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RESEARCH ARTICLE

In situ and ex situ conservation gap analyses of crop wild relatives from Northeast Africa

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Abstract Crop Wild Relatives (CWR) are wild plant taxa closely related to domesticated crops that play a vital role in enhancing crop resilience. This study assessed the conservation status of 97 priority CWR in Northeast Africa through a comprehensive approach, incorporating ecogeographic data and complementarity analysis. The analysis of 4551 occurrence records from 57 CWR highlighted significant gaps in in situ conservation. Notably, the highest number of occurrence records within Protected Areas (PAs) were found in Ethiopia, particularly in Borena National Park, Kafa UNESCO-MAB Biosphere Reserve, and Bonga National Forest Priority Area. However, only 40 taxa (~42%) were identified within existing PAs, with *Solanum campylacanthum* Hochst. cx A. Rich, and *Coffea arabica* L. being the most prevalent. Ecogeographic Land Characterization (ELC) maps identified 45 distinct ecological zones representing the region's diverse habitats. Ex situ analysis revealed 1295 occurrence records from 52 taxa (54%) conserved in genebanks, although only 8% of these taxa were represented by more than 50 accessions. *S. camplyacanthum* and *Avena vaviloviana* (Malz.) Mordv. had the highest number of accessions. Ecogeographical analysis indicated that ELC zones 8, 17, and 18 had the highest frequencies of occurrence in both PAs and genebanks. Complementarity analysis identified 34 potential genetic reserve areas, covering 42 taxa (43%), compared to 33 taxa conserved across 18 PAs identified by coverage analysis. These findings highlight the urgent need for a comprehensive CWR conservation strategy to protect valuable genetic diversity for future crop breeding programs, ultimately enhancing crop resilience in the face of ongoing and future agricultural challenges.

Keywords Conservation · Crop wild relatives · Gap analysis · Genebanks · Protected areas (PAs)

Abbreviations

APGRC	Agricultural Plant Genetic Resources Conservation and Research Centre in Sudan
CWR	Crop wild relatives
ELC	Ecogeographical land characterization
EBI	Ethiopian Biodiversity Institute
FAO	Food and Agriculture Organization of the United Nations
GBIF	Global Biodiversity Information Facility
IUCN	International Union for the Conservation of Nature

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NARI	National Agricultural Research Institute (Eritrea)
PAs	Protected areas
PGR	Plant genetic resources

Introduction

Crop wild relatives (CWR) are wild plant taxa closely related to crops which may possess valuable traits that can be transferred to their related crops and harnessed to enhance the resilience and productivity of our agricultural systems (Maxted et al. 2006). Unlike domesticated crops, CWR have not undergone genetic narrowing, making them crucial sources of adaptable traits, such as resistance to biotic and abiotic stresses, which can improve crop performance in challenging environments (Hajjar and Hodgkin 2007; Heywood et al. 2007; Maxted et al. 2006; Maxted et al. 1997; Prohens et al. 2017). Since the 1980s, CWR have increasingly become a focus of conservation efforts due to their immense potential varietal improve for agricultural production (Meilleur and Hodgkin 2004). However, this diversity is under threat at both taxonomic and genetic levels (Maxted and Magos Brehm 2023), with an estimated 16–35% of CWR taxa classified as Endangered using the IUCN Red List Categories and Criteria (Bilz et al. 2011; Goettsch et al. 2021), and an even more significant threat from genetic erosion (Maxted et al. 2020).

Despite their importance, CWR are frequently under-conserved, with 95% of taxa globally requiring additional collection efforts for ex situ preservation (Castañeda-Álvarez et al. 2016), and no active in situ conservation programs meeting the agreed minimum standards (Iriondo et al. 2008). Rising food demand, population growth, and climate change underscore the need for greater food security, which can be enhanced by broader CWR use in crop breeding (Henry 2009; Tai et al. 2014). As Magos Brehm et al. (2022) suggest, improving in situ conservation for CWR could significantly increase the adaptive genetic diversity available to breeders.

Globally, CWR diversity is concentrated in hotspots that only partially align with general biodiversity or plant diversity hotspots (Vincent et al. 2022). The highest concentration of naturally occurring CWR is found in the region of West Asia and North Africa, which includes Northeast Africa spanning Djibouti, Eritrea, Ethiopia, Somalia, Sudan, and South Sudan (Vincenta et al. 2013). The region is characterized by a rich and variable topography that significantly influences its climate. It includes mountains in Ethiopia and Eritrea, volcanic rift formations, and fertile valleys in the Great Rift Valley in Ethiopia (Asefa et al. 2020; Nyssen et al. 2004a, b). South Sudan is characterized by forests, wetlands, and grasslands (Salih et al. 2013), while the Sudanese and Somali plains stretch between the Sahara and Indian Ocean coasts, respectively, with coastal areas in Djibouti, Eritrea, and Sudan bordering the Red Sea (Abbate and Billi 2022).

The varied elevation and climatic conditions of Northeast Africa have fostered a rich botanical diversity, including a wide variety of crops and intra-crop diversity, and associated CWR of both national and global significance. The region is home to native cereals, pulses, vegetables, forage crops, and fruit trees, and features a high level of endemism driven by its diverse habitats (Darbyshire et al. 2015; Edwards 1991; Nyssen et al. 2004a, b). In the Horn of Africa (Djibouti, Eritrea, Ethiopia, and Somalia), this diversity is especially pronounced, with over 1330 plant species—roughly 24% of the total—classified as endemic (Friis et al. 2005). Additionally, Vavilov (1926) and (Maxted and Vincent 2021) recognize Ethiopia and Eritrea as centers of early crop domestication, underscoring the region's importance in agricultural history and for the retention of unique diversity. The botanical diversity extends into Sudan and South Sudan, where nearly 4000 plant species have been documented (Darbyshire et al. 2015).

In practice, CWR conservation is often focused in Protected Areas (PAs), as these locations: (a) benefit from established conservation practices, (b) are less subject to rapid management changes, (c) can have site management plans adapted for CWR conservation, (d) avoid the prohibitive cost of acquiring non-conservation lands, and (e) already contain many CWR populations (Hunter et al. 2012; Magos Brehm et al. 2022; Maxted et al. 2008, 2016; Vincent et al. 2019). Northeast Africa boasts an extensive network of PAs of 227 (https://www.protectedplanet.net/en), many of which passively protected CWR populations (Maxted et al. 2008). Furthermore, CWR diversity is safeguarded ex situ in genebanks, botanical gardens, and field stations (Braverman 2014; Mounce et al. 2017; Riordan and Nabhan 2019). Passive in situ

conservation is, where populations are maintained in natural environments, without active human management so are more prone to diversity erosion or extinction (Vincent et al. 2019). To address this, active CWR conservation efforts in Northeast Africa need to be evaluated and planned using conservation gap analyses techniques.

Gap analysis identifies geographic areas and genepools that are inadequately represented in current agrobiodiversity conservation actions (Magos Brehm et al. 2017; Maxted et al. 2008; Maxted and Kell 2009). CWR gap analyses have been conducted in various regions, including Europe (Maxted et al. 2015), the Fertile Crescent of the Middle East (Zair et al. 2021), West Africa (Nduche et al. 2022), and the Southern African Development Community (Magos Brehm et al. 2022). However, it is unclear how effective existing ex situ and in situ conservation measures are for safeguarding Northeast Africa's CWR diversity.

Using the priority checklist of CWR for Northeast Africa (Aldow et al. 2023), this study aimed at conducting a comprehensive in situ and ex situ gap analysis for priority CWR in Northeast Africa. It included: (i) assessing their spatial distribution; (ii) identifying suitable areas for genetic reserves, (iii) identifying taxa that are underrepresented in PAs or genebanks; and finally (iv) proposing effective and sustainable conservation strategies for these unique plant genetic resources (PGR) within the region.

Methods

Occurrence data collation, verification, and quality check

Detailed occurrence data for the 97 regional priority CWR in Northeast Africa (Aldow et al. (2023) were compiled using the FAO/Bioversity Multi-Crop Passport Descriptors (FAO 2015), following the recommendations of CAPFITOGEN3 (Parra-Quijano et al. 2023). Data sources were the Global Portal on Plant Genetic Resources (Genesys 2023), the Global Biodiversity Information Facility (GBIF 2023), the International Union for Conservation of Nature (IUCN 2023), and herbarium specimens held in the Royal Botanic Gardens (Kew) (https://www.kew.org/kew-gardens). A total of 4551 occurrence records were collated and georeferenced using Google Maps (https://www.maps.google.com), whenever needed, if they included sufficient geographic descriptions. Geographical coordinates recorded other than decimal degrees were converted using the Canadensys coordinate conversion tool (https://data.canadensys.net/tools/coordinates).

To ensure data quality and avoid redundancy, duplicate occurrence records referring to the same exact record but sourced from different datasets, duplicate herbarium vouchers or accessions from the same population collected by the same person at the same location but held in different institutions, and cultivated populations were identified and removed (Magos Brehm et al. 2017). In addition, geographical records found in neighboring countries were excluded to focus the dataset strictly on the target area. The dataset was further verified using the 'TesTable' tool of CAPFITOGEN3 ((Parra-Quijano et al. 2023), ensuring it was formatted according to the standards. The GEOQUAL tool of CAPFITOGEN3 was then used to evaluate the quality of the collected occurrence data (Parra-Quijano et al. 2023). Records with a total quality (TOTALQUAL 100) of 60% and above were filtered and used in this study to ensure high-quality occurrence records (Cahyaningsih et al. 2021; Magos Brehm et al. 2022; Nduche et al. 2022; Phillips et al. 2016; Zair et al. 2021). The verified dataset was then plotted using the Terra package in R program, version 4.2.3 (R Core Team 2023), to generate occurrence and taxon richness maps and to identify CWR hotspots in the region.

Ecogeographical land characterization

Ecogeographic land characterization (ELC), as outlined by Parra-Quijano et al. (2012a), 2012b), was employed to assess and map ecogeographic variables, helping identify suitable locations for the in situ and ex situ conservation of priority CWR (Brehm et al. 2022; Parra-Quijano et al. 2012a; b). The SelecVar tool from CAPFITOGEN3 was used to select twelve environmental variables (four bioclimatic, four edaphic, and four geophysical) (Table S1) to construct a generalist ELC map describing the adaptive environmental conditions under which CWR are found in the region. An ELC map was created using the ELCmapas tool of CAPFITOGEN3, as it captures the diversity of all the taxa in the region instead

of specific ELC map for each taxon. (Parra-Quijano et al. 2012a, b). This map visualizes the geographic zones with similar environmental conditions. An ELC map with a resolution of 10 × 10 km (about 5 arc-minutes) was generated to illustrate the target region's ecogeographic characteristics, as suggested by Parra-Quijano et al. (2023).

In situ conservation gap analysis

An in situ gap analysis was conducted to identify conservation gaps at both taxon and ecogeographic levels for the priority CWR taxa in Northeast Africa, ensuring comprehensive coverage of geographical variations within the region (e.g., Rodrigues et al. 2004; Langhammer et al. 2007; Magos Brehm et al. 2017).

(1) At the taxon level: the CWR occurrences were plotted onto the PAs map of Northeast Africa using QGIS (QGIS Development Team 2023). PAs maps of each country in the region were obtained from the Protected Planet (https://www.protectedplanet.net/en) and merged into a single PAs map for the entire region. The Northeast African PAs map was then overlapped with the CWR geographical records to identify those records and taxa within and outside the PAs (Khaki Mponya et al. 2021). Additionally, a coverage analysis was integrated into the complementarity analysis using the 'Complementa' tool from CAPFITOGEN3. The coverage analysis assessed the extent to which the existing PAs passively protect the known spatial distribution of target species, identifying conservation gaps where taxa are underrepresented or absent from current conservation efforts, and providing insights on where additional conservation actions may be required (Parra-Quijano et al. 2003).
(2) At the ecogeographical level: CWR regional occurrence records and previously obtained ELC map were analysed in the 'Representa' tool of CAPFITOGEN3. This analysis assesses how well PAs represents the diverse ecogeographic zones across the region. By comparing the CWR distribution with the ELC ecogeographic zones enabled the conservation effectiveness of current PAs to be assessed among with their likely adaptive potential and long-term survival of CWR populations across different habitats.

Complementarity analysis

To identify potential sites for establishing new CWR genetic reserves in the region, the 'Complementa' tool of CAPFITOGEN3 was used to determine complementary areas using 10 × 10 km grids (100 km^2). The concept of complementarity has been employed in biodiversity conservation since the 1970s (Parra-Quijano et al. 2023). Complementarity analysis identifies the minimum number of locations that protect the maximum range of diversity. This method has been applied in countries and regions, such as Finland (Fitzgerald et al. 2023) and Southern Africa (Brehm et al. 2022). This analysis identifies the minimum number of areas required to cover the highest number of CWR taxa across the entire region (Kati et al. 2004; Rebelo and Siegfried 1990). These complementarity genetic reserve sites can be located either within existing PAs, within OECM sites, or in managed sites outside existing protected localities (Magos Brehm et al. 2017).

Ex situ conservation gap analysis

Ex situ conservation gap analysis identifies deficiencies or inadequacies in the representation of taxa or populations within ex situ facilities such as genebanks, botanical gardens, and seed banks. The analysis was conducted at both taxon and ecogeographic levels for those taxa with existing ex situ accessions (Maxted et al. 2007; Parra-Quijano et al. 2012a, b).

(1) At the taxon level: gaps in ex situ conservation were identified by comparing the ex situ accession map with all the occurrence records in the region to identify areas where taxa were found in the wild but were not represented in ex situ collections. The 'Representa tool' of CAPFITOGEN3 was used to assess the representativeness of the ELC categories in the geographical records. The ex situ accession data and the frequencies of ELC zones were compared with all other data showing population presence (Parra-Quijano 2016; Parra-Quijano et al. 2023).
(2) At the ecogeographic level: the 'Representa tool' of CAPFITOGEN3 was used to assess the representativeness of the ELC categories/zones within the ex situ collections. The ELC frequencies of the ex situ accessions of each taxon were com-

pared with the overall ELC frequencies of the taxon's distribution range (Parra-Quijano 2016; Parra-Quijano et al. 2023). The ELC map classified to four quarters low, mid-low, mid-high, high based on ELC map frequencies of zones from which CWR accessions were collected for ex situ conservation generated by 'Representa tool' of CAPFITIGON3. Zones with no occurrence records were classified as Null (Parra-Quijano 2016; Parra-Quijano et al. 2023).

Results

Overview of data and distribution of CWR in Northeast Africa

Out of 5003 occurrence records collated, only 4551 geographical occurrences (~91%) were considered valid after data quality checks. These valid records covered 57 taxa out of the 97 priority taxa. Ethiopia had the highest number of occurrences, with 3459 records (~76%), followed by Eritrea with 409 (9%), Sudan with 292 (~6%), Somalia with 124 (~2.7%), and Djibouti with 18 records (~0.04%) (Fig. 1). High concentrations of CWR occurrences were identified in several regions, including the Central Region of Eritrea to the South Region border with Ethiopia, Imatong Mountain in South Sudan, Southwest (Darfur) Sudan, and Southwest Ethiopia. These areas corresponded to three CWR hotspots that were identified in the Harar region of Ethiopia, North Shewa (Oromia Region), and Adwa (Tigray region), as well as one hotspot in the Central Region of Eritrea (Figs. 1 and 2). The taxa with the highest number of occurrences were *Avena abyssinica* Hochst (816), *Solanum campylacanthum* Hochst. cx A. Rich (455), *Avena vaviloviana* (Malz.) Mordv (452), and wild *Coffea arabica* L. (299) (Table S1).

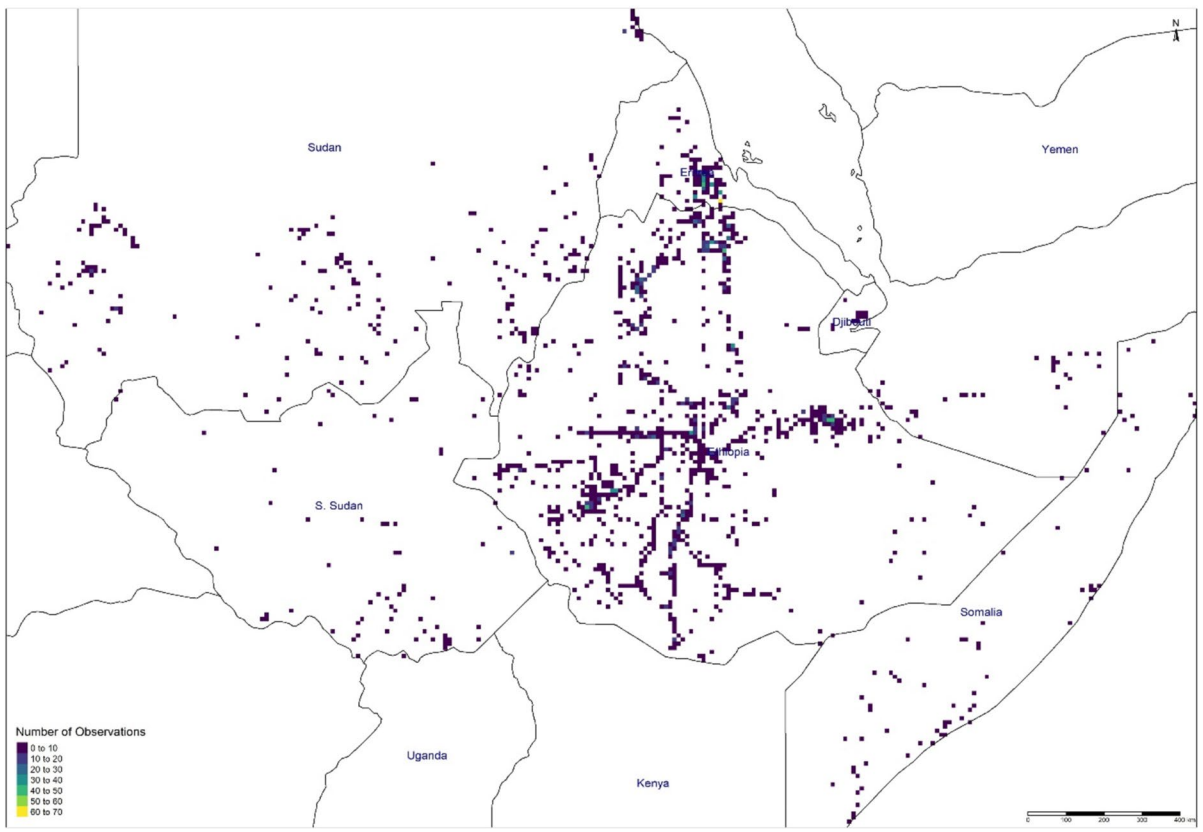


Fig. 1 Occurrence map of 57 priority crop wild relatives (CWR) taxa per grid cell at a 0.1 × 0.1 degree resolution across Northeast Africa

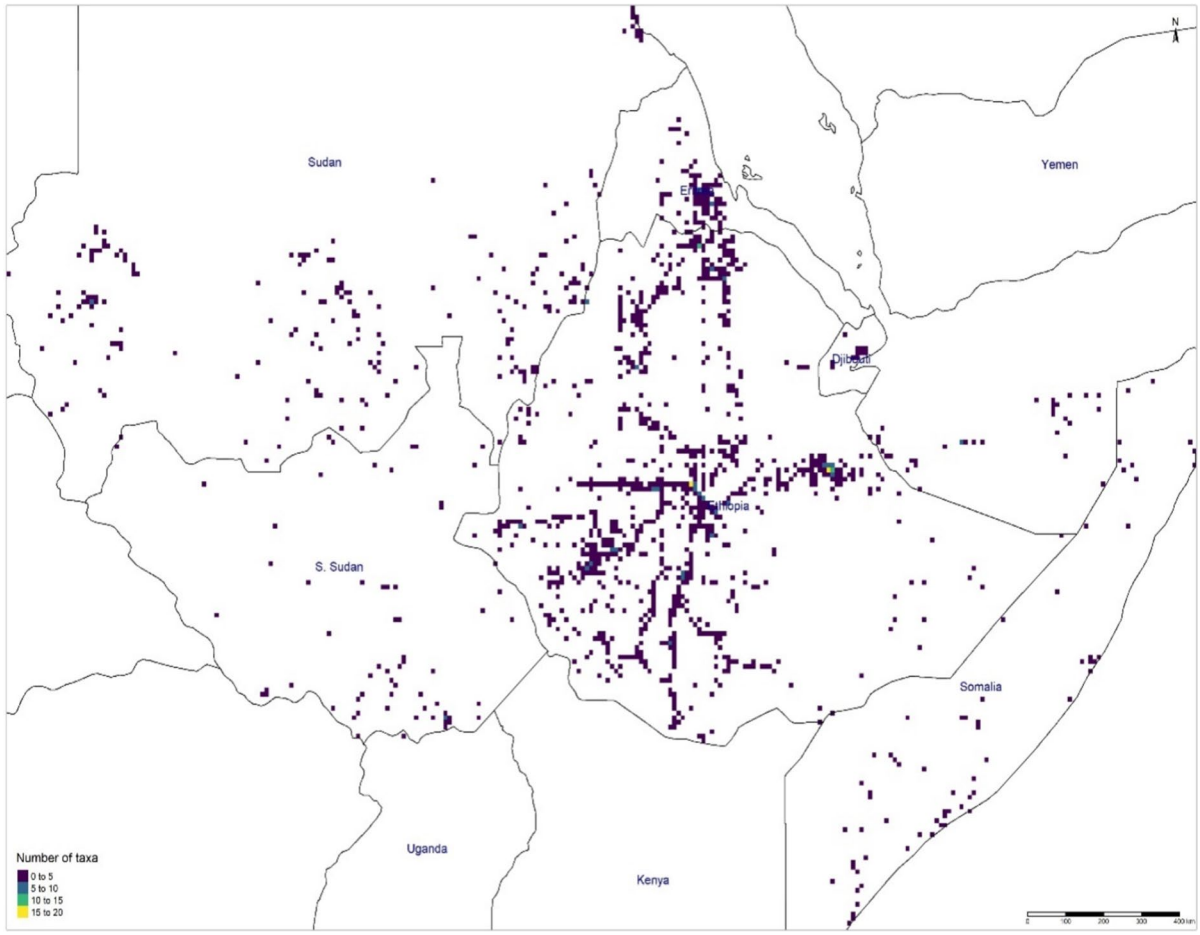


Fig. 2 Taxon richness map for 57 priority crop wild relatives (CWR) across Northeast Africa, with a grid resolution of 0.1 × 0.1 degrees

Ecogeographic land characterization map

The Northeast Africa generalist ELC map included 45 ELC zones representing the ecogeographic diversity in the region (Figure S1). Thirty-three out of the 45 ELC zones were represented by occurrence records, with only 13 (~28.9%) of these zones containing records within PAs. Priority CWR were unequally distributed across the ELC zones in the region, with ELC zones 17, 8, and 18 had the highest number of frequencies in both PAs and genebanks (Figure S2 and Table S2). Species such as *Solanum incanum* L, *S. campylacanthum,* and *Echinochloa colona* (L.) Link occurred in the highest number of different ELC categories in genebanks (Table S3).

In situ gap analysis

Forty taxa (42%) with 499 geographical records (~11% of the total) were present within PAs, with 469 records (~94%) located in Ethiopia (Table S4). Two taxa, *S. campylacanthum* (126 records) and *C. arabica* (125 records), accounted for approximately 50% of all occurrences within PAs (Table S5). Ethiopia stands out as the country in the region with the highest number of occurrence records in PAs. The Ethiopian PAs with the most occurrence records were Borena National Park (65 records), Kafa UNESCO-MAB Biosphere Reserve (45 records), Bonga National Forest Priority Area (33 records), Eastern Hararghe (Harar-Wabi Shebelle) Controlled Hunting

Area (25 records), and Menagesha-Suba National Forest Priority Area (25 records) (Table S4).

In terms of diversity, the PAs with the greatest number of taxa were the Arsi Mountains National Park (10 taxa), and Kafa UNESCO-MAB Biosphere Reserve (6 taxa) in Ethiopia (Table S4). Coverage analysis identified 18 PAs (Fig. 3) that currently passively conserve 33 of the 40 taxa found in PAs. The most frequently conserved taxa across these PAs were *S. campylacanthum*, *C. arabica*, *S. glabratum*, and *S. incanum* (Table S6). The study also revealed that the 18 PAs identified were distributed exclusively in Ethiopia (15 PAs) and South Sudan (3 PAs). The PAs were ranked by taxa diversity, with Arsi Mountains National Park having the highest diversity (Table S7).

Complementarity analysis

In Northeast Africa, the complementarity analysis identified 34 complementary cells (10 km^2) across all countries (Figure S3). These cells encompassed 42 out of 57 taxa (43%) and corresponded to 1295 occurrence records, capturing a significant portion of the regional CWR diversity. Species richness within these grid cells varied, with the highest cell containing up to 12 taxa. Complementarity analysis revealed that taxa in each grid cell were distinct, with subsequent cells containing additional taxa not represented in the earlier cells, ensuring minimal overlap and maximizing conservation coverage (Table S8). Ethiopia had the highest number of potential reserve sites (18), whereas Djibouti and Eritrea had only one each (Figure S3). The most frequently recorded CWR within these potential genetic reserves were S. *campylacanthum* (317 records), *A. abyssinica* (189 records), and *S. incanum* (122 records) (Table S9).

Ex situ gap analysis

Out of the 97 priority taxa, 52 taxa (54%) had at least one accession conserved ex situ, with the total number of 1295 accessions existing in genebanks. Only 8 taxa (8%) were represented with at least 50 accessions or more, while 44 taxa (45%) are underrepresented

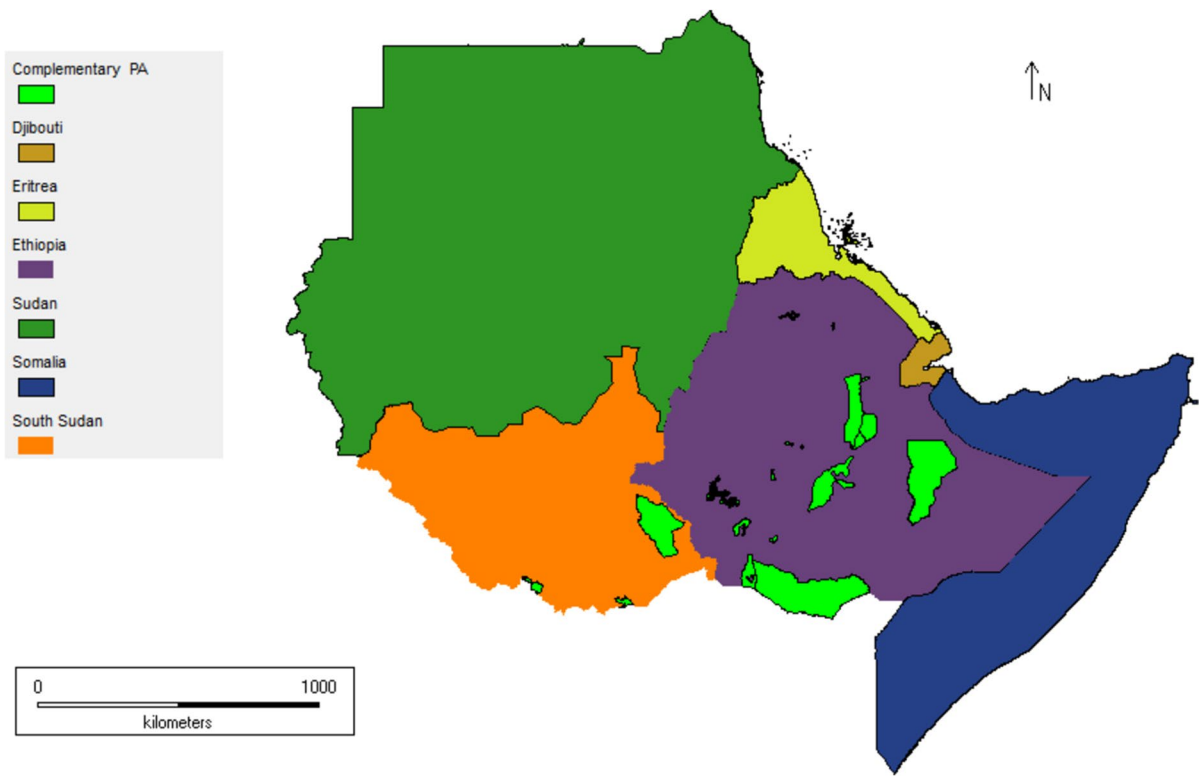


Fig. 3 Identified complementary Protected Areas (PAs) of the crop wild relatives (CWR) in Northeast Africa

with fewer than 50 accessions (Table S10). Most of these accessions were conserved outside of the region in international genebanks, such as the University of Colorado Museum of Natural History and the Royal Botanic Gardens (Kew). Accessions were also conserved in three national genebanks: the University of Hargeisa Herbarium in Somaliland (https://www.gbif.org/dataset/e1966d34-2144-4a07-a6d4-b246d6f047aa), Ethiopian Biodiversity Institute (EBI) (https://www.genesys-pgr.org/wiews/ETH085), and Agricultural Plant Genetic Resources Conservation and Research Centre in Sudan (APGRC) (https://www.genesys-pgr.org/wiews/SDN002), as well as the international genebank in the International Livestock Research Institute (Ethiopia).

The taxa with the highest number of accessions in genebanks were *S. campylacanthum* (113 accessions), *A. vaviloviana* (101 accessions), and *S. incanum* (90 accessions). Some taxa, such as *Carthamus persicus* Desf. ex Willd and *Gossypium anomalum* Wawra & Peyr, Verdc, had only one accession, while others like *C. lanatus*, *Lactuca serriola* L, and *Oryza barthii* A. Chev. had only two accessions each in genebanks. The genera, *Avena* and *Solanum* had the highest number of taxa represented in both local and international genebanks (Table S10).

Ecogeographic diversity analysis showed that only 27 (60%) out of 45 ELC zones were represented in genebanks. The most frequent ELC zones were zone 17 (41 frequences), zone 8 (28 frequences), and zone 18 (22 frequences) (Table S11). Eight taxa, including *Carthamus lanatus* L, were represented in only one ELC zone, while 43 taxa were not represented at all in ELC map (Table S3). Both ex situ and in situ conservation analyses identified 45 taxa that were neither conserved in genebanks nor passively conserved in PAs. These included important crops for food security, such as wild relatives of yam, teff, oat, and sorghum (Table S12).

Discussion and conclusion

The analysis of 97 priority CWR taxa in Northeast Africa revealed critical gaps in conservation efforts. In a region of existing food insecurity, periodic droughts and where there is predicted increased threat from climate change on food production, effective PGR conservation and use is of existential importance to its population. Only 57 taxa had sufficient occurrence data to undertake gap analyses, and only ~ 42% of them are represented in existing PAs and ~ 54% are conserved in genebanks collections, which remain insufficient to ensure their long-term conservation. These findings underscore the urgent regional and national priority to expand in situ and ex situ strategies and their full implementation measures which address the region's unique biodiversity and challenges.

Biased in occurrence records was minimized by selected high-quality data using the GEOQUAL tool in CAPFITOGEN3. However, scientific collections are often opportunistic and expedient, with samples frequently taken from more accessible locations, such as roadsides or areas near human settlements (Parnell et al. 2003; Peterson et al. 1998). Although CWR are known to favor such habitats (Jarvis et al. 2015), there is still likely to be some proximity bias to researchers' residences further concentrating the sampling near these areas (Dennis and Thomas 2000). This creates spatial gaps that neglect less accessible areas or regions that may have substantial diversity (Parnell et al. 2003; Whittaker et al. 2005). Addressing these biases is crucial, and future ex situ collection efforts should target under-sampled areas and diverse habitats to improve the representativeness of occurrence records.

The presence of several CWR within existing PAs is promising. However, effective management and monitoring programs are vital to ensure their long-term survival. Incorporating CWR into PAs management plans is essential, as demonstrated by the successful conservation of *Cinnamomum capparucoronde* Blume, an endemic wild relatives of cinnamon in Sri Lanka (Heywood 2008; Hunter et al. 2012), or PAs in situ conservation of cowpea wild relatives in Africa (Moray et al. 2014).

Analysis of PAs data reveals a higher frequency of unique ELC zones of predicted high CWR genetic diversity found outside their boundaries, 34 zones compared to 13 within PAs. This suggests the potential to expand in situ conservation efforts into these underrepresented areas. However, CWR taxa are often found in disturbed, anthropogenic habitats, like roadsides (Jarvis et al. 2015), which may be rare in PAs consisting of climax communities. Ethiopia, with its higher number of overlapping PAs and CWR hotspots, offers significant opportunities for targeted

conservation efforts. Furthermore, Southwest Ethiopia, identified by Maxted and Vincent (2021) as a major global CWR hotspot, emphasizes the region's importance for conservation. A region-wide approach that considers the broader landscape is essential for the successful conservation of CWR.

Ex situ conservation, particularly through genebanks, is the tried and tested means of safeguarding against unexpected threats such as natural disasters, political instability, and has historically provided 99% of active CWR conservation (Ford-Lloyd and Maxted 1993; Maxted et al. 2006, 2012). The 57 taxa (56%) lacking ex situ conservation necessitate urgent collection efforts, especially in Ethiopia, which holds 76% of the region's CWR occurrences (Luis et al. 2005).

Targeted collection for underrepresented taxa, such as *Gossypium stocksii* Mast. and *Solanum marginatum* L. f., is essential. A systematic approach to duplicating genebank accessions, as recommended by FAO (2009) and ENSCONET (2009), FAO (2014), and others (Brehm et al. 2022; Rao et al. 2006), will bolster CWR conservation outcomes. Strengthening genebank capacities and data sharing remains crucial for addressing gaps in CWR representation and ensuring their availability for future use.

Comprehensive field surveys across the entire Northeast African region are essential to fully understand the distribution of all 97 priority CWR taxa and to inform targeted conservation strategies. These surveys will support both in situ and ex situ conservation efforts, ultimately ensuring the long-term security of these invaluable genetic resources. The limited occurrence records in PAs, excluding those in Ethiopia, negatively impacts our ability to assess taxon richness, identify potential reserve sites, and determine complementary PAs networks. Nevertheless, this research aims to serve as a foundational baseline for future research and conservation efforts targeting priority CWR in the region. We urge PAs managers and researchers to fully document CWR in these areas and establish long-term monitoring programs. Together, in situ and ex situ conservation strategies provide complementary approaches to secure the genetic diversity of CWR for future use.

The poor representation of CWR taxa (54% have no accessions in national and regional genebanks), not only necessitates immediate collection efforts but also highlights the need for monitoring under-conserved populations. Genebank collections globally hold limited CWR, estimated at only 2% to 18% of total accessions (Astley 1991; FAO 2009; Hammer et al. 2003; Maxted and Kell 2009). This gap stems from lower prioritization of CWR, regional conflicts, and limited data accessibility in national genebanks (Iriondo et al. 2011). To address these challenges, prioritizing CWR within conservation agendas, strengthening genebank capacities, and improving data sharing for informed conservation is essential (Engels and Ebert 2021; FAO 2010). Given Northeast Africa's rich CWR resources, an integrated in situ and ex situ conservation approach is essential (Hajjar and Hodgkin 2007; Heywood et al. 2007; Khoury et al. 2010; Maxted et al. 2007; Maxted and Kell 2009).

Enhanced access to CWR for breeding and research is crucial to developing resilient crops (Dempewolf et al. 2014; Maxted et al. 2013), particularly those with high crop improvement potential identified in the region (Aldow et al. 2023). Unless CWR diversity is adequately conserved and made accessible to users, it cannot deliver its potential benefits to humanity. Furthermore, in a region such as Northeast Africa, where poverty, malnutrition, and even starvation are prevalent, failing to conserve these vital resources, which are key to varietal improvement and food security, could be considered inexcusable neglect. Following a global analysis of priority CWR, Maxted and Kell (2009) proposed global CWR conservation priorities that included targeted additional population sampling for ex situ conservation and the establishment of 34 new in situ genetic reserves. Within these priorities, they suggested extensive collecting throughout the region and setting up six genetic reserves for priority CWR in the Northeast Africa region. We reiterate these suggestions and provide further justification and clear recommendations to support this critical initiative for the region.

Recommendations

1. Ground truth predicted high priority sites for genetic reserves identified in the in situ gap and climate change analysis (Aldow et al., In preparation.) and, if suitable, establish CWR genetic reserve in collaboration with local stakeholders at:

a. Priority site 1: Ethiopian highland extending north to the Eritrean border.
b. Priority site 2: Western Sudan border adjoining South Sudan.
c. Priority site 3: Southern Somalia.

2. Sample targeted CWR population identified by the ex situ gap and climate change analysis (Aldow et al., In preparation.). Duplicate collections in national and regional genebanks are recommended; high-priority taxa for further collection and ex situ storage include:

a. *Oryza longistaminata* A. Chev. & Roehr.
b. *Cucumis pustulatus* Naud. ex Hook.f.
c. *Cucumis dipsaceus* Ehrenb. ex Spach.
d. *Eleusine africana* K. Obyrne.

3. Build up existing national genetic resource centers and establish Genetic Resource Centers (GRCs) in Somalia and South Sudan, dedicated to both ex situ and in situ conservation of PGR where they are currently absent, to enhance the efficiency of national CWR conservation and use activities.
4. Ensure all conserved CWR resources, whether conserved ex situ or in situ, are characterized, evaluated, and made readily accessible to users.
5. Build relationship between national breeders and Consultative Group on International Agricultural Research (CGIAR) centers with regional crop interests to produce CWR pre-bred lines that can be fed into national and CGIAR crop improvement programs.
6. Establish national and regional CWR Conservation and Use Strategies and Action Plans that can be reviewed and updated periodically, along with a financial plan to ensure effective implementation.
7. Create a regional CWR conservation network for national genebanks and genetic reserves that oversees and encourages collaboration with other regional and international GRCs, universities, and research institutions to improve documentation, conservation, and knowledge exchange.
8. Collaborate with international organizations, such as the Food and Agriculture Organization of the United Nations (FAO) and CGIAR Centers, to establish an appropriate policy context for CWR conservation and to benefit from their expertise and resources for CWR conservation in Northeast Africa. These programs should include genebanks, PAs authorities, indigenous and local people, as well as other important regional and national stakeholders.
9. Investigate the potential for citizen science in Northeast Africa to support formal PGR and CWR conservation and raise awareness of the value of PGR conservation to food and nutritional security.

Core ideas

1. A significant gap exists for Crop wild relatives (CWR) diversity conservation in Northeast Africa, with 46% of regional priority CWR lacking both in situ conservation and ex situ collections.
2. Current in situ assessments reveal that only 42% of priority CWR are found within Protected areas (PAs), underscoring the need for expanded conservation efforts within these areas.
3. Review of ex situ conservation identified 54% of priority CWR with the total number of 1295 accessions in genebanks in the region, of which only 8% are represented by more than 50 accessions.
4. Complementarity analysis identified 34 potential genetic reserve sites, covering 43% of priority CWR in Northeast Africa.

Author contributions Ahmed Aldow: Conceptualization; designed the study; data curation; formal analysis; investigation; methodology; resources; validation; visualization, writing—original draft; writing—review & editing. Joana Magos Brehm: Helped design the study and draft the paper. Hannes Gaisberger: Methodology design and validation. Nigel Maxted: Helped design the study and draft the paper.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no conflict of interest.

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