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Policy analysis

Vulnerability mapping of 100 priority tree species in Central Africa to guide conservation and restoration efforts

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ABSTRACT

Climate change and other anthropogenic threats are increasingly imperilling the diverse biomes of Central Africa, which are globally important for biodiversity, carbon storage and people's livelihoods. The objectives of this paper were to: (i) map the vulnerability of 100 socio-ecologically important priority tree species in Central Africa to climate change, fire, habitat conversion, overexploitation, overgrazing and (ii) propose a spatially explicit strategy to guide restoration and conservation actions. We performed ensemble distribution modelling to predict the present and future distributions of the 100 species, assembled other anthropogenic threat exposure layers, assessed species' sensitivities to the five threats based on their trait profiles, and constructed species-specific vulnerability maps by combining the species' exposure and sensitivity. The results show that these 100 species are vulnerable to the five threats, with an average of 34% of their distribution ranges under high to very high vulnerability and 60% under medium to high vulnerability to at least one threat. Many species identified as most vulnerable in this study are not considered as threatened by the IUCN Red List, suggesting a need to update their conservation status, potentially through integration of the vulnerability mapping methodology we used here. We generated both species-specific maps and summary maps including all 100 species identifying priority areas for a) in-situ conservation, b) ex-situ conservation, and c) active planting or assisted natural regeneration. We present an online platform to enable easy access to the vulnerability and the conservation and restoration priority maps for decision makers and support conservation and restoration planning across Central Africa.

1. Introduction

Climate change and other anthropogenic threats are increasingly imperilling the biomes of Central Africa (Abernethy et al., 2016; Réjou-Méchain et al., 2021). This region hosts a wide diversity of biomes which are globally important for biodiversity, carbon storage and local people's livelihoods, ranging from the humid forests in the Congo Basin and western coast, to the savannas in the Sahel region and eastern and southern borders (Dinerstein et al., 2017). The African humid forests are the world's second largest rainforest after the Amazon, accounting for 30% of global rainforest cover (Malhi et al., 2013b). These forests are crucial for global carbon storage and they sequester more carbon per hectare than the Amazon forests (Lewis et al., 2013). On the other hand, the African continent also contains the largest area of tropical savannas in the world and, despite the lower tree density, this biome also stores substantial amounts of carbon in vegetation and soil (Grace et al., 2006).

Climate change is expected to impact forests and savannas in Central Africa. Temperatures are predicted to increase by 2–4 °C by the end of

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this century in Central Africa (Aloysius et al., 2016), while expected changes in precipitations vary in sign and intensity between different models across most of the region (Aloysius et al., 2016; Dosio et al., 2021). A recent study found that current climatic niches in African humid forests associated with specific forest types are predicted to move to new areas due to climate change, threatening the survival of such forests and their species (Réjou-Méchain et al., 2021). Several studies have reported that, despite the widespread re-greening of Sahel following the long-term droughts in 1970s–1980s (Brandt et al., 2015; Eklundh and Olsson, 2003; Herrmann et al., 2005), climate change is decreasing tree diversity and increasing the abundance of drought-tolerant species in the Sahel and West African savannas (Brandt et al., 2015; Gonzalez et al., 2012; Herrmann and Tappan, 2013).

Central African biomes are currently under pressure of anthropogenic threats which have increased in unison with rapid population growth during the last decades (Gerland et al., 2014). Population in Central Africa is mostly rural and largely relies on subsistence agriculture and extraction of forest and savanna resources. Over the past decades, deforestation in Central Africa has been mainly driven by vegetation clearance for smallholder agriculture, exploitation of fuelwood, and timber logging (Abernethy et al., 2016; Tyukavina et al., 2018). Although Central Africa has lower deforestation rates than Latin America and Asia due to a lower presence of industrial agriculture (Abernethy et al., 2016; Tyukavina et al., 2018), deforestation in African humid forests still contributes to 11% of global forest loss (Malhi et al., 2013a). Fire is another important threat in Central Africa. While natural fires are very common in African savannas (Andela et al., 2017) and this biome is adapted to burning (Veldman et al., 2015), fires represent a great threat to humid forests in Central Africa as they do not naturally occur in these forests and consequently, tree species are highly vulnerable (Cochrane, 2003).

In response to the current climate and biodiversity crises, several global initiatives have committed to promote conservation and restoration actions across the world. These include the Bonn Challenge that aims to restore 350 million ha of degraded lands and the UN High Ambition Coalition for Nature and People that aims to protect 30% of the planet by 2030. In the context of these initiatives, African countries have pledged to build an 8000 km wall of trees stretching from East to West Africa under the Great Green Wall initiative, and to restore 100 million ha of degraded land by 2030 under the African Forest Landscape Restoration Initiative (AFR100). To ensure long-term success, such conservation and restoration efforts should include careful evaluation of climate change and other anthropogenic threats (Carwardine et al., 2012; Gillson et al., 2013). As threats are not spatially homogeneous and different species have different sensitivities to the same threat, spatially explicit vulnerability assessments can help to define which regions and species are most in need of conservation and restoration (Fremout et al., 2020; Gaisberger et al., 2017, 2021).

The objectives of this paper were to (i) map the vulnerability of 100 socio-ecologically important priority tree species in Central Africa to climate change, fire, habitat conversion, overexploitation, overgrazing and (ii) propose a spatially explicit strategy to guide species-specific conservation and restoration actions. We performed ensemble distribution modelling to predict the present and future distributions of the 100 species, assembled other anthropogenic threat exposure layers, assessed species' sensitivities to the five threats based on their trait profiles, and constructed species-specific vulnerability maps by combining the species' exposure and sensitivity. We produced maps indicating recommended areas for conservation and restoration actions for each species and for the whole study area. We discuss how the results of this study can be used to guide conservation and restoration actions across Central Africa.

2. Methods

2.1. Study area

We performed the analysis in the Central Africa region and the surrounding countries. While our main geographical focus was the Central African region (Cameroon, Central African Republic, Chad, Republic of Congo, Democratic Republic of Congo, Equatorial Guinea, Gabon, São Tomé & Principe), we extended the boundaries of the study area to the extent 0° W–35° E, −15° S–25° N to obtain more reliable suitability distributions of the modelled species, which also occur in surrounding countries. The study area covers 30 countries and seven biomes (Dinerstein et al., 2017) (Fig. S1). For simplicity, from here on we refer to this whole study area as ‘Central Africa’.

2.2. Tree species selection

For the vulnerability mapping, we assembled a list of 100 socio-ecologically important priority species from several priority lists for African tree species (Franzel et al., 2007; IUCN, 2021; Jaenicke et al., 1995; Sacandé and Berrahmouni, 2016; Sacandé and Pritchard, 2004) (Table S1). We selected the species from these priority lists according to the following criteria: i) native from Central Africa; ii) socio-economically important for timber, fuelwood, edible fruits, forage, or other non-wood products; iii) important for conservation or used in restoration programs; iv) with at least 30 presence points after geographical filtering at 5 arcmin resolution. The 100 species belong to 24 families and 70 genera, the most species-rich families being Fabaceae (30 species), Meliaceae (11 species) and Combretaceae (10 species) (Table S1). 54 species mostly occur in the savanna biome, 23 in the humid forest biome and 23 in both biomes (Table S1). The list of the 100 species, families, main biome, priority lists and main uses is provided in Table S1. We present the species richness map of the 100 selected species across Central Africa (i.e. a map indicating the number of species occurring per grid cell) in Fig. S2.

2.3. Species distribution modelling

We compiled species presence points from RAINBIO (Dauby et al. (2016); https://gdauby.github.io/rainbio/download_page.html), GBIF (Global Biodiversity Information Facility; www.gbif.org), and BIEN (Botanical Information and Ecology Network; http://biendata.org/). To reduce spatial bias (Kramer-Schadt et al., 2013), we filtered the presence points using both geographical filtering at 5 arcmin and environmental filtering. We used 45 predictor variables, including 19 bioclimatic variables, 5 variables of cloud cover, 6 variables indicating climatic extremes (VITO, 2020, 2021), 10 soil variables (Hengl et al., 2017), and 5 terrain variables (Table S2). We removed collinear variables using the Variance Inflation Factors (VIF). We selected pseudo-absence and background points using to the target group method described by Phillips et al. (2009) and Mateo et al. (2010). Distribution modelling was carried out using ensembles with up to nine algorithms using the *BiodiversityR* package for R (Kindt, 2018), consisting of random forest, MAXENT, GBM, GLMSTEP, GAMSTEP, MGCV, FDA, SVM, and EARTH. The models were cross-validated with 5 folds and using spatial blocks implemented through the *blockCV* package for R (Valavi et al., 2019), and model performance was assessed using the Area Under the receiver-operator Curve values cross-validated with spatial blocks (cvAUC). We converted the suitability maps into presence-absence maps using the suitability threshold at which model sensitivity equates to model specificity. The detailed methodology for the species distribution modelling is presented in Text S1.

2.4. Threat exposure

Exposure to each of the five threats (fire, habitat conversion, overgrazing, overexploitation, climate change) was estimated following the methodology described in Fremout et al. (2020) and Gaisberger et al. (2021). Exposure maps were generated using freely accessible spatial datasets and according to assumptions from literature and expert knowledge. The exposure maps had values from 0 to 1 (zero to maximum exposure) and had resolution of 30 arcsec (ca. 0.9 km at the equator). The exposure maps for fire, habitat conversion, overgrazing and overexploitation represent current exposure levels, while the exposure maps for climate change represent the predicted future exposure. In addition, we performed a sensitivity analysis to assess the impact of methodological decisions on the results (see Section 2.7), for which we complemented the reference exposure maps with best-case and worst-case exposure maps. The detailed methodology for estimating the reference, best-case and worst-case exposure maps to the five threats is presented in Text S2.

2.5. Species sensitivity and vulnerability

Species sensitivity and vulnerability was estimated following Fremout et al. (2020) and Gaisberger et al. (2021). We estimated the sensitivity of the 100 species to each of the five threats using a set of 16 traits (Fig. 1, Table S3). The 16 traits mostly refer to biological traits (e.g., bark thickness or leaf phenology) but we also included plant uses such as fuelwood and timber provision. We compiled the trait data for the 100 species from an extensive literature search (Table S4). The obtained trait dataset had an average of only 5% missing traits per species, ranging from 0% for the species *Afzelia africana*, *Pterocarpus angolensis* and *Pentaclethra macrophylla* to 13% for *Psorospermum febrifugum* (Table S5).

We defined the relation between each trait and the sensitivity of each species to the five threats following the rationale in Table S3. First, each trait was assigned a weight indicating the expected importance for species sensitivity to any of the five threats, ranging from 1 (very low) to 5 (very high importance) (Fig. 1, Table S3). Then, each trait was divided into several levels linked with a partial score based on the expected influence on the sensitivity of the species, varying between zero (lowest sensitivity) and one (highest sensitivity). For example, leaf palatability was assigned a trait weight of 5 for overgrazing, as it is one of the main traits in defining sensitivity to overgrazing, and species with non-palatable leaves and palatable leaves were assigned partial sensitivity scores to overgrazing of 0.25 and 1, respectively (Fig. 1, Table S3).

We defined the overall sensitivity of the 100 species to each threat by calculating the weighted average of the partial sensitivity scores and the weights (Fig. 1, Table S3). Some specific trait levels were assigned a fixed score: we assigned a sensitivity score to overgrazing of 0.25 to all species with unpalatable leaves, and a sensitivity score to overexploitation of 0.25 to all species that are not used for firewood nor timber. We selected a value of 0.25 because these species are not completely unsusceptible (e.g., a species with unpalatable leaves may still be impacted by trampling).

Vulnerability maps for each species were constructed by multiplying the threat exposure maps with the sensitivity values for each species. We then categorized these vulnerability maps into five categories: zero (0–0.01), low (0.01–0.25), medium (0.25–0.5), high (0.50–0.75) and very high (0.75–1) vulnerability.

2.6. Maps for conservation and restoration

Based on the vulnerability maps, we created species-specific maps identifying priority conservation and restoration actions, following Fremout et al. (2020) and Gaisberger et al. (2021). For constructing these maps, we analysed vulnerability to climate change and vulnerability to current threats separately. We calculated the vulnerability to current threats as the highest among fire, habitat conversion, overexploitation and overgrazing. Because different threats often have additive or synergistic impacts on vulnerability (Côté et al., 2016), we adjusted the values of vulnerability to current threats to 'very high' where the vulnerability value to at least three current threats was 'high', and to 'high' where the vulnerability to at least three current threats was 'medium'.

Based on the vulnerability to current threats and climate change, we generated maps indicating priority areas for conservation and restoration actions for each species. The conservation and restoration actions

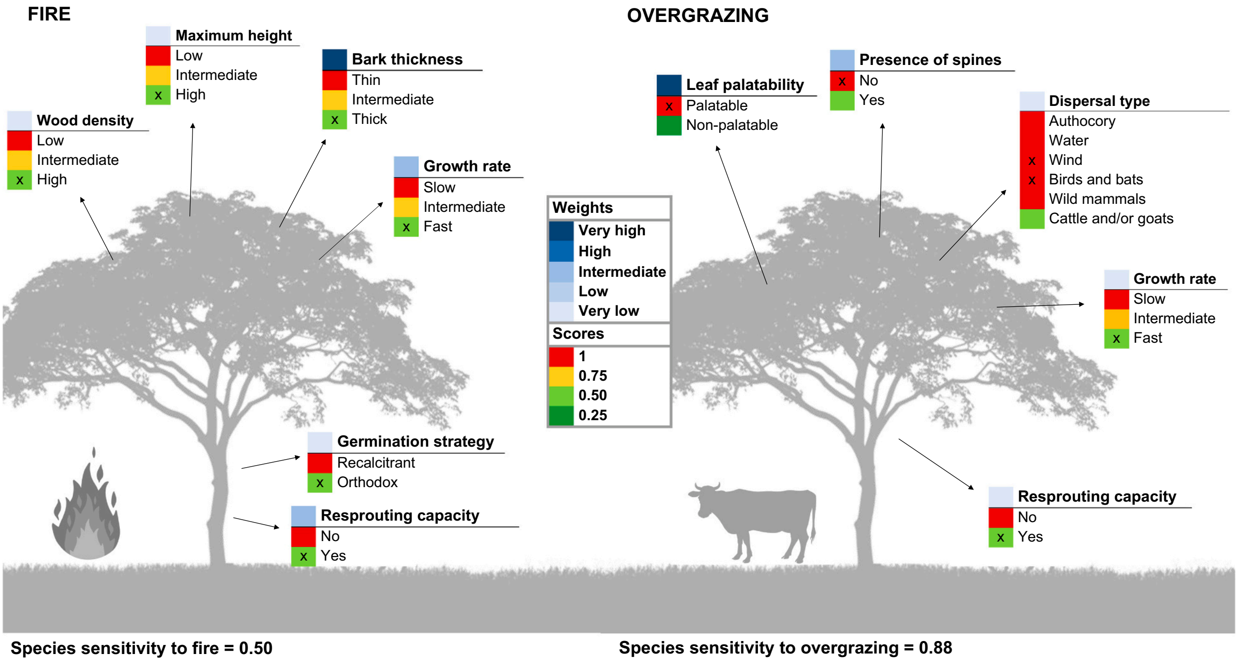

Fig. 1. Illustration of the estimation of the sensitivity of the species *Afzelia africana* to fire (left) and overgrazing (right). Trait weights are indicated by shades of blue and the partial scores by colours from green to red (see legend in the middle). Overall sensitivity values, estimated as the weighted average of the partial scores with the trait weights, are indicated at the bottom of the figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

include: a) in-situ conservation, b) ex-situ conservation or assisted migration, c) active planting or assisted natural regeneration. First, in-situ conservation of tree populations and seed collection for tree planting activities is prioritized in areas with low vulnerability to current threats and climate change. Areas with low vulnerability to current threats are likely to have higher genetic variability and lower inbreeding rates than areas heavily disturbed by humans, while low climate change vulnerability to climate change ensure that local populations will likely remain viable and continue producing seed in the future. Second, ex-situ conservation or assisted migration is prioritized in areas with high vulnerability to climate change. This in order to protect the genetic variability of populations within the same species that currently grow in an area that are expected to become unsuitable under climate change, of which the genetic diversity may be lost if they are not conserved ex-situ or helped to migrate to areas where they are more likely to persist. Third, restoration activities such as active planting or assisted natural regeneration are prioritized in areas under high to very high current threat vulnerability but low vulnerability to climate change, combined with interventions to decrease the current anthropogenic threats. Areas with a high or very high vulnerability to current threats are the ones that most require restoration interventions, while the low vulnerability to climate change increases the likelihood that the planted or regenerating trees will be able to survive in future. Finally, the conservation and restoration maps also identify areas that are not suitable in present but are predicted to become suitable in future under climate change (Text S2).

In addition to the species-specific maps, we also constructed summary maps depicting priority areas for conservation and restoration interventions across Central Africa. These maps were generated based on the number of species per grid cell for which the grid cell in question is recommended for the given conservation and restoration action.

2.7. Sensitivity analysis

Finally, we carried out a sensitivity analysis to estimate how methodological decisions impact the results of the conservation and restoration maps, following Fremout et al. (2020). We included three factors: a) methodological decisions used to construct threat exposure maps; b) trait weighting schemes chosen to calculate sensitivity values; and c) missing trait values. For each factor, we applied two 'treatments' for the vulnerability assessment in addition to the 'reference' treatment (i.e., the original or reference maps). The two treatments for a) correspond to the best-case and worst-case exposure map described in Section 2.4 and Text S2, while the details for the treatments for b) and c) are explained in Text S3. We performed the sensitivity analysis on the conservation and restoration maps and we generated for each species six versions of these maps, corresponding to the six treatments. For each of the six treatments, we calculated the percentage of grid cells within distribution of each species that changes their priority actions recommended as compared to the reference map.

3. Results

3.1. Species distribution modelling

The mean cvAUC value of the distribution models of the 100 species was 0.81. The cvAUC ranged from 0.64 to 0.96 with only seven species out of 100 with cvAUC < 0.70, indicating good to very good distribution models. The list of cvAUC values for the 100 species is provided in Table S6. The average cvAUC value of the individual modelling algorithms ranged from 0.73 ± 0.21 SD (GBMSTEP) to 0.80 ± 0.07 SD (random forest). The ensemble model was the most accurate for 39 of the 100 species, followed by random forest (18 species) and SVM (18 species).

3.2. Species sensitivity and vulnerability

Fig. 2 summarizes the proportion of the current distribution of each of the 100 species under the different vulnerability levels to the five threats. On average 34% (±12 SD) of the grid cells within species distribution ranges had a high to very high vulnerability to at least one of the five threats, while 60% (±14 SD) had medium to very high vulnerability. For the individual threats, the average area under high to very high vulnerability was 19% (±10 SD) for overexploitation, 10% (±9 SD) for habitat conversion, 9% (±13 SD) for climate change, 6% (±7 SD) for overgrazing, and 5% (±4 SD) for fire. When considering the average area under medium to very high vulnerability, the values rose to 38% (±14 SD) for overexploitation, 19% (±14 SD) for habitat conversion, 18% (±19 SD) for climate change, 12% (±12 SD) for overgrazing, and 14% (±8 SD) for fire. The most vulnerable species in terms of proportion of their distribution under high to very high vulnerability were *Prunus africana*, *Cola nitida*, *Dacryodes macrophylla*, *Pouteria altissima*, and *Vachellia gerrardii*, with 58–80% of their distribution under high to very high vulnerability.

3.3. Maps for conservation and restoration

For each of the 100 species, we generated maps highlighting priority areas for conservation and restoration actions for a) in-situ conservation; b) ex-situ conservation or assisted migrations; and c) active planting or assisted natural regeneration. Across the 100 species, on average 40% (±14 SD) of the distribution ranges were prioritized for in-situ conservation, 22% (±12 SD) for restoration, and 9% (±13 SD) for ex-situ conservation, while 11% (±13 SD) of the distribution ranges are expected to change from unsuitable to suitable under climate change. Fig. 3 shows the example of the conservation and restoration map for the species *Faidherba albida*. The conservation and restoration maps for the 100 species together with the vulnerability maps can be visualized online at: https://tree-diversity.shinyapps.io/vulnerability_central_africa/ and can be downloaded at: https://doi.org/10.6084/m9.figshare.19635996.

Fig. 4 shows the number of species per grid cell recommended for conservation and restoration actions across Central Africa. Priority areas for conservation for 20 to 50 species (representing 90–100% species occurring in the areas) are concentrated in the humid forests of Gabon and southern Cameroon and in the savannas in southern Chad, northern Central African Republic and western South Sudan, and occur both inside and outside protected areas (Fig. 4a). Priority areas for restoration for 20 to 50 species (representing 90–100% species occurring in the areas) are concentrated in the humid forests in southern Nigeria and in the savannas from Togo, Benin, Nigeria to northern Cameroon, and they are mostly within converted areas (Fig. 4b).

3.4. Sensitivity analysis

Table S7 summarizes the results of the sensitivity analysis. The conservation and restoration maps are robust against the trait weighting schemes and missing traits (average change 2–9%), while they are more influenced by the methodological decisions used to construct threat exposure maps (average change 23–25%).

4. Discussion

In this study, we quantified the vulnerability of 100 socio-ecologically important priority tree species across Central Africa to climate change, fire, habitat conversion, overexploitation, overgrazing. Our results show that several species are threatened, with an average of 34% of their distribution ranges under high to very high vulnerability and 60% under medium to high vulnerability to at least one threat. Considering the commitment of African countries towards AFR100 and other international initiatives, it is essential that conservation and

(caption on next page)

Fig. 2. Summary of sensitivity and vulnerability estimates of the 100 tree species for the five threats. Black dots indicate the species sensitivity values to the five threats. The cumulative bar plots indicate the relative frequency of species vulnerability values to each of the five threats (columns 1–5) and the relative frequency of the maximum vulnerability values (column 6). The bars show the proportions of the current distribution range of each species with a zero, low, medium, high and very high vulnerability to the five threats; and are indicated with colours from light yellow to dark red. The relative frequency of the maximum vulnerability values refers to the highest vulnerability among the different threats within a grid cell. The species are ordered according to decreasing proportion of the distribution range with high or very high vulnerability to at least one of the five threats (column 6). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

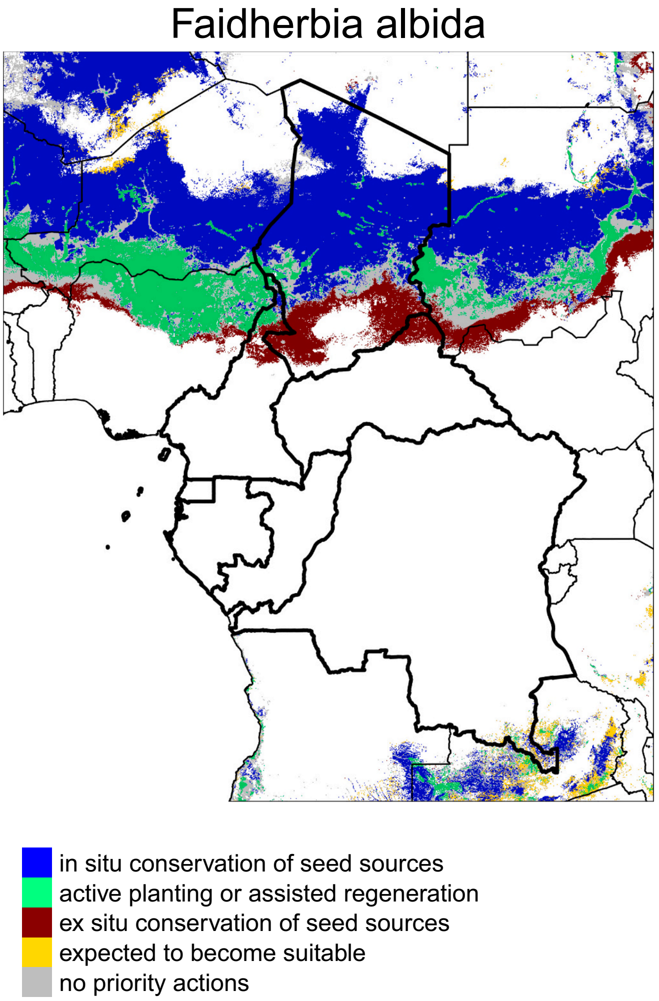

Fig. 3. Map of restoration and conservation priority areas for *Faidherbia albida*, indicating priority areas for in-situ conservation of seed sources (blue), active planting or assisted natural regeneration (green), ex-situ conservation of seed sources (dark red), areas expected to become suitable (yellow), and areas with no priority actions (grey). Countries of Central African region are indicated with thick borders. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

restoration plans in the region include a careful evaluation of these threats.

Our vulnerability assessment suggests that overexploitation represents the highest threat to the selected tree species in the study area (19% of the species distribution areas under high to very high vulnerability on average), followed by habitat conversion and climate change (9% each), while overgrazing and fire have lower importance (5–6%). The lower expected impact of climate change at least in the humid forest biome corroborates previous studies which postulated that African humid forests are more resilient to climate change than other tropical forests (Asefi-Najafabady and Saatchi, 2013; Bennett et al., 2021) largely due to a history of unstable post-Pleistocene climate which already led to the selection of more climate-resilient species (Willis et al., 2013). The lower vulnerability to habitat conversion is in line with the fact that deforestation in Central Africa is mostly driven by small-scale vegetation clearance for smallholder agriculture which leads to lower deforestation rates, while large-scale deforestation driven by industrial agriculture is still limited (Abernethy et al., 2016; Tyukavina et al., 2018). However, the recent expansion of both industrial agriculture (Feintrenie, 2014; Ordway et al., 2017) and subsidence agriculture (Herrmann et al., 2020; Tyukavina et al., 2018) may increase the threat of habitat conversion in the near future. Considering the high impact of overexploitation, it is fundamental that at least this threat is included in conservation and restoration planning in Central Africa, in addition to the more commonly considered threats of climate change and habitat conversion (e.g. Bomhard et al., 2005; Gomes et al., 2019; Triviño et al., 2018).

The overall high vulnerability to anthropogenic threats of the selected 100 species poses concerns about the conservation status of tree species in Central Africa. The most vulnerable species identified in this study should be considered high priority species for conservation actions. The five most vulnerable species had 58–80% of their area under high to very high vulnerability. Yet of these only *Prunus africana* is classified as 'vulnerable' according to the Global IUCN Red List, while *Cola nitida* and *Pouteria altissima* are considered 'not threatened' and *Dacryodes macrophylla* and *Vachellia gerrardii* are not assessed. This suggests that there may be a need to re-evaluate the current IUCN Red List assessments for these and other species, potentially through integration of the vulnerability mapping methodology we used here. Eighty-five out of the 100 species considered in this study have been assessed in the Global IUCN Red List, but among the countries in the Central African region, only Cameroon currently has a National Red List for Vascular Plants (Onana and Cheek, 2011). It is essential to have country-level assessments to evaluate the conservation status of tree species in different countries and conserve the genetic variation that exists across their distributions. Of the 98 species occurring in Cameroon among the 100 species analysed in this study, only 31 were included in the National Red List of Cameroon, with 11 species classified as threatened while the remaining 67 were not assessed (Table S8). Furthermore, 4 out of the 20 species considered as not threatened and 17 out of 67 not assessed by the National Red List of Cameroon have more than 50% of their distribution area within Cameroon under high to very high vulnerability (Table S8). This illustrates the urgent need in Central African countries to develop National Red Lists, to which our vulnerability mapping methodology can contribute.

The vulnerability mapping methodology used in this study can contribute to IUCN Red List assessments and to inform large-scale conservation and restoration planning. The methodology can be useful to complement the IUCN Red List assessments, as it uses a spatially-explicit estimation of the impact of current anthropogenic threats and includes the future impact of climate change. The methodology has already been applied in tropical forests in South America (Fremout et al., 2020) and Asia (Gaisberger et al., 2021), and future studies could further improve the method used to create the exposure maps and to estimate trait-based sensitivity values, in order to make it applicable to other regions and ecosystems as well. Regarding the exposure maps, while the exposure maps of fire, habitat conversion, overgrazing and climate change were calculated using databases directly related to the respective threat exposure, the exposure map of overexploitation was constructed by combining the proxies of human population density and accessibility to cities (Text S2). If available in a study area, estimates of exposure to

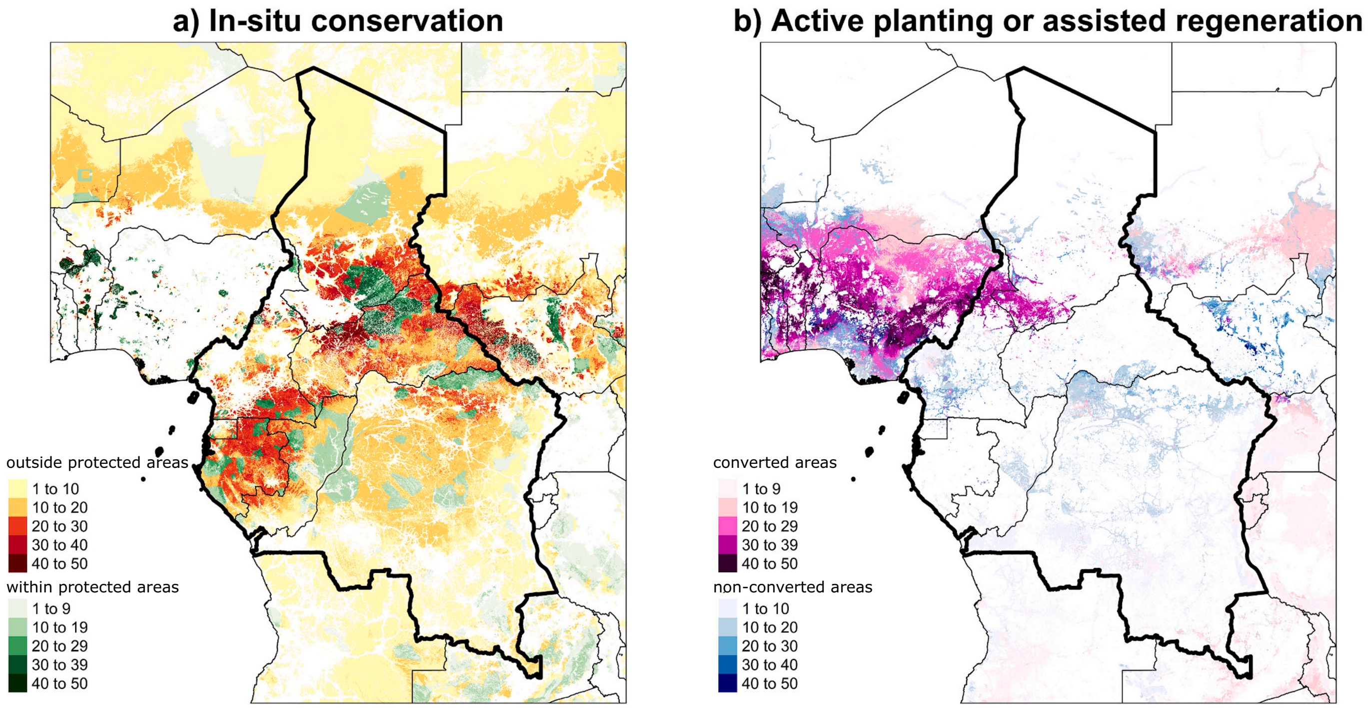

Fig. 4. Summary maps for priority conservation and restoration areas of the 100 socio-economically important tree pecies. The maps indicate the number of species per grid cell recommended for a) in-situ conservation and b) active planting or assisted natural regeneration actions. In a) we indicate in different colours priority areas falling within protected areas (shades of green) and outside protected areas (shades of red), while in b) we indicate priority areas falling within non-converted areas (shades of blue) and converted areas (shades of purple). Countries of Central African region are indicated with thick borders. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

overexploitation could be improved by including spatial data describing other determinants of overexploitation, such as law enforcement and use of forest resources (Fremout et al., 2020). On the other hand, depending on the study area, other threats in addition to the five used in this study could be added. For instance, in Central Africa, other relevant threats include mining (Edwards et al., 2014) and conflict zones (Mirzabaev et al., 2021). Regarding the trait-based sensitivity estimates, it would be important to standardize the set of traits selected for each threat according to latest studies and possibly also include ‘hard’ traits directly linked to the functional mechanisms determining species vulnerability (Fremout et al., 2020) such as leaf flammability for fire or xylem hydraulic conductivity for climate change, at least for species for which these data are available.

The general conservation and restoration maps that we generated (Fig. 4) can help prioritize conservation and restoration actions. Large areas in the humid forests in southern Nigeria and in the savannas from Togo, Benin, Nigeria to northern Cameroon are indicated as priority for restoration activities, as the tree populations in these regions are under higher threat especially from overexploitation and habitat conversion compared to less populated forests in the Congo Basin (Fig. S3). Some of these priority areas for restoration activities in northern Nigeria and northern Benin are already part of the Great Green Wall initiative, but additional efforts are needed in other areas. Large-scale restoration projects with active planting and assisted natural regeneration should focus on degraded forests which have not been converted to agriculture yet in southern Nigeria, while promoting agroforestry in farmed landscape might be a better option for converted areas in Togo, Benin, northern Nigeria, northern Cameroon. Considering the high impact of overexploitation, restoration projects should promote planting of species that are important to local people for timber, fuelwood, fruits, and other non-wood products. Importantly, restoration interventions in savannas and grasslands should focus on restoring the original tree cover of these ecosystems rather than afforestation, which could instead threaten the unique biodiversity and ecosystem service provision of these ecosystems characterized by low tree density (Tölgyesi et al., 2021; Veldman et al., 2019).

On the other hand, priority areas for conservation are concentrated in the humid forests of Gabon and southern Cameroon and in the savannas in southern Chad, northern Central African Republic and western South Sudan. Considering the overall low expected impact of climate change on the species of interest across the region, there are no specific areas prioritized for ex-situ conservation of many species simultaneously. However, individual species such as *Dacryodes macrophylla*, *Prunus africana* and *Pouteria altissima* may be severely impacted by climate change and may require collection of seeds for ex-situ conservation or assisted migration to preserve the genetic variability of populations that grow in areas that are predicted to become unsuitable under climate change.

Apart from prioritizing the most suited tree species and areas, to achieve successful restoration, it is also critical to ensure that functional seed systems are put in place (Atkinson et al., 2021). Such systems are crucial to obtain sufficient quantities of genetically diverse and locally adapted planting material, capable to persist under climate change and able to meet the diverse restoration goals. Such seeds should be sourced from areas identified as priority for in-situ conservation in Fig. 4 whenever possible. In countries with large-scale restoration needs, it will be critical to protect remaining seed sources, such as forest fragments but also trees on farms or even in cities (Rimlinger et al., 2021). Further, there may be a need for multilateral collaboration within and across countries to facilitate seed exchange. To ensure long-term success, it is also imperative to involve local people in the decision making of projects (Mansourian and Berrahmouni, 2021).

The maps indicating vulnerability and conservation and restoration actions for the 100 species are available online to facilitate their use by forest practitioners and policy makers: https://tree-diversity.shinyapps.io/vulnerability_central_africa/ and can be downloaded at: https://doi.org/10.6084/m9.figshare.19635996. To further support restoration projects in the region, the distribution maps generated in this study were also integrated into the Diversity for Restoration (D4R) tool, which provides location-specific information on suitable tree species and seed sources for restoration projects: https://www.diversityforrestoration.org/ (Fremout et al., 2021). The D4R tool is currently available for Cameroon and Burkina Faso and will be expanded to other countries in Central Africa. We hope that the maps and results from this study can contribute to inform conservation and restoration projects in Central Africa.

5. Conclusions

In this study, we assessed the vulnerability to climate change, fire, habitat conversion, overexploitation, overgrazing of 100 socio-ecologically important priority tree species and generated maps identifying priority areas for conservation and restoration actions across Central Africa. We found that on average 34% of the distribution ranges of the 100 species is under high to very high vulnerability and 60% under medium to high vulnerability to at least one threat, which calls for actions to protect these species. Many species identified as most vulnerable in this study are not considered as threatened by the IUCN Red List and there are no national assessments for tree species in the Central African countries apart from Cameroon, suggesting a need to update of the IUCN Red List for these countries. The conservation and restoration priority maps are available on a platform online in order to contribute to AFR100 and other conservation and restoration initiatives in Central Africa. The vulnerability mapping methodology used in this study can complement IUCN Red List assessments and inform large-scale conservation and restoration planning.

CRediT authorship contribution statement

V.C.: conceptualization, data collection (threat exposure data, occurrence data, trait data), methodology, formal analysis, writing – original draft; M.E.: data collection (occurrence data, trait data), writing – review and editing, funding acquisition, project administration, supervision; T.F.: conceptualization, formal analysis, methodology, writing – review and editing; H.G.: conceptualization, data collection (threat exposure data), methodology, writing – review and editing; H.W., E.V., K.D.R.: preparation of climatic layers; C.K.: writing – review and editing, funding acquisition; H.T.: data collection (occurrence data, trait data); E.T.: conceptualization, methodology, writing – review and editing, funding acquisition, supervision.

Data availability statement

We stored the data in the figshare platform and this is available at https://doi.org/10.6084/m9.figshare.19635996.

Declaration of competing interest

The authors have no conflict of interests to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2022.109554.

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