort required to review and validate the assessment. Thus, in situations where a verified dataset is available, PACA provides a cost-effective way to initiate the Red List assessment process for a large number of species. This is even more relevant as the process of generating taxonomically verified and high-quality species distribution datasets becomes increasingly automated (see, for example, BIEN, <http://bien.nceas.ucsb.edu/bien/biendata/bien-3/>). We thus predict that approaches such as PACA will become particularly useful in the near future. Within this rapidly evolving context, the PACA approach constitutes a useful, time-efficient, and informative first step toward full IUCN assessments and hence can contribute to achieving Target 2 of the GSPC while also helping to promote improved biodiversity management.

## MATERIALS AND METHODS

### Flora of tropical Africa dataset

We used a taxonomically verified database of tropical African vascular plant species distribution: RAINBIO (8, 12). This database contains 590,231 georeferenced records representing distribution information for 25,222 native species in sub-Saharan Africa, excluding Madagascar and southern Africa. Invasive or planted or cultivated species were not included [see (12) for details on cleaning and quality-checking the data].

Global assessments require knowledge of all known occurrences for a given taxon. Non-endemics to our study area, i.e., species with occurrences both within and outside tropical Africa, are problematic because RAINBIO does not include occurrences records from outside the continent (12). A species with a few records in tropical Africa might be assessed using the PACA approach as potentially threatened, although it is widely distributed outside Africa and therefore likely not threatened. To reduce this bias, we first excluded occurrences of species only found in South Africa, Swaziland, and Lesotho because only a small portion of the available records for these countries were included in the RAINBIO database (this concerns 2254 species and 3332 occurrences). We then applied the following procedure to identify species whose range extends beyond our study area by comparing the distribution as described by the RAINBIO database to that based on records from GBIF. Specifically, we searched GBIF for occurrences of 22,968 species in the RAINBIO database using the “rgbif” R package (44) and extracted occurrences for each from GBIF (excluding those with georeferencing issues, R code available at [https://github.com/gdauby/stewart\\_el\\_al\\_PACA](https://github.com/gdauby/stewart_el_al_PACA)). On the basis of these GBIF occurrence records, the number of occupied cells at

10-km resolution was calculated, as well as the number of continents in which the species has been recorded. Species identified by PACA as potentially threatened under Criterion B based on the RAINBIO dataset (see the method explaining the preliminary assessment below) and occupying more than 10 10 km × 10 km cells based on the GBIF data were tagged. GBIF occurrences were found for 21,345 species (96.9% of those in the RAINBIO dataset). Using RAINBIO, the number of species classified as potentially threatened under Criterion B (i.e., belonging to CR, EN, or VU categories, see below) was 15,470. Among these species, 1220 were recorded from more than 10 10 km × 10 km cells in the GBIF dataset, indicating that subpopulations for these species are missing in the RAINBIO database. When scrutinizing these species, it was found that the additional subpopulations are often artifacts of georeferencing errors or involved doubtful records. Hence, because the rationale of PACA is to provide preliminary conservation assessments, we adopted a conservative approach and only removed species occurring in more than two continents (20 species) or occupying more than 15 10 km × 10 km cells based on the GBIF dataset (912 species) to reduce the risk of incorrectly removing species that are truly threatened. The final dataset used in this paper thus comprised 580,208 distribution records for 22,036 species. Hence, from the initial list of 25,222 species, a total of 3186 were judged to have their known occurrences poorly covered by the RAINBIO database and/or have distributions likely to lie primarily outside our tropical African study area and were thus not assessed here.

### IUCN-based PACA

Depending on the type of information available for a species, an IUCN conservation assessment can be undertaken using any or all of five criteria, A to E. Criterion A is based on estimates of population (number of mature individuals) reduction over 10 years or three generations, Criterion B is based on geographic range, Criterion C is based on population size, Criterion D mainly concerns very small or restricted populations based on the number of mature individuals and AOO, and Criterion E is based on a quantitative analysis of extinction probability within a given number of years. In the absence of detailed information about population size (i.e., the number of mature individuals), which is commonly the case for plant taxa, standard practice calls for using estimates of geographic range obtained from occurrence records (e.g., georeferenced herbarium specimens) for assessments using Criterion B (26). As part of the PACA process, we generated a framework for estimating whether a species faces potential population reduction (required for Criterion A) or future decline in key geographic parameters (needed for Criterion B). Thus, PACA is aligned with two key elements of the IUCN Red List: Criterion A, relating to population size reduction, and Criterion B, relating to geographic range. Approaches aligned with the three other Red List criteria were not implemented as they require data that are unavailable for most plant species, especially across the tropics.

All IUCN parameters needed for preliminary assessments of taxa based under Criterion B (see below) were calculated using the R package ConR ver. 1.2.1 (38). Using an as-yet unreleased version ([https://github.com/gdauby/stewart\\_el\\_al\\_PACA](https://github.com/gdauby/stewart_el_al_PACA)), we also implemented assessments aligned with the parameters of Criterion A (see below).

### Decline in habitat quality

When using both Criteria A and B, an assessment of observed, estimated, inferred, suspected or projected decline in AOO, Extent of Occurrence (EOO) (see definitions below), and/or habitat quality is

needed for each taxon [subcriteria A2 and/or A3 under Criterion A; subcriterion (b) under Criterion B; see below, Table 1]. This is generally assessed on a taxon-by-taxon basis using detailed knowledge about land-use changes and the impacts of threats on the species, which is not possible when simultaneously assessing thousands of taxa. Our method is able to treat a large number of species by estimating population reduction and decline in geographic parameters indirectly based on two sources of information that are likely to be informative. For the first of these, we used land cover characterized by a moderate to high human influence to develop a “human affected” layer. This was done using the land-cover map of Africa produced by (45), which describes 27 land cover types based on remote sensing data at 1-km resolution. We constructed a raster layer for each land cover type by aggregating the original raster at 10-km resolution and computing the proportion of each land cover type within 10-km<sup>2</sup> cells. We identified seven land cover types indicative of moderate to high level of human impact: degraded evergreen forests, mosaic forests/croplands, croplands (>50%), croplands with open woody vegetation, irrigated croplands, tree crops, and cities. These layers are directly linked to the main threats on African flora, viz. small- and large-scale agriculture, urbanization, roads, and logging. A given occurrence was considered to be facing a decline in habitat quality if it occurred within a cell where the summed proportion of the seven land cover types indicative of human impact was higher than 50%. The second source of information on human impact was based on the prediction that mining activities will increase significantly in the next few decades across Africa (14). Using a map of major mineral deposits where industrial mining activities are taking place or will likely take place in near future, according to (46, 47), we estimated a decline in habitat quality for any site located within a 10-km radius of such a deposit, based on the inferred scale of the environmental effects of mining activities given in (48).

We identified a decline in habitat quality for a taxon [which is applicable under subcriteria A2 and A3, and invokes subcriterion (b) under Criterion B] when at least one of its known occurrences was found either in an area characterized by moderate to high human impact and/or in a 10-km radius around a major mineral deposit. In the specific case where all known occurrences of a species were found within one or more protected areas, we assumed no decline in habitat quality.

#### **PACA aligned with IUCN Red List Criterion B**

Assessing species under Criterion B of the IUCN Red List relies on two subcriteria: B1 and B2, based on the EOO and the AOO, respectively. In order for a species to be assessed as threatened, threshold values under at least two of three subcriteria must also be met as follows: (a) number of locations, (b) inferred/projected decline in various parameters including habitat quality, and (c) extreme fluctuation of populations (Table 1). Subcriterion (c) is rarely applicable for plants and was not considered here.

The EOO is the smallest surface contained in a polygon drawn from an imaginary boundary encompassing all known occurrences of a taxon (namely, the hull convex). At least three points are needed for calculating this parameter, so the EOO was not computed for taxa with less than three unique occurrences.

The AOO is the area within the EOO occupied by the taxon. The AOO is estimated by calculating the sum of occupied cells after superimposing a grid with cells of 2 km<sup>2</sup>. In ConR, the AOO is estimated by four different positions of the grid cell, and the one resulting in the minimum number of occupied cells is retained (38). A single record per taxon can be used to estimate AOO and thus undertake

the assessment, a common practice in tropical plant Red Listing workshops.

The number of locations, as defined by IUCN, is a “geographically or ecologically distinct area in which a single threatening event can affect all individuals of the taxon.” This parameter is difficult to estimate automatically [see (38) for discussion about how it is estimated]. For the purpose of the PACA approach, the number of locations was estimated on the basis of two considerations. First, all the occurrences found within a single protected area were considered to represent a single location, based on the rationale that these occurrences would be equally affected by a single event such as downgrading, downsizing, or degazetting the protected area [e.g., (37)], although we acknowledge that these events can have various impacts that are hard to estimate at broad scales. The number of locations was thus estimated using a shapefile of terrestrial protected areas for tropical Africa downloaded from the World Database on Protected Areas ([www.protectedplanet.net](http://www.protectedplanet.net)). Second, for occurrences located outside protected areas, the number of locations was estimated as the number of occupied cells within a superimposed grid of 10 km<sup>2</sup>. This grid cell size is suggested as a suitable proxy for detecting a threat that would equally affect all individuals of a taxon contained therein [e.g., mining activities; see (48)].

On the basis of the calculations of EOO and AOO, the estimate of the number of locations and whether or not potential past or future decline was inferred, we automatically assigned each taxon to one of three preliminary threat categories (see IUCN guidelines):

- 1) Potentially CR: EOO < 100 km<sup>2</sup> or AOO < 10 km<sup>2</sup> and locations = 1 and at least one of its occurrences subjected to decline in habitat quality because it is found in a cell classified as human affected or identified as actually or potentially subjected to mining.
- 2) Potentially EN: EOO < 5000 km<sup>2</sup> or AOO < 500 km<sup>2</sup> and locations ≤ 5 and at least one of its occurrences found in a human affected or mining cell.
- 3) Potentially VU: EOO < 20,000 km<sup>2</sup> or AOO < 2000 km<sup>2</sup> and locations ≤ 10 and at least one of its occurrences found in a human affected or mining cell.

#### **PACA aligned with IUCN Red List Criterion A**

As a complement to inferring PACA using key parameters of IUCN Criterion B, we also inferred parameters for Criterion A based on the observed, estimated, inferred, suspected, or projected reduction in the population size of a taxon, i.e., in number of mature individuals. For most plant species, little, if any, information about population dynamics through time is available. We thus inferred population reduction by making a quantitative estimate of the percentage of population decline using the AOO for each taxon that meets either subcriterion A2 or A3. A2 relies on observed, estimated, inferred, or suspected population reduction in the past, “where the causes of reduction may not have ceased or may not be understood or may not be reversible.” A3 is based on projected, inferred, or suspected population reduction to be met in the near future (up to 100 years or three generations, whichever is smaller).

Using the human impact and mining layers described above, we estimated a population reduction percentage for each taxon by inferring a potential decrease in AOO (AOO<sub>DEC</sub>). This was done by using the ratio between an AOO estimated from all occurrences (AOO<sub>FULL</sub>) and an AOO estimated only from occurrences situated outside human affected or mining areas (AOO<sub>RED</sub>). The value of AOO<sub>DEC</sub> = (AOO<sub>FULL</sub> - AOO<sub>RED</sub>) / AOO<sub>FULL</sub> × 100. AOO<sub>DEC</sub> thus represents the decrease in AOO if all occurrences occurring within the human affected or mining areas were lost in the

near future. Using  $AOO_{DEC}$  as computed here and applying the threshold values for IUCN Criterion A, we assigned each taxon to one of the following preliminary threat categories:

- 1) Potentially CR:  $AOO_{DEC} \geq 80\%$ ;
- 2) Potentially EN:  $AOO_{DEC} \geq 70\%$ ;
- 3) Potentially VU:  $AOO_{DEC} \geq 50\%$ .

### Names for PACA categories and subcategories

Assessments obtained using the PACA method must be regarded as “preliminary” because they are not the result of a full IUCN assessment, a taxon-by-taxon procedure based on exhaustive information (e.g., bibliographic, remote sensing data, and in situ observations) on the threats affecting each individual taxon. Species were therefore assigned to three PACA-derived categories based on the automatic batch output from ConR (see Table 1 and Fig. 1): (i) LT, encompassing species flagged as potentially CR or potentially EN, (ii) PT, encompassing species flagged as potentially VU, and (iii) PNT, encompassing species that potentially do not fall into one of the three IUCN threatened categories (i.e., which would correspond to the IUCN Red List categories of NT or LC).

For species assessed as PNT, we further distinguished three subcategories: (i) LR, which includes species whose EOO, AOO, and number of locations all fall within the thresholds for CR and EN but for which we did not infer a decline in the quality of habitat; (ii) PR, which is similar to LR but for species whose EOO, AOO, and number of locations fall within the limits for VU; and (iii) LNT, which includes all other species that do not belong to the categories described above.

### Geographic distribution of threatened species

After species were assigned to a PACA category (Table 1), we compiled distributional data to summarize and map the estimated level of threat across Africa. A gridded spatial representation of threat was undertaken using an “adaptive resolution” SU method (49). This approach adapts the size of the SU as a function of a user-defined threshold of minimum occurrence records. A shapefile of the adaptive SU grid was created by uploading the RAINBIO database to the Infomap Bioregions application (49) using the following parameters: maximum cell capacity = 1000, minimum cell capacity = 250, maximum cell size = 8°, and minimum cell size = 0.5°. We also represented our results for each country and each terrestrial ecoregion (33) found in Africa. In each case (grids, adaptive SU, and ecoregion), we estimated the total number of taxa recorded and the proportion of taxa assessed as LT and PT, under Criteria A and B separately, and by combining both criteria, i.e., a taxon would, for example, be categorized as LT if it is assessed as LT by at least one of the two criteria.

### Threat per habit

We assessed the proportion of threatened species corresponding to each of four major habits: herbs, trees, lianas, and shrubs. Information about species habit was extracted from the RAINBIO database (12).

### Comparison with full published IUCN assessments

For each species, the full published IUCN assessment was downloaded from the IUCN website using the API tools of the “redlist” R package (version 2018-2, [www.iucnredlist.org](http://www.iucnredlist.org)). To evaluate the extent to which the results of the PACA approach matched those of full Red Listing, we computed a Kappa coefficient for evaluating agreements between full published IUCN categories and PACA categories.

### SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/5/11/eaax9444/DC1>

Fig. S1. Total number of species assessed as Likely/Potentially Threatened following criterion A, B, and both A and B.

Fig. S2. Total number of species preliminarily assessed as LR/PR following the Criterion B.

Fig. S3. Summary statistics for full conservation assessments of plant species published on the IUCN Red List portal (version 2018-2, [www.iucnredlist.org](http://www.iucnredlist.org)).

Fig. S4. Proportion of species preliminarily assessed as Likely/Potentially Threatened following Criterion A and Criterion B for four habit types.

Table S1. Proportion (in %) of LT/PT species assessed under Criteria A, B, and both A and B for all countries within our study area (tropical Africa).

Table S2. Number of LT/PT species assessed under Criteria A, B, and both A and B for all countries within our study area (tropical Africa).

Table S3. Proportions of likely/potentially threatened species assessed under Criteria A, B, and both A and B across ecoregions.

Table S4. Number of likely/potentially threatened species assessed under both Criteria A and B and total number of species for four different habits for each ecoregion.

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