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Towards the establishment of genetic reserves for key crop wild relatives in Lebanon: Analysis of strategies across diverse ecogeographical landscapes

Eliane Sayde [a,1], Mariana Yazbek [b,2], Cecilia Zucchini [a,3], Lamis Chalak [c,4], Valeria Negri [a,5], Lorenzo Raggi [a,6,*]

[a] *Dipartimento Di Scienze Agrarie, Alimentari E Ambientali, Università degli Studi di Perugia, Borgo XX Giugno 74, Peugia 06100, Italy*
[b] *International Center for Agricultural Research in Dry Areas (ICARDA), Beirut, Lebanon*
[c] *Department of Plant Production, Faculty of Agronomy, Lebanese University (LU), Beirut, Lebanon*

A R T I C L E I N F O

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A B S T R A C T

This study aims to identify best areas for the establishment of a genetic reserves network in Lebanon to achieve the *in situ* conservation of 35 targeted CWR taxa belonging to *Aegilops* L., *Triticum* L., *Avena* L., *Hordeum* L., *Cicer* L., *Lens* Mill. and *Pisum* L. CWR occurrence were analysed taking advantage of the CAPFITOGEN3 toolbox. A generalist Ecogeographical Land Characterization map (ELC-map) was generated the combination of CWR taxon populations with each defined ELC category (namely "CWR-Eco unit") was then identified and considered as main conservation target. Two different complementarity analyses were performed to identify the minimum number of sites required to conserve the maximum number of CWR-Eco units inside and outside protected areas. The gap existing in *ex situ* conservation of the target CWR diversity was estimated by comparing the unique CWR-Eco units conserved in genebanks with those occurring in the wild. A total of 24 ELC categories were defined for Lebanon harboring 253 different CWR-Eco units from a total of 1460 CWR populations. According to complementary analysis results, 22.2 % of the considered protected areas harbor populations of 18 target CWR taxa (51.4 % of the total). A network of 79 cells (5 × 5 km each) is required for the conservation of the whole predicted diversity of taxa not included in the 6 identified protected areas. A total of 215 CWR-Eco units (85.0 % of the total) are covered by *ex situ* conserved material.

1. Introduction

The conservation of global biodiversity, in the context of climate change, has been increasingly assessed as crucial. Recently many

* Corresponding author.
E-mail address: lorenzo.raggi@unipg.it (L. Raggi).
[1] ORCID: 0000-0002-1468-9019.
[2] ORCID: 0000-0001-8610-3809.
[3] ORCID: 0009-0005-4726-3208.
[4] ORCID: 0000-0003-1301-982X.
[5] ORCID: 0000-0003-2941-121X.
[6] ORCID: 0000-0003-0484-8669.

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studies have disclosed the gradual loss of plant diversity in forests and damage in habitats, highlighting the urgent need for effective conservation efforts (Riva et al., 2022). Crop wild relatives (CWR), which are the wild plant species that are closely related to cultivated crops, are among the key elements of this biodiversity (Perrino and Perrino, 2020). Part of biodiversity, CWR are also an important source of genetic diversity for crop improvement (Maxted et al., 2008). Indeed, CWR play an essential role in attaining food security and sustaining agricultural production, particularly in the face of climate change and other environmental challenges (Dempewolf et al., 2017; Hajjar and Hodgkin, 2007; Maxted et al., 2010; N. Maxted et al., 2020; Vincent et al., 2013). Their conservation and adequate utilization in plant breeding is essential in developing new crop varieties that can better tolerate extreme conditions, in comparison to current ones, and thus ensure a more stable food supply for a growing population.

It is increasingly clear that *ex situ* conservation techniques (e.g., the conservation of seed samples in genebanks) alone are insufficient to meet breeder's needs for diversity that is necessary to mitigate the impact of climate change on agriculture (Lobell et al., 2008); *in situ* conservation of CWR, which involves the conservation of the populations in their natural habitat (CBD, 1992), is also necessary and needs to be rationally planned. One of the most efficient ways to implement this approach is the establishment of genetic reserves (i.e. managed areas) within existing protected areas (PA) as they already receive some legal protection. Indeed, a system of protected areas is the basis for CWR *in situ* conservation strategies of many different countries (Heywood and Dulloo, 2005; Iriondo et al., 2008; Maxted et al., 2000a, 2000b, 2000c, 2000d; Vincent et al., 2012) and has been also proposed for Europe (Labokas et al., 2018; Maxted, 2003), in particular for *Aegilops* L. in Italy (Perrino and Wagensommer, 2021; Perrino et al., 2014) and major wild cereals in the Mediterranean Basin and West Asia (Phillips et al., 2019).

However, adequate CWR conservation in PAs is a challenging task due to insufficient resources and funding, inadequate understanding of CWR populations and potential conflicts between the objectives of conservation and development (Heywood, 2018). In many cases, modifying existing management plans could be sufficient to improve the CWR conservation without the costs associated with establishing new protected areas from scratch (Magos Brehm et al., 2019; Maxted et al., 2008). Finally, because CWR taxa are commonly found in disturbed anthropogenic environments, and less frequently in the climax community often designated as conventional PAs, it is important to consider sites both inside and outside existing PAs for the establishment of genetic reserves (Jarvis et al., 2015).

Urgent action is needed to address gaps in conservation and collaborate with breeders to adapt cultivation improvement programs (Dempewolf et al., 2014; Engels and Thormann, 2020). This includes conserving threatened CWR *in situ*, addressing gaps in germplasm conservation, informing Plant Genetic Resources (PGR) conservation plans and activities and aligning with policy and legislative frameworks (Maxted and Magos Brehm, 2023).

Ecogeographic land characterization (ELC) maps are a tool that can be of service to breeders to employ the adequate utilisation of germplasm, as they help to describe different potential environmental conditions for plant taxon adaptation to assess the representation of the ecogeographic variability and to identify potential sites for *in situ* conservation and *ex situ* collection (Castañeda-Álvarez et al., 2011; Parra-Quijano et al., 2007, 2012). This approach justifies *in situ* conservation efforts, establishment of germplasm collections with minimal ecogeographic redundancy, evaluation of ecogeographical representativeness in germplasm collections and detection of gaps as well as elaboration of core collections.

Lebanon, identified among the world's richest country in CWR diversity (Vincent et al., 2013) and primary hotspot for CWR food plant species diversity (Vincent et al., 2019), is an interesting case study for studies towards the development of a comprehensive CWR conservation plan. With a total of 27 recognized PA, 10 of which include a routinely management effectiveness evaluations (UNEP-WCMC and IUCN, 2020), and more than 25 designated Important Plant Areas (IPAs), Lebanon still faces challenges threatening the CWR richness it houses (Bou Dagher-Kharrat et al., 2018; Talhouk et al., 2017).

In this study we identified and proposed the establishment of a genetic reserves network in Lebanon, both within and outside existing protected areas to achieve the *in situ* conservation of 35 targeted CWR taxa belonging to *Aegilops* L., *Triticum* L., *Avena* L., *Hordeum* L., *Cicer* L., *Lens* Mill. and *Pisum* L. Specifically, the principle of complementarity (Rebelo and Siegfried, 1990) was applied to identify and select a minimum number of protected sites rich in CWR diversity to protect as much genetic diversity as possible both inside and outside PA. Gaps in *ex situ* conserved diversity of target CWR taxa were also identified.

2. Material and methods

2.1. Target taxa and target area (geographic)

The work focuses on targeted CWR diversity in Lebanon. In particular, the CWR taxa that are target of this study have been already identified, prioritized (based on taxa relevance for Lebanese economy and world food security, level of fertility with the corresponding crop and genome type), and inventoried in Sayde et al. (2023). The taxa belong to the families of *Poaceae* and *Fabaceae* and to the genera of *Aegilops* L., *Triticum* L., *Avena* L., *Hordeum* L., *Cicer* L., *Lens* Mill. and *Pisum* L.

2.2. Data acquisition

Records of populations distribution of priority taxa utilized in this study were retrieved from Sayde et al. (2023, 2024a), which consists of a compilation of records of occurrences collected and conserved in genebanks, obtained from GENESYS, records of populations that occur in the wild, obtained from GBIF, and from field surveys carried out in 2022 and 2023. Data from GENESYS and GBIF databases went already through a quality control following the cleaning process described in Rubio Teso et al. (2020a,b). In brief the cleaning was based on several steps where records whose coordinates do not match with the country borders or inaccurate localities have been removed, as well as records coming from untrusted sources; additionally records dated before 1950 were also removed and duplicates simplified keeping the records with locality field information, most recent and informative. More details on the procedure can be found in Sayde et al. (2023).

2.3. CAPFITOGEN toolbox

The CAPFITOGEN3 toolbox (Parra Quijano et al., 2021) is a set of tools (i.e. scripts) designed to analyse spatial and ecogeographic diversity for the conservation and sustainable use of plant genetic resources (http://www.capfitogen.net/en/). In the present study all the analyses carried out using CAPFITOGEN3 were performed in 'local mode' in R ("R Development Core Team," 2022) here after the word "tool" always refers to the different tools of the CAPFITOGEN3 toolbox.

2.3.1. Data quality assessment

The dataset, consisting of 1460 records after quality control, was formatted with conformity to the data template required by the CAPFITOGEN3 tool which makes use of the FAO-Biodiversity's multi-crop descriptor (FAO-BIOVERSITY 2015). The results of the formatting eligibility were analysed and data was corrected with *TesTable* tool, which allows to prepare of the data to be used in the different tools of CAPFITOGEN3. The general quality of the records in the dataset was assessed using *GEOQUAL* tool which results are summarized by the *TOTALQUAL100* parameter; a threshold of ≥ 50 was used to select occurrences to be included in further analyses.

2.3.2. Ecogeographic land characterization map

A generalist Ecogeographical Land Characterization (ELC) map was generated to identify the main ecogeographic condition of the Lebanese territory. The different ecogeographic conditions and landscape scenarios were revealed using *ELCmapas* tool (Parra-Quijano et al., 2012). *SelectVar* tool was initially used to identify the most relevant variables belonging to bioclimatic, geophysics, and edaphic groups of ecogeographical components taking advantage of the Random Forest Classification (RFC) (Cutler et al., 2007). In the *SelecVar* tool, utilized for the variable selection procedure, the distribution of all target taxa was considered so to create a comprehensive ELC map that characterizes the Lebanese landscape as a whole. This map is not specifically tied to the adaptive scenarios of individual taxa, but rather reflects the diverse ecogeographic conditions found throughout Lebanon.

The generalist ELC map of Lebanon was then generated using the identified variables and the "*elbow*" calculation method into *ELCmapas*. Differences among ELC categories and correlations among the means of the environmental variables were analysed using a Principal Components Analysis (PCA) in R software. The first two PCA axes were displayed in a biplot where the projection of the original variables was included as implemented in the package 'factoextra' (Kassambara, 2016). The "cos2" value was also calculated and displayed for each ELC category and variable.

2.3.3. Creation of CWR-Eco units as indicators of genetic diversity of CWR taxa

The concept of CWR-Eco units, applied in this study, refers to the combinations of each CWR taxon with each of the ELC categories corresponding to the sites where their populations occur (Rubio Teso et al., 2021). The assignment of the populations to the ELC categories of the map was performed with the *Representa* tool in CAPFITOGEN3. The different CWR-Eco units represent the potentially different genetic diversity comprised by the populations of a given CWR. The occurrences that were assigned to ELC_0 category, due to their proximity to the borders or coast, were given a different ELC category by manually checking their distribution on QGIS and attributing it to the adjacent category. For those cells where an ELC category was not assigned due to lack of variable data, the ELC category was assigned by extracting values from the nearest cell.

2.3.4. Complementarity analysis for in situ conservation

Complementarity analysis, based on Rebelo's iterative method (Rebelo and Siegfried, 1990), was performed to identify the minimum number or sites required to conserve the maximum number of CWR-Eco units. To this purpose, areas most rich in terms of number of target CWR taxa and ecogeographic diversity, were used as a proxy for genetic diversity and estimated according to the adaptive scenario where populations occur based on the ecogeographic approach (Parra-Quijano et al., 2012), were identified.

A first complementarity analysis was conducted aiming at identifying priority areas for establishing genetic reserves within the current network of protected areas. The analysis required the distribution of CWR-Eco units and the perimeter of PA: the former was retrieved from the results of *Representa* tool, while the latter from World Database on Protected Area (WDPA, https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA).

A second complementarity analysis was performed to identify the minimum set of 2.5 arc-min cell (approximately 5 $\times$5 km) so to cover all the CWR-Eco units not included in the network of PA identified in the first analysis (Magos Brehm et al., 2022).

2.4. In situ vs ex situ diversity

The gap in *ex situ* conservation of the target CWR diversity was estimated by comparing the unique CWR-Eco units conserved in genebanks with those occurring in the wild in Lebanon. The entry database was divided in two sections: 1) "*In situ database"* encompasses entries retrieved from GBIF and field surveys achieved between 2022 and 2023; "*Ex situ database"* includes entries retrieved from GENESYS, representing populations conserved *ex situ*. The distribution of *in situ* and *ex situ* CWR-Eco units was compared and *ex situ* gaps identified for each CWR-Eco combination. This analysis will help identify the target CWR diversity that still needs to be conserved *ex situ*.

3. Results

3.1. Target taxa and populations distribution

3.1.1. Target Taxa and data quality analysis

A list of 35 different CWR taxa represented by a total of 1460 populations (Table S1, Supplementary materials). was compiled from the results of the cleaning and inventorying outcomes described in Sayde et al. (2023) and Sayde et al. (2024a) (Table 1). According to *GEOQUAL* analysis results, all population records scored a *TOTALQUAL100* value over 50 and none of them was discarded.

With 557 populations belonging to 15 taxa *Aegilops* genus is the most represented followed by *Hordeum*, *Triticum* and *Avena* represented by four different taxa each and including 331, 222 and 179 populations, respectively. Both *Lens* and *Cicer* are represented by three taxa including 108 and 28 populations, respectively. With two taxa only, and a total of 35 populations, *Pisum* has the lowest taxa representation among all the considered genera (Table 1).

3.1.2. General distribution of populations

The distribution of CWR amongst the governorates was heterogeneous: Bekaa had the highest number of population (576) belonging to 24 different taxa, followed by Baalbak-El Hermel (442 populations of 29 taxa) and Mount Lebanon (237 populations of 28 taxa). The other governorates were represented by smaller numbers of target CWR populations: the North governorate (84 populations of 16 taxa), the South governorate (45 populations of 12 taxa), Akkar (31 populations of 8 taxa), El Nabatieh (31 populations of 11 taxa) and lastly Beirut (14 populations of 8 taxa).

Populations of the considered key taxa are quite widespread across the Lebanese country (Fig. 1). In particular, *Hordeum spontaneum* K.Koch (180 populations), *Aegilops geniculata* Roth (139), *Aegilops biuncialis* Vis. (134), *Avena sterilis* L. (132), *Hordeum bulbosum* L. (105), *Aegilops triuncialis* L. (94), *Aegilops peregrina* (Hack.) Maire & Weiller (39) and *Lens ervoides* (Brign.) Grande (36) show a very wide distribution across various regions. In contrast, *Aegilops speltoides* Tausch (13) and *Aegilops sharonensis* Eig (4) are restricted in the coastal zones, from the North to the South of Lebanon. *Lens culinaris* Medik. subsp. *orientalis* (Boiss.) Ponert (56 populations), *Triticum urartu* Thumanjan ex Gandilyan (47), *Lens culinaris* Medik. subsp. *culinaris* (26), *Triticum boeoticum* Boiss (13) and *Aegilops searsii* Feldman & Kislev ex K. Hammer (6) populations are restricted to the internal plain of Bekaa and Baalbek-El Hermel. Even more

Table 1
Number of populations of the target CWR taxa after data cleaning, divided according to the source database.

CWR taxa	GBIF	GENESYS	Survey	TOTAL
Aegilops biuncialis Vis.	8	48	78	134
Aegilops caudata L.	5	14	2	21
Aegilops columnaris Zhuk.	11	28	17	56
Aegilops crassa Boiss ex Hohen.	0	1	0	1
Aegilops cylindrica Host	1	16	1	18
Aegilops geniculata Roth	23	56	60	139
Aegilops kotschyi Boiss	0	11	0	11
Aegilops peregrina (Hack.) Maire & Weiller	16	23	0	39
Aegilops searsii Feldman & Kislev ex K. Hammer	2	4	0	6
Aegilops sharonensis Eig	4	0	0	4
Aegilops speltoides Tausch	8	5	0	13
Aegilops triuncialis L. subsp. *triuncialis*	11	48	35	94
Aegilops umbellulata Zhuk.	1	7	0	8
Aegilops uniaristata Vis.	0	2	0	2
Aegilops vavilovii (Zhuk.) Chennav	2	9	0	11
Avena barbata Pott ex Link	18	11	9	38
Avena eriantha Durieu	0	2	2	4
Avena fatua L.	1	3	1	5
Avena sterilis L.	48	47	37	132
Cicer incisum (Willd.) K. Malý	1	0	0	1
Cicer judaicum Boiss	3	20	0	23
Cicer pinnatifidum Jaub. & Spach	1	3	0	4
Hordeum bulbosum L.	29	57	19	105
Hordeum marinum Huds	2	5	0	7
Hordeum murinum L.	2	37	0	39
Hordeum spontaneum K.Koch	13	92	75	180
Lens culinaris Medik. subsp. *culinaris*	0	17	9	26
Lens culinaris Medik. subsp. *orientalis* (Boiss.) Ponert	0	0	56	56
Lens ervoides (Brign.) Grande	3	19	4	26
Pisum fulvum Sm.	0	9	6	15
Pisum sativum L. subsp. *elatius* (M. Bieb.) Asch. & Graebn	2	10	8	20
Triticum boeoticum Boiss	1	11	1	13
Triticum dicoccoides (Asch. & Graebn.) Schweinf	42	63	55	160
Triticum timopheevii (Zhuk.) Zhuk.	1	1	0	2
Triticum urartu Thumanjan ex Gandilyan	4	33	10	47
TOTAL	263	712	485	1460

restricted, a relatively small number of populations of *Aegilops crassa* Boiss ex Hohen (1 population) and *Avena eriantha* Durieu (4 populations) are only present in Baalbak-El Hermel governorate. Additional data on taxa and population number found in each governorates are indicated in Table S2 (Supplementary materials).

3.2. CAPFITOGEN toolbox analyses

3.2.1. Variables identified for Ecogeographical land characterization map

The selection procedure (*SelecVar*) of variables to be used for the ecogeographical land characterization map identified *Elevation*,

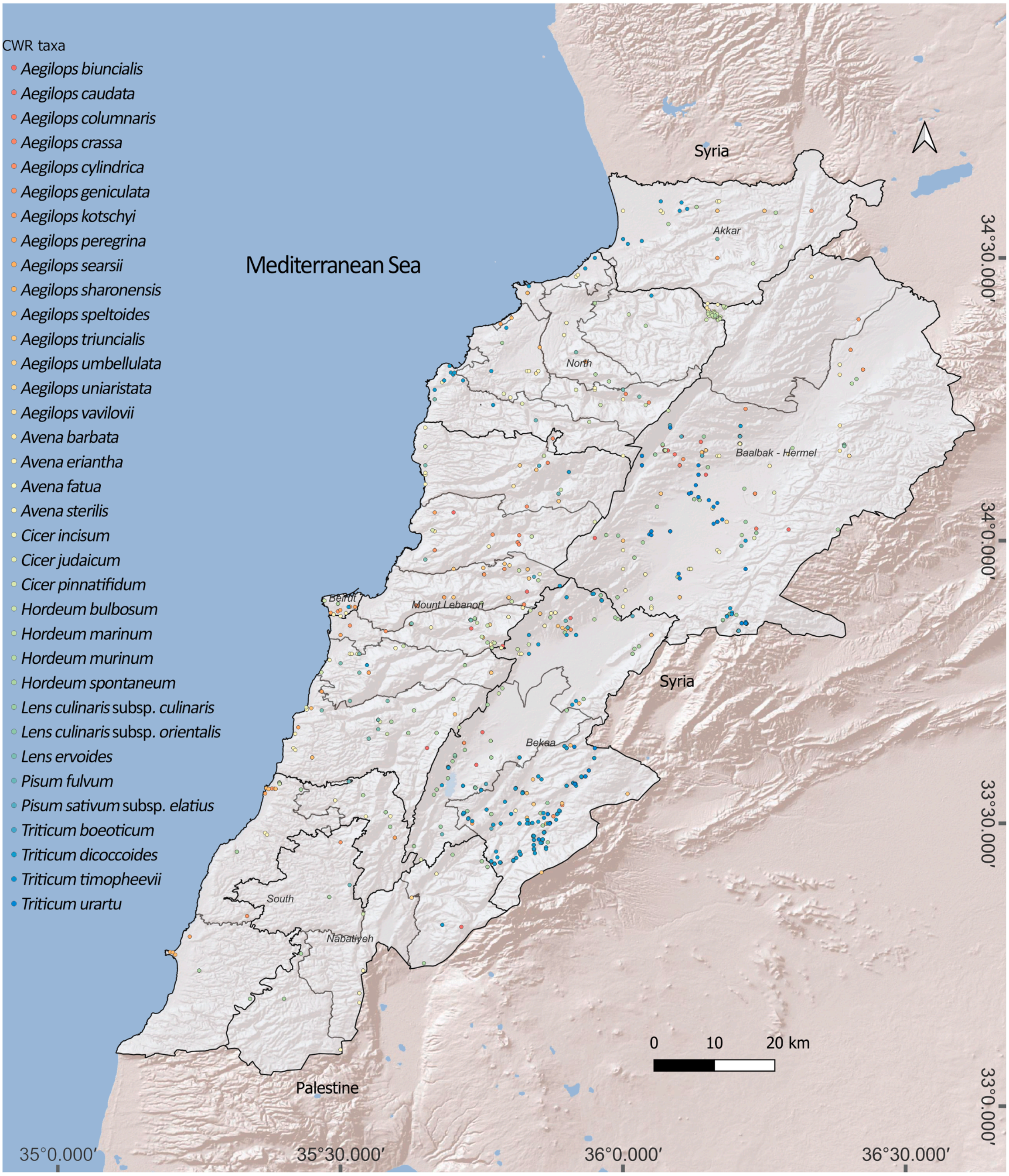

Fig. 1. Distribution of 1460 CWR populations across Lebanon. (Map drawn to geographic coordinate system: WGS84).

Longitude and *Latitude*, among the geophysical components, *Annual Mean Temperature*, *Mean Temperature of Warmest Quarter* and *Mean annual precipitation*, among the bioclimatic components, and *Clay content* of 0–2 micrometre, *Sand content* of 50–2000 micrometer and *Available soil water capacity* among the edaphic components. More details on selected variables are available in Table S3 (Supplementary Materials).

3.2.2. Ecogeographical land characterization (ELC) mapping

24 different ELC categories representing different bioclimatic, edaphic and ecogeographic conditions of Lebanon were identified using the *ELCmapas* tool; a total of 14,629 cells were then successfully assigned to one of the identified categories that allowed the

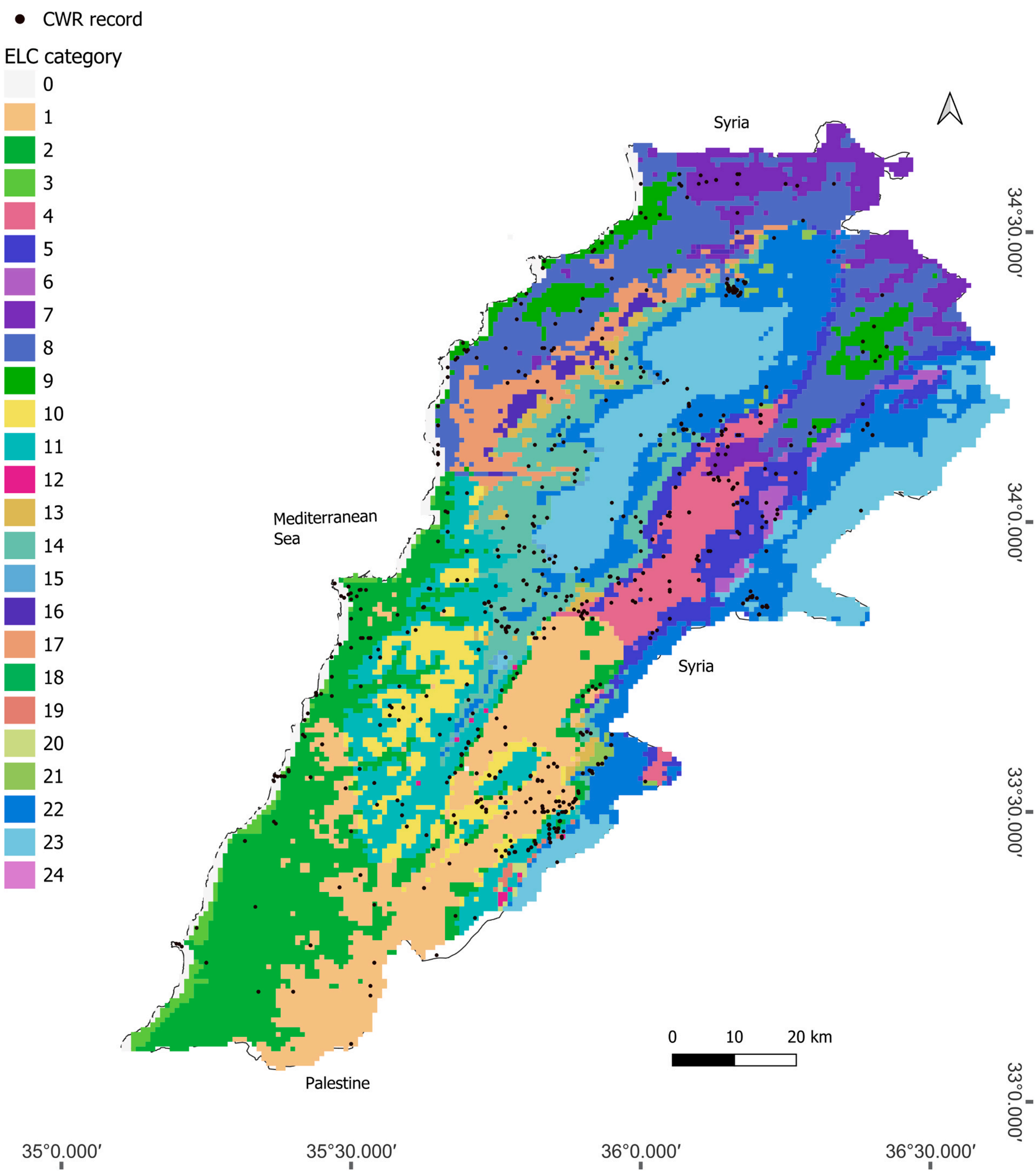

Fig. 2. Ecogeographic land characterization (ELC) map of Lebanon, showing the territory subdivision into the 24 different ELC categories identified. Map drawn to geographic coordinate system: WGS84.

development of the ELC map (Fig. 2). The most represented category is ELC_2 that comprises 2046 cells (14.6 % of the total) followed by ELC_23 (1689, 11.5 %), ELC_1 (1639, 11.2 %), ELC_22 (1629, 11.1 %), ELC_8 (1539, 10.5 %) and ELC_11 (1029, 7.0 %) (Table S4, Supplementary Materials).

3.2.3. Principal component analysis (PCA) of ELC categories

PCA was conducted to analyse the bioclimatic, edaphic and geophysical differences among the identified ELC categories. The first two principal components accounted for 68.2 % of the total variability (Fig. 3b). The first principal component (41.8 % of total

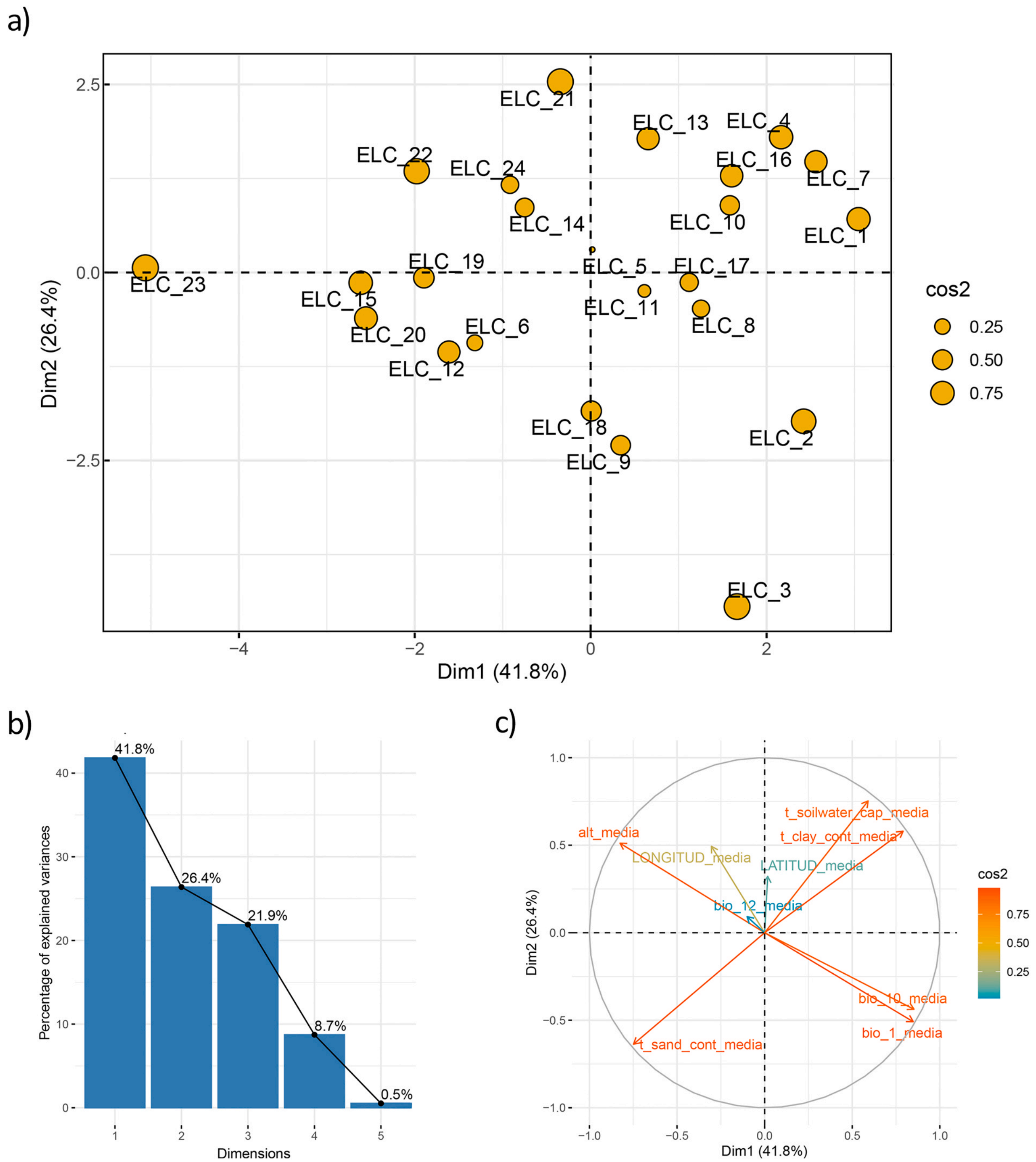

Fig. 3. (a) First and second PCA axes of the geophysical, bioclimatic and edaphic variables used to define the 24 categories of ELC map developed for Lebanon. (b) Scree Plot of the eigenvalues for the first 5 individual PC. (c) Variables PCA biplot across the first two principal axes.

variability) distinguishes between the categories from ELC_1 to ELC_13 (mainly located int the right part of the plot) and those from ELC_14 to ELC_24 (mainly in the left part).

Main differences between the two groups of categories are attributed to annual mean temperature (bio_1) and mean temperature of the warmest quarter (bio_10) with high values in categories of the first group (from ELC_1 to ELC_13) and mean altitude (alt_media) for which the opposite was true (high in in categories from ELC_14 to ELC_24) (Fig. 3a and c).

The second principal component (26.4 % of total variability) differentiates ELC categories mainly according to the mean available soil water capacity (t_soilwater_cap) and sand (t_sand_cont) and clay (t_clay_cont) soil content (Fig. 3a and c). Even if clear groups cannot be identified with respect to PC2, ELC_3 and ELC_21 showed quite high and quite low values of the cited variables, respectively and are placed at the extremes of the second axis (Fig. 3a and c).

3.2.4. *Population distribution across ELC categories*

The analysis showed significant variation in the distribution of the CWR populations across the ELC categories. Categories that are remarkably most represented in terms of population occurrences are ELC_14 (236 populations), ELC_22 (230), ELC_11 (218), ELC_1 (147), ELC_4 (141) and ELC_2 (135).

ELC_14 was found to be also the richest category in terms of number of different CWR taxa (28), belonging to all the 7 targeted genera, represented by a total of 236 populations. In this category the highest number of populations was recorded for the taxa *Ae. geniculata* (27 populations), *H. bulbosum* (23) and *Ae. triuncialis* and *A. sterilis* with same number of populations (22). ELC_22 follows with 23 different taxa (total of 230 populations) and particularly reach in *H. bulbosum, H. spontaneum*, *Ae. biuncialis* and *A. sterilis* (34, 33, 27, 22 population, respectively). Including 21 different taxa represented by a total of 141 populations, ELC_4 is particularly rich in *A. sterilis* (22 populations) and *Ae. biuncialis* (17) while ELC_11, also including 21 taxa and 218 populations, is rich in *H. spontaneum* (44 populations), *Ae. biuncialis* (32), *Ae. geniculata* (30), *T. dicoccoides* (26) and *L. culinaris* subsp. *orientalis* (23) (Table 2). Target CWR populations were not present in ELC_16, ELC_18, ELC_19, ELC_20 and ELC_24. The full list of taxa and corresponding number of populations in each ELC category is available in Table 2.

3.2.5. *CWR-Eco units as indicators of genetic diversity of CWR taxa (Assignment of populations to ELC categories)*

The *Representa* tool used to assign populations to ELC categories allowed to assign all the 1460 population to one of the 24 distinct ELC categories. This resulted in the identification of 253 unique combinations of CWR taxa and ELC categories (i.e. 253 different CWR-Eco units), an estimation of the varied adaptation of CWR taxa to different environmental conditions across Lebanon (Table 2).

Among the investigated taxa, *Ae. geniculata* and *T. dicoccoides* exhibited the greatest estimated diversity, being found in 15 distinct ELC categories each; in other word, the two species exhibit enough diversity to exist in 15 different environments as defined by the corresponding ELC categories. *H. bulbosum* followed closely with 14 CWR-Eco units, each of *Ae. triuncialis*, *H. murinum*, and *H. spontaneum* with 13 CWR-Eco units. Finally, *Ae. biuncialis*, *Ae. peregrina*, and *Ae. sterilis* were associated with 12 CWR-Eco units (Table 2).

3.3. *Complementarity analysis for in situ conservation*

3.3.1. *The complementarity analysis inside PAs and CWR-Eco unit coverage*

Results of the complementarity analysis inside protected areas showed that, out of 27, only six PA harbour populations of target CWR taxa highlighting a significant gap in the current conservation network. However, they conserve 58 populations (4 % of the total) belonging to 18 different taxa that represent 33 different CWR-Eco units (Table 3). This makes the 13 % only of the total diversity potentially passively conserved inside PAs (Fig. S1, Supplementary Materials). This coverage includes 17.8 %, 16.1 %, 15.3 %, 13.6 % and 7.1 % of *Hordeum, Triticum, Aegilops, Lens* and *Avena,* respectively (Table 3). The six PAs are distributed along five Lebanese governorates: North, Baalbak-Hermel, Mount Lebanon, Bekaa, South (Fig. 4).

As for the taxa diversity, this network of the six PA includes the 50.0 % of the predicted diversity of *Ae. cylindrica* with two different CWR-Eco units located in two different ELC categories (ELC_14 and ELC_23), the 26.7 % of *T. dicoccoides* diversity (four different CWR-Eco units in four different ELC categories: ELC_1, ELC_8, ELC_9 and ELC_22) (Fig. 5). As for the rest of the taxa present in this network, the same percentage of *Ae. triuncialis* and *H. spontaneum* CWR-Eco units (23.1 %) are included in PAs in categories ELC_1, ELC_8, ELC_9 and ELC_22 and ELC_2, ELC_22 and ELC_11, respectively. Only 8.3 % and 10.0 % of total estimated population diversity of *A. sterilis* and *T. urartu*, respectively, are present in PAs (Fig. 5).

Among the six PA identified harbouring CWR diversity the “Shouf Biosphere Reserve - SBR”, which includes Ammiq Wetland and surrounding villages on the eastern and western slopes of the Barouk and Niha mountains, is of particular interest. This PA contains the most diverse CWR-Eco units (20), supporting potential conservation of 42 populations belonging to 11 CWR taxa (Table 3). The “Yammouneh Nature Reserve”, in the Governorate of Baalbak-Hermel, ranks second in terms of CWR-Eco units richness holding four populations of four taxa resulting in a total of four CWR-Eco units. The presence of the CWR-Eco unit *Ae. vavilovii*_23 in Yammouneh ensures the *in situ* conservation of at least one of the only two identified populations for this taxon in ELC_23.

In “Deir el Nouriyeh cliffs of Ras Chekaa” PA, three CWR-Eco units are found: *T. dicoccoides*_8, *T. dicoccoides*_9 and *A. sterilis*_8 corresponding to the 13.3 % and 8.3 % of the total estimated diversity of the two taxa, respectively. In “Mount Hermon Nature Reserve” (MHNR), the country’s 18th nature reserve elected (Law No. 202, 2020), only 2 CWR-Eco units were located: *T. dicoccoides_22* and *H. spontaneum_22*. In “Jabal Moussa Biosphere Reserve” (JMBR), located in Keserwan District and part of UNESCO Network of Biosphere Reserves since 2009, *Ae. cylindrica*_14 and *A. barbata*_14 is present. The fifth PA containing target CWR populations identified in this study is “Jabal Al Rihane Biosphere Reserve” with two CWR-Eco units: *Ae. peregrina*_10 and *Ae.*

Table 2
Distribution of populations in the defined ELC categories. For each taxa the number of populations in each defined ELC category and the number of populations located in the protected areas, here proposed for the establishment of genetic reserves, by ELC category combination (in brackets), are reported. The total number of CWR-Eco units and of populations by taxa is also reported.

CWR taxa	ELC_1	ELC_2	ELC_3	ELC_4	ELC_5	ELC_6	ELC_7	ELC_8	ELC_9	ELC_10	ELC_11	ELC_12	ELC_13	ELC_14	ELC_15	ELC_17	ELC_21	ELC_22	ELC_23	Total CWR_Ecounits	Total populations
Ae. biuncialis	11 (0)	8 (0)		17 (0)	7 (0)		1 (0)			7 (0)	32 (3)	1 (0)	1 (0)	20 (0)				27 (0)	2(1)	12 (2)	134 (4)
Ae. caudata					7 (0)	1 (0)								8 (0)				5 (0)		4 (0)	21 (0)
Ae. columnaris	8 (0)	2 (0)		3 (0)	10 (0)	1 (0)				2 (0)	5 (1)	1 (0)		13 (0)				10 (0)	1(1)	11 (2)	56 (2)
Ae. crassa				1 (0)																1 (0)	1 (0)
Ae. cylindrica				1 (0)							1 (0)			10 (1)				3 (0)	3 (1)	4 (2)	18 (2)
Ae. geniculata	13 (0)	19 (0)		10 (0)	4 (0)		1 (0)	2 (0)		9 (0)	30 (2)	1 (0)	1 (0)	27 (0)	1 (0)	1 (0)		18 (0)	2 (1)	15 (2)	139 (3)
Ae. kotschyi				1 (0)				1 (0)	4 (0)	1 (0)	1 (0)			3 (0)						6 (0)	11 (0)
Ae. peregrina	7 (0)	11 (0)	1 (0)		1 (0)		2 (0)	1 (0)	3 (0)	6 (0)	1 (0)			3 (0)		1 (0)			2 (1)	12 (1)	39 (1)
Ae. searsii					5 (0)						1 (0)									2 (0)	6 (0)
Ae. sharonensis		2 (0)	2 (0)																	2 (0)	4 (0)
Ae. speltoides	1 (0)	5 (0)	2 (0)					2 (0)	3 (0)											5 (0)	13 (0)
Ae. triuncialis	7 (0)	9 (0)		15 (0)	6 (0)		3 (0)			8 (0)	10 (1)		2 (0)	22 (1)	1 (0)		1 (0)	8 (0)	2 (1)	13 (3)	94 (3)
Ae. umbellulata	2 (0)			1 (0)										4 (0)				1 (0)		4 (0)	8 (0)
Ae. uniaristata														2 (0)						1 (0)	2 (0)
Ae. vavilovii				1 (0)	2 (0)			1 (0)						3 (0)				2 (0)	2 (1)	6 (1)	11 (1)
A. barbata	5 (0)	1 (0)		6 (0)	1 (0)		1 (0)	6 (0)			1 (0)			9 (1)				8 (0)		9 (1)	38 (1)
A. eriantha				1 (0)				2 (0)										1 (0)		3 (0)	4 (0)
A. fatua					1 (0)			2 (0)						1 (0)				1 (0)		4 (0)	5 (0)
A. sterilis	10 (0)	13 (0)	1 (0)	23 (0)	8 (0)		3 (0)	18 (1)	6 (0)		5 (0)			22 (0)				22 (0)	1 (0)	12 (1)	132 (1)
C. incisum															1 (0)					1 (0)	1 (0)
C. judaicum	1 (0)	4 (0)	1 (0)		1 (0)	1 (0)		5 (0)			5 (0)		2 (0)	1 (0)		1 (0)			1 (0)	11 (0)	23 (0)
C. pinnatifidum		1 (0)						2 (0)						1 (0)						3 (0)	4 (0)
H. bulbosum	4 (0)	10 (2)	3 (0)	5 (0)	1 (0)		2 (0)	1 (0)		4 (0)	13 (5)		1 (0)	23 (1)		1 (0)		34 (0)	3 (0)	14 (3)	105 (8)
H. marinum					1 (0)						1 (0)		1 (0)	3 (0)					1 (0)	5 (0)	7 (0)
H. murinum	3 (0)	6 (1)		9 (0)	2 (0)		2 (0)	2 (0)	2 (0)	2 (0)	5 (1)		1 (0)	3 (0)		1 (0)		1 (0)		13 (2)	39 (2)
H. spontaneum	24 (0)	16 (1)		16 (0)	9 (0)			1 (0)	1 (0)	16 (0)	44 (11)	1 (0)		14 (0)			4 (0)	33 (1)	1 (0)	13 (3)	180 (13)
L. culinaris subsp. culinaris	4 (0)			3 (0)		3 (0)				2 (0)				5 (0)				8 (0)	1 (1)	7 (1)	26 (1)
L. culinaris subsp. orientalis		5 (0)		2 (0)						8 (0)	23 (5)			3 (0)			2 (0)	14 (0)		7 (1)	57 (5)
L. ervoides		9 (0)			1 (0)		1 (0)	3 (0)		1 (0)	6 (1)			3 (0)				1 (0)		8 (1)	25 (1)
P. fulvum	1 (0)			4 (0)						1 (0)	3 (0)			4 (0)		1 (0)		1 (0)		7 (0)	15 (0)
P. sativum subsp. elatius	1 (0)			5 (0)						2 (0)	3 (0)			4 (0)				2 (0)	3 (0)	7 (0)	20 (0)
T. boeoticum	6 (0)						1 (0)							2 (0)			2 (0)	2 (0)		5 (0)	13 (0)
T. dicoccoides	36 (1)	14 (0)		3 (0)	1 (0)		3 (0)	8 (2)	9 (3)	15 (0)	26 (0)	2 (0)		16 (0)	1 (0)	1 (0)	6 (0)	19 (1)		15 (4)	160 (7)
T. timopheevii	2 (0)																			1 (0)	2 (0)
T. urartu	1 (0)			14 (0)	5 (0)		6 (0)			1 (0)	2 (0)			7 (0)			1 (0)	9 (0)	1 (1)	10 (1)	47 (1)
Total	147 (1)	135 (4)	10 (0)	141 (0)	73 (0)	6 (0)	26 (0)	57 (3)	28 (3)	85 (0)	218 (30)	6 (0)	9 (0)	236 (4)	4 (0)	7 (0)	16 (0)	230 (2)	26 (9)	253 (31)	1460 (56)

Table 3
Proposed sites for the institution of genetic reserves within Protected Areas in Lebanon. For each Protected Area, the list of included CWR taxa, the number of CWR-Eco units and of populations are reported.

WDPA Id	Protected Area name	Taxa	CWR-Eco units	Populations
902497	Shouf Biosphere Reserve	*Ae. biuncialis, Ae. columnaris, Ae. genicualata, Ae. peregrina, Ae. triuncialis, H. bulbosum, H. murinum, H. spontaneum, L. culinaris* subsp. *orientalis, L. ervoides, T. dicoccoides*	20	42
555576133	Yammouneh Nature Reserve	*Ae. cylindrica, Ae. vavilovii, T. urartu, Lens culinaris* subsp. *culinaris*	4	4
220098	Deir el Nouriyeh cliffs of Ras Chekaa	*T. dicoccoides, A. sterilis*	3	6
555716224	Mount Hermon Nature Reserve	*T. dicoccoides, H. spontaneum*	2	2
555547555	Jabal Moussa Biosphere Reserve	*Ae. cylindrica, A. barbata*	2	2
555547538	Jabal Al Rihane Biosphere Reserve	*Ae. peregrina, Ae. kotschyi*	2	2
Total	-	18	33	58

*kotschyi*_10; in this PA, 16.7 % of the diversity of each of the two species could be conserved (Table 3).

3.3.2. Complementarity analysis outside PAs and future in situ conservation sites

Considered that 87 % of the identified CWR-Eco units are located outside current PAs in Lebanon, the second performed complementarity analysis has a particularly high value from the point of view of CWR *in situ* conservation. The grid cell analysis has identified a network of 79 cells (5 ×5 km each) necessary for conserving the predicted CWR diversity only occurring outside current PA (Fig. S2, Supplementary Materials). Due to the impracticality of initiating genetic reserves in all these cells, the top 14 sites were selected based on their potential as genetic reserves to conserve 50 % of the CWR diversity not already included in PA. As for the followed approach, any grid cell that had less than five different CWR-eco units was dismissed from the priority areas. Noteworthy, the resulting chain of 14 complementary priority sites (17.7 % of the total) would allow the conservation of 122 CWR-eco units of 32 target taxa (almost 50 % of the predicted diversity) (Fig. 4 and S3, Supplementary Materials).

The prioritized sites outside PAs are mainly occurring on the eastern side of Lebanon. The 2 top priority conservation sites, with the highest estimated diversity, are located in Bekaa governorate, both in Rashaya district, corresponding to Rashaya El-Wadi and Yanta and Kfarqouk areas (Sites I and II, Fig. 4); each of the two sites holds 18 different CWR-Eco units. Another major priority site in this network includes 13 different CWR-Eco units; the site is located in Baalback-El Hermel governorate, which includes the cities of Iaat, Chlifa and Deir el Ahmar (Site III, Fig. 4). Nine different CWR-Eco units can also be found in the vicinity of the previous site, in the priority site IV, covering Baalback village and Iaat in the same governorate and district. Eight different CWR-Eco units are found in each of the two proposed priority conservation sites located in Aiha (Rashaya district) and Arsal (Baalbak district) (Sites V and VI, respectively). It is evident that the sites proposed as priority conservation areas in Rashaya district are connected and in the proximity of Mount Hermon Nature Reserve.

The combination of the taxa currently occurring inside PAs with those proposed in the future genetic reserves network will allow the conservation of the 94.3 % of the taxa considered (33 out 35). Interesting enough, this network will also ensure the conservation of 142 CWR-Eco units, the 56.1 % of the total diversity estimated for the target CWR taxa as estimated by distribution of populations across 24 ELC categories identified (Table S5, Supplementary Material).

3.4. In situ vs ex situ diversity gap analysis

The gap analysis showed that 215 CWR-Eco units (85.0 % of the total occurring in the wild) are currently conserved *ex situ* while the remaining 38 still require collection efforts; these 38 CWR-Eco units correspond to 21 different taxa (Table S6, Supplementary Materials).

Materials originally collected in all the defined ELC categories are present in genebank collections; areas corresponding to ELC_14 are those where the highest number of collections were performed regarding both number of involved populations (139, corresponding to the 58.9 % of the total) and CWR taxa (27, 96.4 % of the total) (Table S5, Supplementary Materials). As for the second group of areas in terms of number of collected materials, namely ELC 22, the 78.3 % of the estimated diversity is already conserved *ex situ* (18 out of 23 CWR-Eco units) while only the 27.0 % of the total number of populations is conserved (62 out of 230). A similar situation is also true for the areas corresponding to the categories ELC 4 and ELC 11.

Remarkably, 100 % of the unique diversity found in ELC categories number 1, 6, 12 and 13 is currently conserved *ex situ* (Fig. 6, top). This corresponds to the 73.5 %, 100.0 %, 83.3 % and 88.9 % of the total populations occurring in each of the cited ELC categories, respectively (Fig. 6, bottom). On the opposite, only the 33.3 % of the diversity found in ELC 3 is conserved *ex situ* (2 CWR-Eco units) which correspond to the 20.0 % of the total populations based on available occurrence records. The full list of CWR-Eco units that still require collection efforts is present in Table S7 (Supplementary Material).

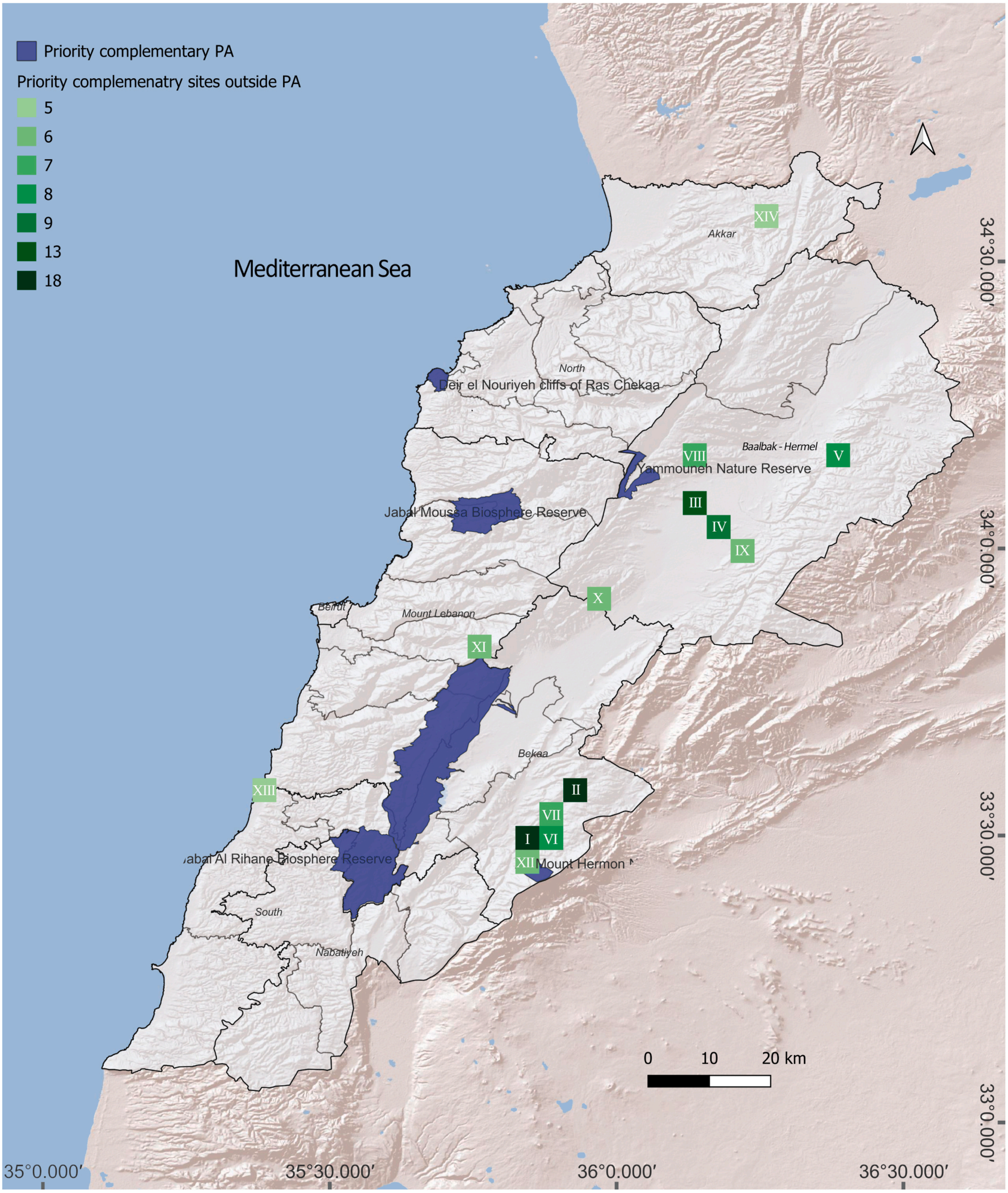

Fig. 4. Geographical distribution of protected areas in Lebanon. Areas proposed for the institution of genetic reserves are highlighted in dark green. Map drawn to Geographic Coordinate System: WGS84.

4. Discussion

This study presents a first comprehensive overview of sites that are suitable for the institution of genetic reserves across Lebanon for the active protection of key CWR taxa from genera important for global food security, local economy and plant breeding, such as *Aegilops*, *Triticum*, *Avena*, *Hordeum*, *Cicer, Pisum* and *Lens.* These genera have been already inventoried and prioritized in Sayde et al.

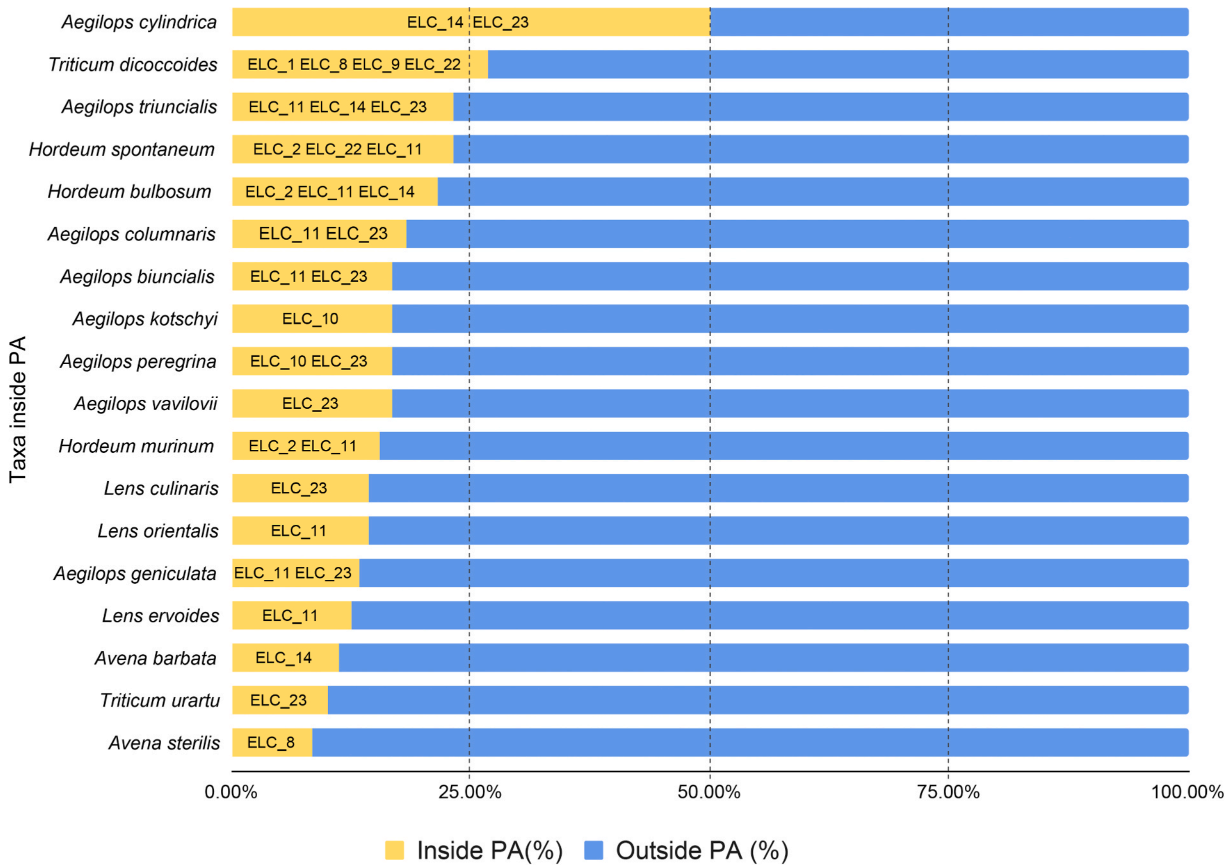

Fig. 5. Histogram representing the percentage of CWR taxa conserved inside PAs (pale orange) and outside PAs (pale blue). The list of the ELC categories in which the populations were found inside PAs is also mentioned.

(2023). Indeed, this investigation is based on data from the latter mentioned study as well as from new data collected during survey missions carried out by some of the authors in 2022 and 2023 (Sayde et al., 2024a). Survey missions were necessary to verify records (i.e. the presence of CWR population *in situ*) that were retrieved from Genesys and GBIF and from the ICARDA genebank database. This point is quite critical considering that populations can disappear as consequence of different disturbance factor such as climate change, habitat destruction, degradation, fragmentation, deforestation and urbanization; the importance of up-to-date confirmation of the presence of populations was recently highlighted by Magos Brehm et al. (2022) and Rubio Teso et al. (2020a),b). More relevant, the addition of 500 new CWR population records acquired in field surveys, and here analyzed for the first time, significantly elevate the interest of presented data and reliability of the proposed conservation recommendations. The approaches adopted in this study have been highlighted and recommended by Maxted et al. (2024) to be applied in West Asia and North Africa (WANA), which include Lebanon, to significantly improve CWRs *in situ* and *ex situ* conservation and will potentially at least double the availability of the full breadth of CWR diversity found in WANA to breeders, and so enhance regional and global food and nutritional security.

4.1. Ecogeographic influences on CWR distribution

The methodology of complementarity, for the identification of the minimum number of sites to conserve the maximum possible CWR diversity, has been already successfully applied in Italy (Raggi et al., 2024), in Finland (Fitzgerald et al., 2023), in Malawy (Khaki Mponya et al., 2021), in Indonesia (Rahman et al., 2021), in Southern Africa (Magos Brehm et al., 2022) and West Africa (Nduche et al., 2023). All previous analyses aimed to identify the best areas, and protected areas in particular, for the establishment of genetic reserves. However, the results from Lebanon reveal a significant range of differences across various levels in comparison with the results of the previously mentioned countries/regions. For example, even though Finland's land area is roughly 32 times larger than Lebanon, it exhibited only 10 ELC categories for the general ecological map, while in Lebanon higher number of categories was identified with 24 different ELC categories. Due to the observed differences, it is necessary to highlight a customized or tailored approach in conservation planning. Effective and active conservation requires a case-by-case strategy, adapted to the unique ecological characteristics of each country or region.

Based on the results of PCA analysis and the distribution of populations on the different ELC categories, the six ELC categories holding the highest number or target CWR taxa populations (namely ELC 14, 22, 4, 11, 1 and 5) show high variability in terms of

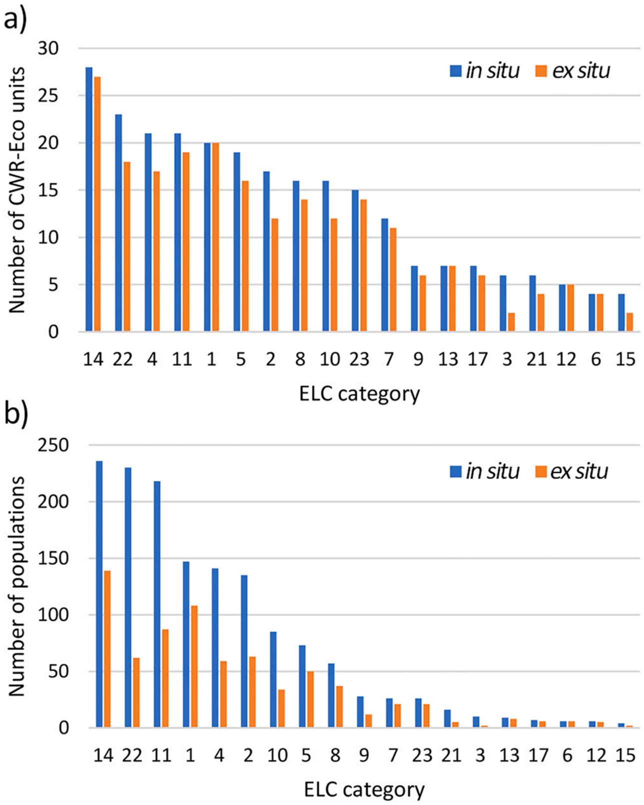

Fig. 6. (a) Number of *in situ* and *ex situ* unique CWR taxa (i.e. CWR-Eco units) and (b) population records arranged by ELC category.

ecogeographical conditions. For example, ELC 14 includes areas with elevations ranging from 900 m a.s.l up to 1800 m a.s.l. with non-extreme mean annual temperature variabilities compared to other ELC categories; in ELC 14 precipitations are significantly higher than in other ELC categories while availability of top soil water shows medium to higher capacity compared to the other categories. All these categories have in common a medium to high annual precipitation that could sustain their high CWR diversity. Further investigation and data are needed to fully understand the factors and habitat types governing these ELC categories that are particularly rich in CWR diversity.

4.2. Conservation implication and strategy

In the current situation, the number of CWR-Eco units, and indirect estimation of diversity, occurring inside PAs allows for the conservation of only 4 % of the total diversity of target taxa. This low percentage shows the existence of several gaps in the diversity conserved within protected areas. Certainly, additional surveys inside PAs for the localization of populations of priority taxa are essential since the low percentage of covered diversity could also be due to an incomplete assessment of these areas. The additional surveys can be also triggered by the fact that the here presented distribution maps show the presence of many of the target CWR taxa outside but nearby the perimeter of PAs in Lebanon suggesting that other populations could be present within the borders of nearby PA.

4.3. Conservation opportunities in Shouf Biosphere Reserve

The Shouf Biosphere Reserve (SBR) is Lebanon's largest PA valorized for its relevant value directly linked to fauna and flora biodiversity as well as for other cultural and ethnobotanical values (Baydoun et al., 2023; Hani et al., 2017, 2022a,b). This PA is under a detailed and active management plan for the conservation of its biodiversity (https://shoufcedar.org/); therefore, promoting an active conservation of CWR priority taxa assessed in this study, as well as all the other CWR taxa found in SBR, in a future genetic reserve established inside SBR could be a major opportunity towards *in situ* conservation of CWR in Lebanon. Establishing a genetic reserve within SBR could substantially advance the conservation of both the priority CWR taxa identified in this study and other taxa found within the reserve.

Although the prime objective of the genetic reserve is to maximise the total genetic diversity of the target taxa in a single site or network of sites, it is essential to be accompanied by an understanding of the auto-ecology (single species) and syn-ecology (multiple species and their interactions) of the target taxa (Maxted et al., 2020b). Therefore, the core of the reserve should be designed by the target taxa and populations of the associated species, essential pollinators and dispersers of the target species. At this regard, the here presented CWR population localization data, together with baseline data on environment and associated plant taxa as well as disturbance factors collected during the 2022 and 2023 survey missions Sayde et al. (2024a), would be of high value to develop and implement effective conservation actions within the designated protected area.

4.4. Conservation opportunities in Jabal Moussa Biosphere Reserve

Jabal Moussa (JMBR) was designated as UNESCO Biosphere Reserve in 2008 and a Global Important Bird Area (according to the BirdLife International criteria) and a member of the IUCN in 2009 (Www.Jabalmoussa.org/). JMBR is described as a true mosaic of ecological systems, broadly representing the "evergreen sclerophylic broussailles and forests" biogeographic region within a Mediterranean biome with a major ethnobotanical value (Baydoun et al., 2017; Douaihy et al., 2017; Hani et al., 2022a,b; Karam et al., 2021; Mitchell et al., 2018). In our study, *Ae. cylindrica* and *A. barbata* were the only two CWR taxa with geo-localized populations occurring in this PA. However, data from the literature reports the presence in this PA of additional CWR taxa of high relevance for both conservation and use, that are listed in our priority CWR taxa list, including: *Ae. ovata, Ae. triuncialis, Avena sterilis, P. sativum* subsp. *elatius, H. bulbosum* and *H. marinum*. These taxa are only documented based on their presence in JBMR (UNESCO, MAB Gobierno De Espana and APJM, 2012) without accurate geographic localities. Therefore, a more accurate *in-situ* conservation of PGR occurring in JBMR can be only achieved through targeted field surveys to accurately map and conserve these CWR populations inside the BR.

4.5. Implementing genetic reserves outside protected areas

Results of the complementarity analysis outside protected areas showed that conservation efforts would be necessary in 79 sites to conserve at least one population for each CWR-Eco unit non already present in Lebanese PA. Unfortunately, this is quite complex and costly to be implement into a real conservation design as explained by Contreras-Toledo et al. (2019), Fielder (2015) and Phillips et al. (2016). These studies argue that the additional diversity value of lower ranking sites decreases substantially, so initial *in situ* activity might be more effective if focused on the top identified sites that contain highest diversities. In the case of this study, 49 % of the total diversity can be conserved in future genetic reserves initiated in the identified top 14 priority sites. This would allow the active conservation of 122 CWR-Eco units belonging to 32 targeted CWR taxa; these priority areas are mainly located on the Eastern side of Lebanon, in the Bekaa and Baalbak-Hermel governorates.

4.6. Strategic recommendations of genetic reserves in Rashaya

The Rashaya district, in the vicinity of Mount Hermon Nature Reserve (MHNR) presents a particular case with high density of priority areas that could be considered for the establishment of genetic reserves; these sites are among those with highest priority considering diversity richness. In addition, the priority areas distribution map shows connectivity between the proposed sites, which allows the possibility of initiating a genetic reserve in the form of genetic trails that follow the management plans of MHNR, providing well defined and highlighted paths for hikers and tourists awareness. This design benefits from ecotourism, takes account of needs of visitors and interested members of the public, so the provision of natural trails and guided walks within the buffer and transitional zone, educational boards, reserve information packs, as well as an association with agro-biodiversity, which allows restaurant that utilizes the resources being conserved would be ideal (Ceballos-Lascuráin, 1996; Hawkes et al., 1997; Maxted et al., 2000a, 2020b, 2020c, 2020d).

In recent years, active management strategies have been implemented inside the reserve, and are continuously evolving. While is also essential to mention that the district of Rashaya and MHNR are also rich in populations of other relevant CWR taxa (Ghossain et al., 2020; Sayde et al., 2024b), as well as an ethnobotanical and cultural value (Arnold et al., 2015; Baydoun et al., 2015; Baydoun et al., 2024; El Zein et al., 2024). Genetic reserves here proposed in Rashaya district, namely in Kfarqouk and in Yanta, aim to conserve 18 different CWR-Eco units and are in clear agreement with the proposal of *in situ* conservation actions in the area dating back to ICARDA Annual Report (1993). The latter suggests initiating in these sites *in situ* conservation measures for *T. boeoticum, T. urartu* and *T. dicoccoides*.

4.7. Genetic reserves initiative in Baalbak - Hermel

Genetic reserves proposed in Baalbak-Hermel governorates, in particular, Arsal and Nabha are sites holding respectively eight and seven different CWR-Eco units. These sites have been already highlighted for the conservation of CWR populations in Amri et al. (2005) in the scope of a 4-year monitoring project funded by GEF/UNDP (The Global Environment Facility-the United Nations Development Programme-funded project on "Conservation and Sustainable Use of Dryland Agrobiodiversity").

In Aarsal, a large population of wild *Pyrus*, few plants of wild *Amygdalus* L., *Crataegus* L., *Prunus* L., *Pistacia* L., as well as *Aegilops*, *Trifolium* Tourn. ex L*., Medicago* L. and *Vicia* L. species are found; a restricted population of *T. dicoccoides* is also found in field edges. Additional, landraces of figs and grapes are planted in the reclaimed lands. This wide taxonomical richness of important landraces and CWR taxa is found in a small area assigned to two ELC categories (namely ELC 5 and 22).

The results of the GEF/UNDP study (2005) and of the current study allowed to confirm the taxonomic diversity of Nabha priority area. Indeed, this area is characterized by the presence of a large number of wild relatives of target herbaceous and other fruit tree species including populations of three wild *Triticum* species, a large population of *Prunus ursina* Kotschy and few populations of *Pyrus syriaca* Borkh., *Pistacia atlantica* Desf.*, Amygdalus communis* Bunge and of other wild fruit trees. Many species of the genus *Aegilops*, feed legume species and medicinal plants are also found in this priority area. This specific diversity is also accompanied by an estimated high genetic diversity hosted by different ELC categories (namely ELC1, 4, 5, 14 and 22). Given the richness and diversity existing in the area, it has been already recommended in 2005 for the implementation of *in situ* conservation. According to results presented in this study relative to ecogeographical diversity and complementarity, sites in the Nabha priority area are recommended for more elaborative measures of initiating genetic reserves.

4.8. Prioritizing additional survey sites

Complementarity analysis shows three sites that cover six ELC categories each, but are of low priority to establish genetic reserves due to low targeted CWR records in these sites. Therefore, it is recommended to prioritise the following sites (Fig. S1, Supplementary Materials) in priority area 7 (Bqarsouna), 30 (vertically between El-Laklouk and Afka) and 49 (Zahle and Ferzol) to be targeted with more surveys to explore the diversity in the different ELC categories. These surveys could uncover additional CWR taxa not previously documented, guiding conservation efforts.

A comprehensive conservation strategy, integrating the protection of CWR-Eco units occurring inside PAs and outside within the proposed network of genetic reserves, would allow the *in situ* conservation of 142 CWR-Eco units of 33 different taxa; this network will ensure the conservation 56.12 % of the total estimated diversity. However, additional surveys are necessary to ensure that the full range of ecogeographic diversity is conserved in the network (Maxted et al., 2015; Maxted and Kell, 2009).

4.9. Challenges in ex situ conservation

According to our estimates, the efforts for *ex situ* conservation managed to successfully conserve 85.0 % of the total diversity existing in Lebanon for the CRW taxa target of this study. Indeed, 218 different CWR-Eco units (out of 253) have been already collected and are currently stored in genebanks (Table S8, Supplementary Material). Even though these data suggest a well representation of target CWR diversity in *ex situ* conservation facilities, relevant gaps remain in the number of populations collected. Zair et al. (2021) raised alarms about the need for additional collections for priority CWR taxa in the Fertile Crescent, *Ae. peregrina*, *A. eriantha*, *A. barbata*, *Hordeum marinum*, *H. murinum*, *C. incisum*, *L. ervoides and L. culinaris* subsp. *orientalis* that were also considered as of high priority and urgent for collection.

Amongst the CWR-Eco units for which extra *ex situ* conservation efforts are needed (i.e., are present *in situ* and absent *ex situ*) those of *T. dicoccoides* are particularly relevant. Indeed, according to here presented data, this species has a wide ecogeographical distribution being present in over 15 different ELC categories; populations occurring in six of these categories are not represented in genebank collections. Finally, *Ae. sharonensis* and *C. incisum* still remain without genebank collections and urgently need to be included in the *ex situ* conservation system.

5. Conclusion

This study is the first to systematically designate the most suitable areas for the establishment of genetic reserves in Lebanon, based on eco-geographical land characterization analyses and species distribution, for key genera considered of global importance for food security: *Aegilops* L., *Triticum* L., *Avena* L., *Hordeum* L., *Cicer* L., *Lens* Mill., and *Pisum* L. It also provides recommendations for active *in situ* and *ex situ* conservation relying on predicted diversity and complementarity approaches. These approaches allowed to set concise strategies for the *in situ* conservation of priority CWR taxa to be implemented inside 6 PAs, where they are present, as well as in other 14 other sites in Lebanon where genetic reserves could be started. Given the holistic nature of this work, the recommendations to establish genetic reserves within existing PAs appear promising. In this process stakeholder involvement is crucial, especially since we have identified several PAs with demonstrably successful ongoing conservation efforts for various species. As for the *ex situ*, while our analysis reveals a high *ex situ* conservation rate for the studied diversity, further studies are needed to determine the optimal number of populations required for the effective conservation of each taxa's diversity, and whether this diversity is adequately conserved in terms of number of populations and safety duplicates.

Ethics Statement

Not applicable: This manuscript does not include human or animal research

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2025.e03413.

Data availability

All data are available in the manuscript.

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