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RESEARCH ARTICLE

The primal garden: Tajikistan as a biodiversity hotspot of food crop wild relatives

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Abstract

Despite being located within a primary region of crop diversity, documentation of Tajik crop and crop wild relative (CWR) resources is far from comprehensive, particularly regarding CWR. Here, we compile the first inventory of food CWR of Tajikistan. A total of 549 food CWR taxa belonging to 36 families and 125 genera were documented as occurring in the country. Among them, 71 taxa were recognized as native close relatives of globally important crops (category 1A), 67 as native distant relatives of these crops (1B) and 411 as native taxa with an undetermined relationship to these crops (1C). This documented CWR diversity far exceeds previous scientific assessments for the country and, in doing so, distinguishes the Tajik region from surrounding countries. Within the country, the results indicate a clear gradient of food CWR taxonomic richness from the eastern part of the country (least diversity) to the western part (greatest diversity). This trend adds important new information to the body of literature published by N. I. Vavilov and others, who mainly stressed the importance of the Pamir region (Eastern Tajikistan) for crop and CWR diversity.

Keywords CWR · Crop wild relatives · Inventory · Food crops · Genetic resources · Conservation · In situ · Food security · Central Asia

1 Introduction

The world's major regions where various crop species were domesticated and subsequently evolved over thousands of years were first outlined a century ago by the Russian scientist N. I. Vavilov. Based on observations of diversity within and among cultivated plant species, as well as the presence of crop progenitors and other crop wild relative (CWR) taxa, Vavilov listed Central Asia among the key centres of origin of cultivated plants (Vavilov 1926), now commonly referred to as primary regions of diversity (Khoury et al. 2016). During his travels, in 1916 and again in 1924, he conducted studies in the Pamir region of Tajikistan, where he documented 37 distinct varieties of common wheat (*Triticum aestivum* L.) and 10 varieties of dwarf wheat (*Triticum sphaerococcum* Percival), among others (Muminjanov 2008).

Since Vavilov's activity — tragically interrupted by the politics of the time — the diversity and potential of crop and CWR genetic resources in Tajikistan have only received occasional attention, which is worrying given increasing threats to native plant diversity from economic development, globalization, demographic change and other factors (Muminjanov 2008; Sõukand et al. 2021). Recent

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phytosociological and taxonomic studies have led to a comprehensive flora published for the country, with 4269 plant species listed (Nowak et al. 2020b). In a series of articles by Ovchinnikov, published between 1957 and 1991, at least 1226 Tajik species were documented as useful plants, 168 of those directly used as food. In a neighbouring region, a study by Sitpayeva et al. (2020) in Kazakhstan's Tian Shan mountains confirmed unique species richness of CWR with almost 300 species documented. Based on these data, the number of CWR species in Tajikistan may far exceed the current estimates indicated within global databases (e.g. Vincent et al. 2019).

CWR inventories have been compiled for many countries worldwide, but in the Central Asian region, various gaps remain (USDA-NPGS 2021), with the exceptions of works focused on China (Kell et al. 2015) and Kazakhstan (Sitpayeva et al. 2020). Other research has focused mainly on selected prioritized taxa, for example, in Uzbekistan, where scientists identified five CWR species of key importance from among 70 previously selected wild nutritional, technical and ornamental plants as part of a UNEP/GEF CWR project (Hunter 2012).

In view of the still scarce knowledge of CWR in the Central Asian region, in this paper, we present the first comprehensive inventory of Tajikistan's CWR, based on the national flora (Nowak et al. 2020b) in combination with additional work by the authors, as well as other relevant data on plant genetic resources. We assess this diversity in the context of that documented in nearby as well as more distant countries and outline hotspots of diversity within Tajikistan that could represent areas of focus for conservation.

2 Methods

2.1 Research area

Tajikistan covers 141,400 km^2 and is located in Middle Asia. Its territory is land locked and mountainous, with elevation varying from 300 m to 7495 m and mountains making up 93% of the territory (TAJSTAT 2018a). It stretches between the continental Asian deserts in the west and south and the great mountain ranges of Tian Shan, Kunlun, Hindu Kush and Karakorum in the north, east and south-east, all having vertical belts from hot to permafrost deserts. According to bioclimatic classifications, the country is typified by a Mediterranean (i.e. wet winters and dry summers) type of macrobioclimate (Rivas-Martínez et al. 2002). However, the strong influences of the vast Asiatic continent make the climatic conditions much harsher than that of the Mediterranean. The Irano-Turanian bioclimatic zone should be distinguished from the Mediterranean by higher continentalism, lower precipitation with the precipitation peak from winter to spring, a longer dry season and lower winter temperature minima (Djamali et al. 2012). The area has a low percentage of cloud cover and, subsequently, high level of solar insolation (2090–3160 h of sunshine). It is characterized by a considerable variation in annual temperatures and moderate humidity. In the alpine and nival belts of the high mountains, the climate is much harsher than in lower elevations. At lower elevations, the average temperatures range between 23 to 30°C in July and −1 to 3°C in January, while in the eastern Pamirs, the average temperature in July is 5 to 10°C, and the average temperature in January is −15 to −20°C. Annual precipitation ranges in the western Pamir-Alai from ca. 350 mm (Zeravshan Mts.) to ca. 600 mm in the Hissar Range (in some locations up to 2000 mm). In the western part of the country, the lower limit of permanent snow is at an altitude of 3500–3600 m a.s.l. and in its eastern regions at 5800 m a.s.l. (Latipova 1968; Narzikulov and Stanyukovich 1968; Safarov 2003).

2.2 A Tajik national CWR inventory

The creation of a Tajik national inventory of food CWR followed UN Food and Agriculture Organization's (FAO) methodological guidance (Maxted et al. 2013). The prioritized food crop checklist is available in the Supplementary Information subsection. Our database builds on the list of 4269 native Tajik flora (Nowak et al. 2020b) supplemented by research conducted between 2006 and 2020 within the borders of the country (Nowak et al. 2020a). The selection of genera related to the most important food crops was based on FAOSTAT world production information (group with domain code "QC-Domain:Production:Crops") (FAO 2020). We also included genera recognized as synonyms of crop genera based on information in the Catalogue of Life (Bánki et al. 2022), as well as genera with very close genetic relationships to crop genera and that exhibit the same methods of use or were previously recognized as CWR in other peer-reviewed scientific publications. This produced a list of 627 important food CWR species present in Tajikistani flora, among which 549 are native (Table 1).

The gene pool relationship level between food CWR and their associated crops was determined based on information from USDA GRIN-Global Taxonomy (USDA-NPGS GRIN-Global 2021) and the Harlan and de Wet CWR Inventory (Vincent et al. 2013). The 141 species with genetic relationship information in these data sources were assigned to primary, secondary and tertiary relative groups. All species were then classified following Khoury et al. 2020: 1A, indicating native close relatives of globally important crops; 1B, distant (tertiary) native relatives of crop species; 1C, taxa within the crop genus with an undetermined relationship to the crop(s); 1D, non-native, close relatives; and 1E, non-native, distant relatives (Table 2). CWR native to Tajikistan

Table 1 Number of taxa recognized as national CWR in different databases for Central Asian countries.

	Tajikistan	Uzbekistan	Kyrgyzstan	Afghanistan	Pakistan	China
GRIN-Global Taxonomy CWR database	118	116	146	153	172	723
Harlan and de Wet CWR Inventory database	69	88	71	105	110	394
Results of the current study	549					

(1A, 1B, 1C) was further analysed in terms of their distribution and conservation status in the country. All accepted taxonomic names were verified against the Taxonomic Name Resolution Service (Boyle et al. 2013).

2.3 Spatial analysis

To explore the potential spatial distribution of CWR in Tajikistan, we used a database listing ca. 4300 vascular plant species in Tajikistan, which are reported in the 10-volume work dedicated to the flora of the former Soviet Socialist Republic of Tajikistan, prepared by a multiauthor team (Kinzikaeva 1988; Kochkareva 1986; Ovchinnikov 1957, 1963, 1968, 1975, 1978, 1981; Rasulova 1991) and supplemented by a few other authors (Nowak et al. 2020b). This database contains the following information about each species: (1) its presence and absence in phytogeographical subregions; (2) its presence and absence in elevation ranges at every 100 m band, which is the maximum precision reported in the Flora of Tajikistan; and (3) conservation status for each species at the national and global scale (Nowak et al. 2020b). From this database, we extracted data for the 549 native CWR species of Tajikistan.

To understand the geographic and ecological patterns of Tajik CWR, we used a system of operational geographic units (OGUs) defined by phytogeography and elevation. Each unit represents a polygon of a phytogeographical subregion according to the division proposed by Grubov (2010) (Fig. 1) and a 100-m elevation belt. In this way, we obtained 808 OGUs, each of which with relatively homogeneous environmental parameters within (Raduła et al. 2021). Using the available literature, based on the presence/absence data, we compiled all assessed CWR elevation distributional ranges for each phytogeographical subregion in Tajikistan. We then calculated potential CWR richness for each OGU. The elevations above 5100 in East Tajikistan A, B and C, Alaian and Zeravshanian C and above 5700 in West Pamirian A, B and C, East Pamirian, were omitted because no vascular plants occur at those ranges.

Finally, we calculated maps of elevation ranges in phytogeographical subregions based on a digital elevation model (DEM) with ca. 100 m resolution (Jarvis et al. 2008). To each OGU, based on CWR data, we attributed information about CWR richness and conservation status.

2.4 Conservation status and prioritization

An updated conservation status of CWR species was created based on the Tajik plant conservation status database created by Nowak et al. for the Red List of vascular plants of Tajikistan (2020b). Priority CWR taxa for conservation were identified based on degree of threat, with focus on critically endangered, endangered and vulnerable species (CR, EN, VU) (Maxted et al. 2007). We also included data on the distribution of CWR species recently recognized as extinct (EX). We performed a conservation gap analysis similar to those proposed by Burley (1988) and Maxted et al (2007) by using distributional data for the priority CWR taxa to identify national CWR hotspots. We did not, however, suggest placement of the proposed hotspots based on already existing conservation areas coverage because of the insufficient effectiveness of plant conservation in these areas due to management and design gaps (Fig. 6). Instead, we prioritized geographical areas with the highest CWR distribution density. In three cases, localities of the highest CWR diversity coincided with already established protected areas; in these, genetic CWR reserves were proposed within protected area borders.

Finally, to propose CWR in situ conservation areas in Tajikistan, we used the CLUZ tool for QGIS based on the Marxan software for conservation planning (Smith 2019). For analytics, we used distribution data on food CWR species endangered at the national level. Additional determinants influencing locality selection included urbanized areas, percentage of food CWR species in relation to the subregional plant inventory and distribution of localities within country's borders (prioritizing evenness across the country). Highly urbanized areas were determined by coordinate search in Google Earth Pro (Gorelick et al. 2017).

3 Results and discussion

3.1 CWR inventory of Tajikistan

A total of 549 food CWR belonging to 36 families and 125 genera were identified as occurring in Tajikistan (Table 2). The families with the highest numbers of taxa include the *Poaceae* (27), *Brassicaceae* (18) and *Rosaceae* (14). The genera with the highest number of taxa include *Allium* (85),

Table 2 Overview of assessed taxa. *CWR*, total number of CWR species in listed genus; *1A*, number of native close relatives of globally important crops; *1B*, number of native distant relatives of globally important crops; *1C*, number of native relatives with undetermined relationship to globally important crops.

No.	Family	Genus	Related crop	CWR	1A	1B	1C
1	Amaryllidaceae	*Allium*	Onion, garlic, chives, leek, shallots	85	3	4	78
2	Poaceae	*Elymus*	Wheat	20	-	19	1
3	Caprifoliaceae	*Valerianella*	Corn salad	19	-	-	19
4	Asteraceae	*Scorzonera*	Scorzonera	17	-	-	17
5	Fabaceae	*Vicia*	Vetch, faba bean	16	4	3	9
6	Rosaceae	*Rosa*	Rose	16	-	-	16
7	Amaranthaceae	*Chenopodium*	Quinoa, canagua, coaihua	15	-	1	14
8	Fabaceae	*Cicer*	Chickpea	14	-	1	13
9	Convolvulaceae	*Convolvulus*	Sweet potato	13	-	-	13
10	Apiaceae	*Bunium*	Black caraway	11	1	-	10
11	Fabaceae	*Melilotoides*	Fenugreek	11	-	-	11
12	Rosaceae	*Crataegus*	Hawberry	10	-	-	10
13	Brassicaceae	*Lepidium*	Cress	9	-	-	9
14	Fabaceae	*Lathyrus*	Grasspea, Sweet pea	9	5	1	3
15	Polygonaceae	*Rheum*	Rhubarb	9	1	-	8
16	Polygonaceae	*Rumex*	Sorrel	9	-	-	9
17	Berberidaceae	*Berberis*	Barberry	8	-	-	8
18	Cyperaceae	*Cyperus*	Chufa	8	-	-	8
19	Fabaceae	*Medicago*	Alfalfa	8	-	1	7
20	Poaceae	*Hordeum*	Barley	8	2	6	-
21	Asparagaceae	*Asparagus*	Asparagus	7	1	-	6
22	Brassicaceae	*Arabidopsis*	Cabbage etc.	7	-	1	6
23	Fabaceae	*Trigonella*	Fenugreek	7	-	-	7
24	Asteraceae	*Lactuca*	Lettuce	6	2	1	3
25	Brassicaceae	*Isatis*	Cabbage etc.	6	-	1	5
26	Linaceae	*Linum*	Linseed	6	2	1	3
27	Poaceae	*Avena*	Oat	6	4	2	-
28	Rosaceae	*Pyrus*	Pyrus	6	2	-	4
29	Brassicaceae	*Sisymbrium*	Cabbage etc.	5	-	-	5
30	Grossulariaceae	*Ribes*	Currant, gooseberry	5	1	1	3
31	Papaveraceae	*Papaver*	Poppy	5	-	-	5
32	Poaceae	*Leymus*	Wheat	5	-	4	1
33	Solanaceae	*Solanum*	Potato, eggplant, tomato	5	-	1	4
34	Cupressaceae	*Juniperus*	Juniper berries	4	-	-	4
35	Fabaceae	*Glycyrrhiza*	Liquorice	4	1	-	3
36	Poaceae	*Aegilops*	Wheat	4	4	-	-
37	Poaceae	*Elytrigia*	Wheat	4	-	3	1
38	Poaceae	*Helictotrichon*	Oat	4	-	-	4
39	Rosaceae	*Amygdalus*	Almond, cherry, peach, etc.	4	2	1	1
40	Asteraceae	*Carthamus*	Safflower	3	1	1	1
41	Asteraceae	*Cephalorhynchus*	Lettuce	3	-	-	3
42	Asteraceae	*Cicerbita*	Lettuce	3	-	-	3
43	Brassicaceae	*Camelina*	Cabbage etc.	3	-	1	2
44	Brassicaceae	*Crambe*	Crambe	3	-	-	3
45	Brassicaceae	*Stroganowia*	Cress	3	-	-	3
46	Poaceae	*Eragrostis*	Teff	3	1	-	2
47	Poaceae	*Eremopyrum*	Wheat	3	-	-	3
48	Poaceae	*Setaria*	Foxtail millet	3	2	1	-
49	Rosaceae	*Prunus*	Almond, cherry, peach, etc.	3	-	-	3
50	Rosaceae	*Sorbus*	Rowanberry	3	-	-	3
51	Sapindaceae	*Acer*	Sugar maple	3	-	-	3

Table 2 (continued)

No.	Family	Genus	Related crop	CWR	1A	1B	1C
52	Solanaceae	*Lycium*	Goji berry	3	-	-	3
53	Solanaceae	*Physalis*	Ground cherry	3	-	-	3
54	Amaranthaceae	*Amaranthus*	Amaranth	2	-	-	2
55	Apiaceae	*Apium*	Celery	2	1	-	1
56	Apiaceae	*Pimpinella*	Anise	2	-	-	2
57	Asteraceae	*Epilasia*	Scorzonera	2	-	-	2
58	Asteraceae	*Steptorhamphus*	Lettuce	2	-	-	2
59	Brassicaceae	*Barbarea*	Cabbage etc.	2	-	-	2
60	Brassicaceae	*Brassica*	Cabbage etc.	2	2	-	-
61	Brassicaceae	*Cardaria*	Cress	2	-	-	2
62	Brassicaceae	*Eutrema*	Wasabi	2	-	-	2
63	Capparaceae	*Capparis*	Caper	2	1	-	1
64	Fabaceae	*Ononis*	Liquorice	2	-	-	2
65	Lamiaceae	*Mentha*	Mint	2	1	-	1
66	Lamiaceae	*Thymus*	Thyme	2	-	-	2
67	Poaceae	*Agropyron*	Wheat	2	-	1	1
68	Poaceae	*Bothriochloa*	Sorghum	2	-	-	2
69	Poaceae	*Digitaria*	Fonio	2	-	2	-
70	Poaceae	*Echinochloa*	Barnyard millet, Japanese millet	2	-	1	1
71	Poaceae	*Pennisetum*	Pearl millet	2	-	-	2
72	Poaceae	*Secale*	Rye	2	1	-	1
73	Poaceae	*Taeniatherum*	Barley	2	-	-	2
74	Rosaceae	*Rubus*	Raspberry, blackberry	2	1	-	1
75	Alismataceae	*Sagittaria*	Kuwai	1	-	-	1
76	Amaranthaceae	*Spinacia*	Spinach	1	1	-	-
77	Anacardiaceae	*Pistacia*	Pistacia	1	1	-	-
78	Apiaceae	*Carum*	Caraway	1	1	-	-
79	Apiaceae	*Cuminum*	Cumin	1	1	-	-
80	Apiaceae	*Daucus*	Carrot	1	1	-	-
81	Apiaceae	*Foeniculum*	Fennel	1	1	-	-
82	Asteraceae	*Cichorium*	Chicory	1	1	-	-
83	Brassicaceae	*Capsella*	Cabbage etc.	1	-	1	-
84	Brassicaceae	*Descurainia*	Cabbage etc.	1	-	1	-
85	Brassicaceae	*Eruca*	Rocket	1	1	-	-
86	Brassicaceae	*Erucastrum*	Cabbage etc.	1	1	-	-
87	Brassicaceae	*Nasturtium*	Watercress	1	-	-	1
88	Brassicaceae	*Rorippa*	Cabbage etc.	1	-	-	1
89	Brassicaceae	*Sinapis*	Cabbage etc.	1	1	-	-
90	Convolvulaceae	*Ipomoea*	Sweet potato	1	-	-	1
91	Cornaceae	*Swida*	Cornel berry	1	-	-	1
92	Cucurbitaceae	*Melo*	Muskmelon	1	1	-	-
93	Ebenaceae	*Diospyros*	Persimmon	1	-	1	-
94	Elaeagnaceae	*Hippophae*	Sea-buckthorn berry	1	1	-	-
95	Fabaceae	*Lens*	Lentil	1	1	-	-
96	Fabaceae	*Pisum*	Pea	1	-	-	1
97	Fabaceae	*Radiata*	Fenugreek	1	-	-	1
98	Grossulariaceae	*Grossularia*	Currant, gooseberry	1	1	-	-
99	Juglandaceae	*Juglans*	Walnut	1	1	-	-
100	Lamiaceae	*Origanum*	Oregano	1	-	-	1
101	Lythraceae	*Punica*	Pomegranate	1	1	-	-
102	Malvaceae	*Hibiscus*	Kenaf, meshta, rosella hemp	1	-	-	1

Table 2 (continued)

No.	Family	Genus	Related crop	CWR	1A	1B	1C
103	Moraceae	*Ficus*	Fig	1	1	-	-
104	Oxalidaceae	*Xanthoxalis*	Oca	1	-	-	1
105	Poaceae	*Asthenatherum*	Oat	1	-	-	1
106	Poaceae	*Brachiaria*	Little millet, proso millet	1	-	-	1
107	Poaceae	*Erianthus*	Sugarcane	1	-	1	-
108	Poaceae	*Heteranthelium*	Wheat	1	-	-	1
109	Poaceae	*Imperata*	Sugarcane	1	-	1	-
110	Poaceae	*Parapholis*	Wheat	1	-	-	1
111	Poaceae	*Paspalum*	Kodo millet, ditch millet	1	-	-	1
112	Poaceae	*Psathyrostachys*	Wheat	1	-	-	1
113	Poaceae	*Saccharum*	Sugarcane	1	1	-	-
114	Poaceae	*Trachynia*	Wheat	1	-	-	1
115	Polygonaceae	*Fagopyrum*	Buckwheat	1	1	-	-
116	Portulacaceae	*Portulaca*	Purslane	1	1	-	-
117	Rhamnaceae	*Ziziphus*	Jujube	1	1	-	-
118	Rosaceae	*Cerasus*	Almond, cherry, peach, etc.	1	-	-	1
119	Rosaceae	*Comarum*	Strawberry	1	-	-	1
120	Rosaceae	*Fragaria*	Strawberry	1	-	1	-
121	Rosaceae	*Louiseania*	Almond, cherry, peach, etc.	1	-	1	-
122	Rosaceae	*Malus*	Apple	1	1	-	-
123	Rosaceae	*Padellus*	Almond, cherry, peach, etc.	1	1	-	-
124	Rosaceae	*Persica*	Almond, cherry, peach, etc.	1	1	-	-
125	Vitaceae	*Vitis*	Grape	1	1	-	-

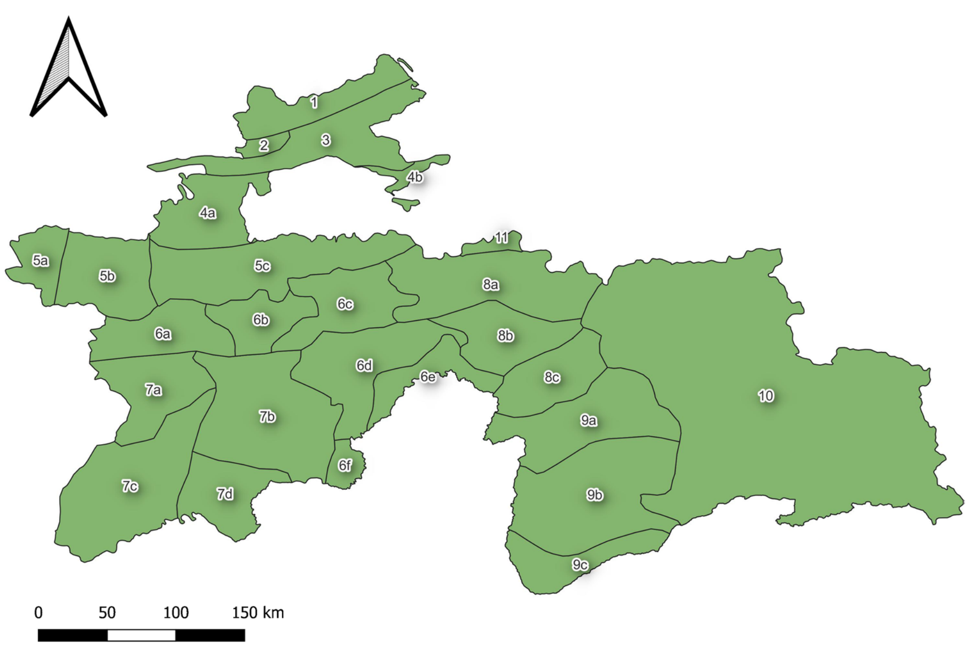

Fig. 1 Map of Tajikistan with its phytogeographical division (Grubov 2010): 1, Kuraminian; 2, Mogoltausian; 3, Prisyrdarian; 4a, Turkestanian A; 4b, Turkestanian B; 5a, Zeravshanian A; 5b, Zeravshanian B; 5c, Zeravshanian C; 6a, Hissaro-Darvasian A; 6b, Hissaro-Darvasian B; 6c, Hissaro-Darvasian C; 6d, Hissaro-Darvasian D; 6e, Hissaro-Darvasian E; 6f, Hissaro-Darvasian F; 7a, South Tajikistanian A; 7b, South Tajikistanian B; 7c, South Tajikistanian C; 7d, South Tajikistanian D; 8a, East Tajikistanian A; 8b, East Tajikistanian B; 8c, East Tajikistanian C; 9a, West Pamirian A; 9b, West Pamirian B; 9c, West Pamirian C; 10, East Pamirian; 11, Alaian.

Elymus (20) and *Valerianella* (19). Seventy-one taxa were recognized as native close relatives of globally important crops (1A), 67 as native distant relatives of these crops (1B) and 411 as native taxa with an undetermined relationship (although likely distant) to these crops (1C). According to Nowak et al (2020b) and Ovchinnikov (1957, 1963, 1968, 1975, 1978, 1981) there are 162 endemic species among the CWR priority species listed. The most numerous group of endemics consists of species from the genus *Allium* (48 species). There are also 9 endemic species belonging to the genus *Cicer*, 9 to the genus *Melilotoides*, 7 to the genus *Elymus* and 7 to the genus *Rosa*.

3.2 Spatial analysis

The highest potential richness of food CWR taxa occurred in intermountain valleys and in floodplains. This mainly entailed the southwestern phytogeographical subregions of Tajikistan — Tajikistan 7a–c, with up to 187 taxa. Conversely, the lowest richness occurred in the East Pamirian subregion (11) (Grubov 2010), with a maximum of 53 taxa (Fig. 2).

Comparing overall subregional plant richness to the number of food CWR taxa, the differences between these subregions were lower and the diversity in Pamirian intermountain valleys was more visible (Fig. 3). This analysis confirms an exceptionally high number of food CWR in southwestern Tajik regions not only in terms of their overall richness, but also their high proportion in relation to the overall local flora. The percentage of CWR in this area reached 15% of all plant species, while the percentage of food CWR in East Pamirian subregion was 7.3%. However, this analysis also shows that the highest percentage of CWR taxa in relation to local flora occurred in the Mogoltausian (Fig. 1 (2)) region, where the percentage value reached 16.7%.

The subregions with the highest overall number of important food CWR taxa were South Tajikistanian B (261 species), South Tajikistanian A (259 species) and Hissaro-Darvasian A (240 species). Subregions with the lowest numbers of food CWR species were Alaian (20 species), Turkestanian B (74 species) and East Pamirian (78 species) (Fig. 4).

After standardizing data by average number of food CWR taxa per 100 km^2 in each subregion, a much clearer diversity gradient was evident, from the eastern part of the country (least diversity) to the west (most) (Fig. 5). High values of species per 100 km^2 in Mogoltausian, Turkestanian B and Hissaro-Darvasian F regions were related to their relatively small areas and occurrence in numerous CWR distribution areas.

3.3 Conservation prioritization

Based on Nowak et al. (2020b) for the Tajik Red List of vascular plants at a national level, 180 (32.79% of total) have been assessed as threatened. These include 31 (5.65%) as critically endangered (CR), 85 (15.48%) endangered (EN), 62 (11.29%) as vulnerable (VU) and 2 (0.36%) as recently

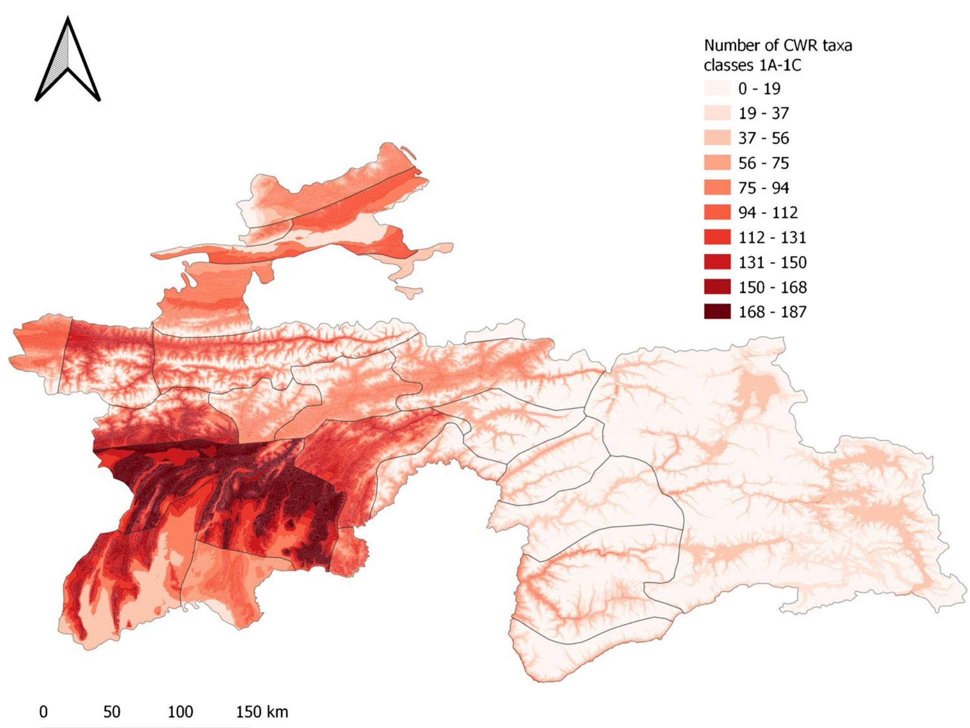

Fig. 2 Richness of food CWR species (1A–1C) in Tajikistan.

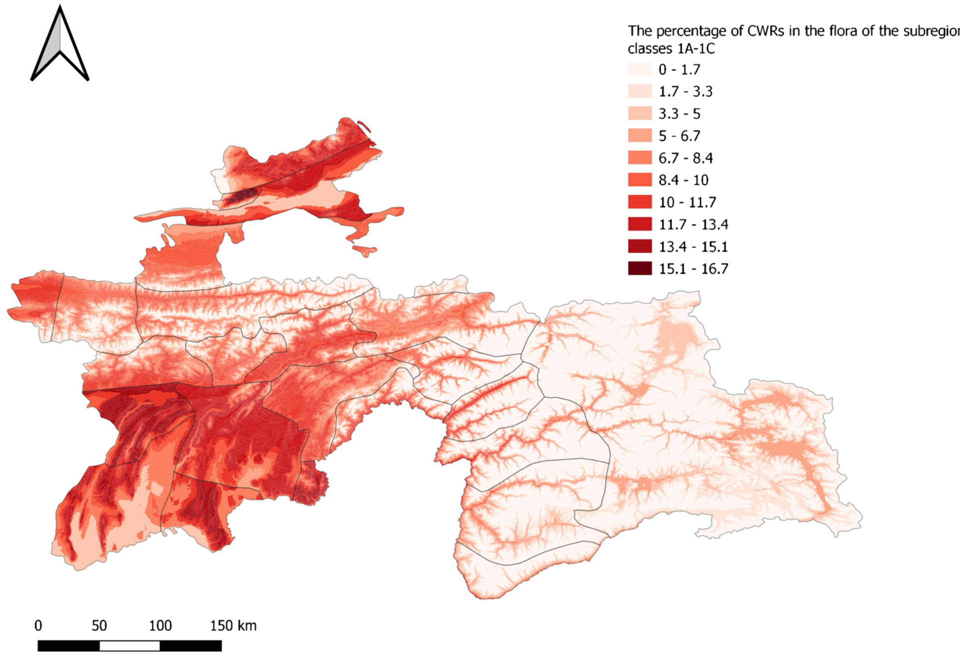

Fig. 3 Percentage of food CWR taxa (1A–1C) in relation to subregional plant diversity.

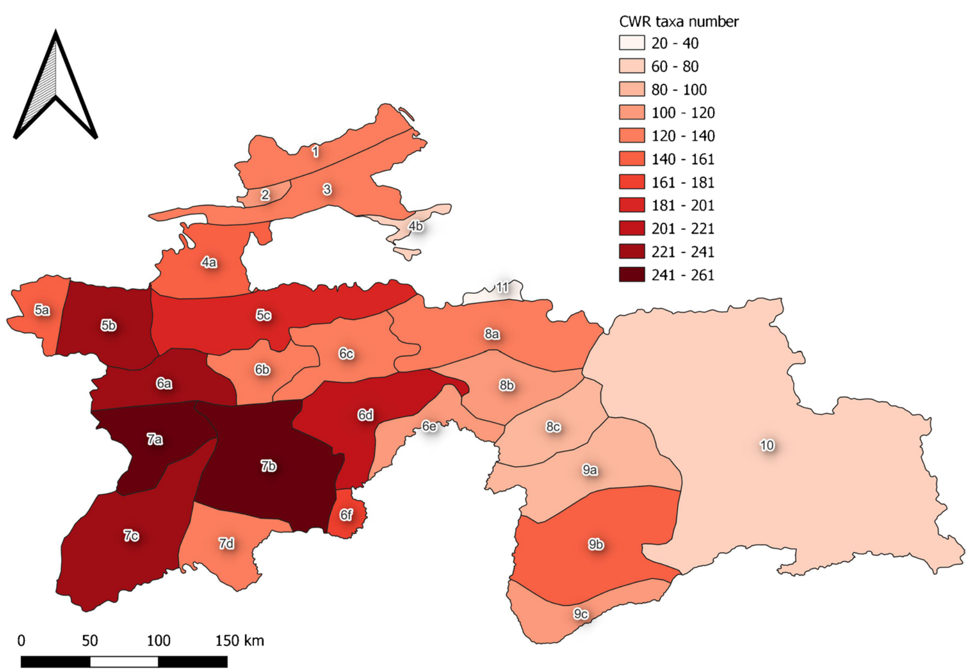

Fig. 4 Number of food CWR taxa (1A–1C) in different phytogeographical subregions.

extinct (not seen for more than 50 years). Globally, 72 Tajik food CWR taxa (13.11%) have been classified as threatened, including 20 critically endangered (3.64%), 32 (5.83%) endangered, 18 (3.28%) vulnerable and 2 (0.36%) extinct.

Based on richness and distribution of endangered CWR taxa, we identified 11 hotspots which might be considered as candidates for protected area status (Fig. 6).

Geobotanical subregions with the highest number of endangered CWR included 7a, South Tajikistanian A; 7b, South Tajikistanian B; and 7c, South Tajikistanian C. In these areas, the highest richness of endangered CWR taxa occurred in the valleys of rivers Kafirnigan, Vakhsh and Surkhob which should be given consideration as possible areas for CWR genetic reserves (Fig. 6 (1, 2, 3)). The proposed specific location of a genetic reserve for CWR conservation, when considering both existing conservation areas and CWR hotspots as suggested by Maxted et al (2007), would be situated in an overlaying area of Sarikhosor Nature Park and

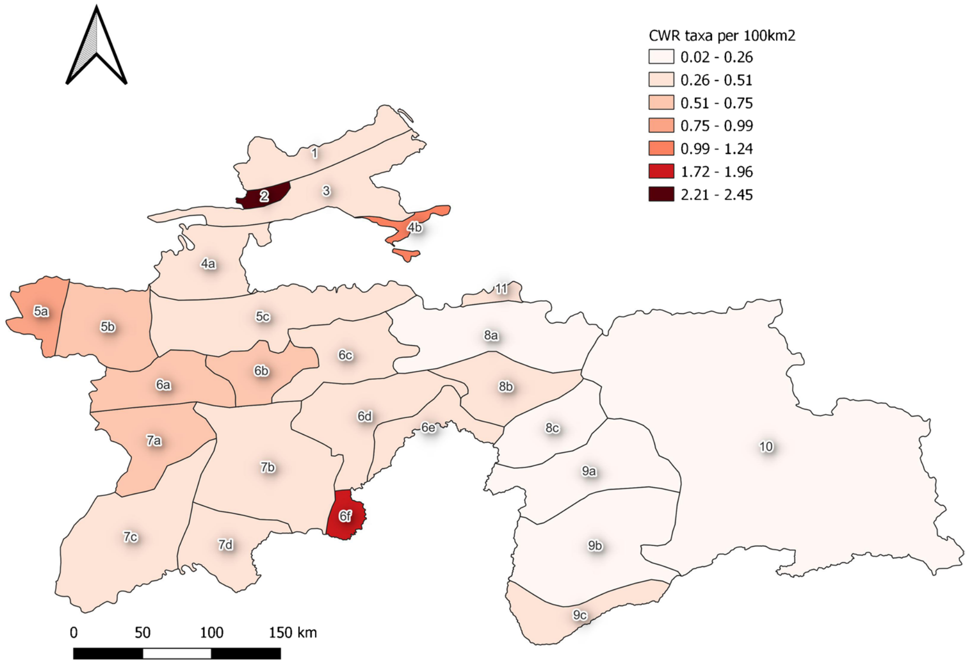

Fig. 5 Number of CWR taxa per 100 km^2 in different phytogeographical subregions.

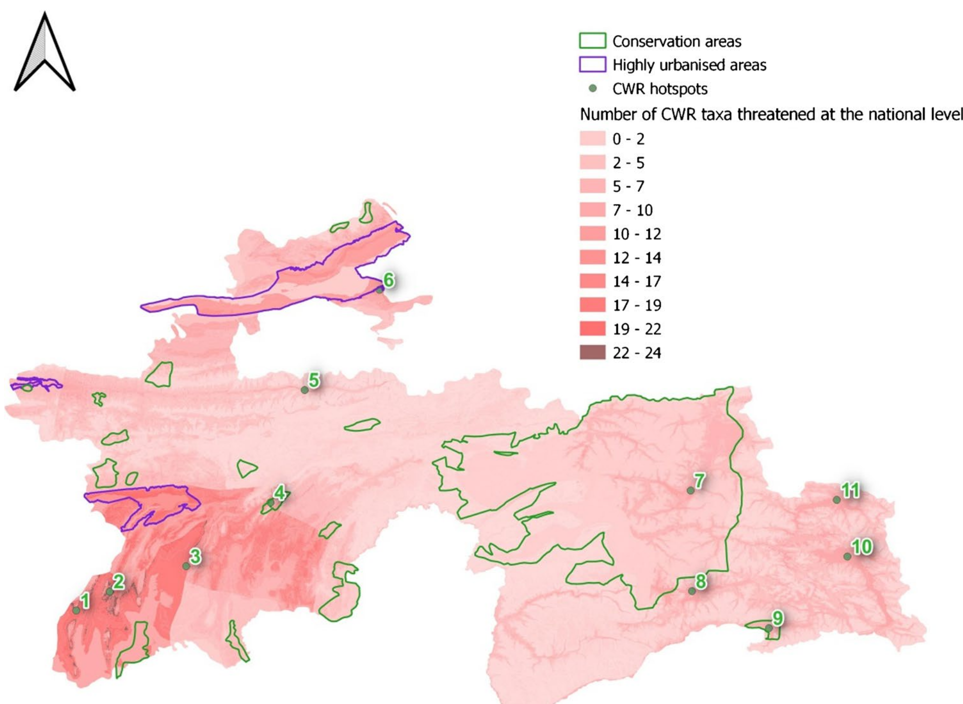

Fig. 6 Distribution of food CWR taxa considered as threatened at the national level and proposed locations of CWR conservation areas. 1, area between western Tajik border and Tuyuntau ridge (37.58341, 67.98862); 2, area between Payryaga-Tau mountain range and Vakhsh valley (37.7507, 68.2778); 3, area between Sarband Red Hills and Mount Khoja (37.95651, 68.91297); 4, area lying within Sarikhosor Nature Reserve (38.49089; 69.62135); 5, Zeravshan river valley (39.43542, 69.90817); 6, area between Konibodom and Isfara river (40.27517; 70.53624); 7, area within Tajik National Park, between Muzkul Nature Reserve and Verkhniy Muzkul Nature Reserve (38.59149, 73.15082); 8, Gunt valley (37.74664; 73.16204); 9, Zorkul lake valley lying in Zorkul Nature Reserve (37.43608, 73.80910); 10, Murgab valley (38.03711, 74.46748); 11, Rangkul lake valley (38.51304, 74.37843).

Nureksky Nature Reserve. Both areas are classified as habitat/species management areas (category IV) by the IUCN (UNEP-WMC 2021). Simultaneously, this area overlaps with distribution areas of high number of endangered CWR taxa (Fig. 6 (4)). Another area which should be recognized as a local hotspot for CWR genetic diversity and possible placement of a genetic reserve lies in the Zeravshan river valley (Fig 6 (5)). Despite high urbanization of the Prisyrdarian region, it may also be important to locate a proposed CWR protected area between the city of Konibodom and the Isfara River (Fig. 6 (6)).

East Pamirian CWR hotspots are characterized by less endangered CWR taxa and to lower floristic richness in general (Nowak et al. 2020a). The CWR hotspot locations based on the highest richness of endangered CWR taxa in the East Pamirian subregion were located in the Gunt valley, the eastern part of Murgab valley and the valley of Rangkul lake. Two hotspots were also located within the borders of the Zorkul and Muzkul Nature Reserve (IUCN Category VI) (Fig. 6 (7, 8, 9, 10, 11)).

We note that the placement of new conservation areas in central-west Tajikistan is likely to be more challenging due to high urbanization in this area.

3.4 Neighbouring countries and international comparisons

The area of Hissaro-Darvaz open woodlands of Tajikistan, as well as other “redkolesa” (groves) in Kazakhstan, Kyrgyzstan and Uzbekistan, has been described as a mix of steppe and sparse woodlands with important CWR species from the *Amaryllidaceae*, *Brassicaceae*, *Poaceae*, *Lamiaceae* and *Rosaceae* families, with particular attention given to wild nut and fruit forests (Stolton et al. 2006). This area is considered as an important hotspot of biodiversity globally but is still poorly known in terms of the composition of its native flora (Mittermeier et al. 2011; Liu et al. 2020).

We identified the highest potential richness of food CWR taxa in intermountain valleys and in floodplains of Tajikistan, findings which agree with research conducted in the neighbouring Kazakhstani Tian Shan (Sitpayeva et al. 2020). Our spatial analysis demonstrates that the highest richness of food CWR taxa occur in western regions of Tajikistan, potentially contradicting Vavilov’s emphasis on the Pamirs as the most important region in Middle Asia for food-related diversity (Vavilov 1926). This said, the presence of at least 78 CWR taxa of important crops in the East Pamirian subregion (38,629 km^2) should still be considered a high level of diversity, worthy of conservation and exploration. Our analysis provides novel insights into previously under-recognized diversity in the plant genetic resources community in the southwestern subregions — South Tajikistanian B (8781 km^2) with 261 taxa and South Tajikistanian A (4055 km^2) with 259 taxa.

While comparing the number of food CWR listed in the present analysis with global databases containing information on CWR occurring in Tajikistan and neighbouring countries, there are recognizable differences between these sources of data. The number of taxa recorded in our CWR list for Tajikistan is considerably larger than the number listed in GRIN-Global Taxonomy CWR database (+ 431 taxa) and that of the Harlan and de Wet CWR Inventory (+ 480 taxa) (Table 1). The absolute number obtained from our investigation is also considerably higher than counts for all neighbouring countries except China, which is 67 times larger than Tajikistan. These discrepancies are most likely a result of our more comprehensive and long-term effort to document Tajik flora. Thus, more CWR should also be expected to be recorded in the future in surrounding countries.

We also note that out of 549 native CWR taxa, 411 belong to group 1C — with an undetermined relationship to the main crop species. This is evidence that further work is needed in Tajikistan to understand its natural heritage of CWR and the potential value of these plants as genetic resources for crop improvement.

According to crop wild relatives’ global portal (2022), 29 national CWR inventories have been compiled. These include collective lists for the Nordic and Euro-Mediterranean countries. Moreover, in the last year, checklists for countries such as Tunisia (El Mokni et al. 2022) and Romania (Sandru 2021) have been compiled. Countries with a defined inventory of CWR include 5 African countries, 3 North American countries, 1 South American country, 4 Asian countries and 16 European countries. From these, the number of priority CWR species ranges from 105 species in Guatemala (Azurdia et al. 2011) to 871 in China (Kell et al. 2015). Considering the number of prioritized CWR species defined in our study for Tajikistan (549), this country may be distinguished as a CWR hotspot in terms of species richness.

3.5 Local importance of CWR

Many crops, including native CWR, are used by local people for food, medicine, energy and other livelihood purposes (Kassam et al. 2010). However, the Statistical Agency of Tajikistan (TAJSTAT 2018b) reports information only for a few agricultural crops, such as production and consumption of potatoes, cotton and grapes, and does not include CWR at all. Moreover, there is little research on this topic in Tajikistan. For example, a Google Scholar search using the key terms “crop wild relative” and “Tajikistan” shows only 37 results. Most of these mentions of Tajikistan appeared in publications about CWR occurring in other countries, without details about CWR in the region of interest (Google Scholar 2022). The same search terms entered into the general Google search engine returned 871 results, but similar problems were encountered (Google Search 2021). So far, Tajikistan has appeared in a global CWR study with 173 priority crop relatives shown, including a wheat relative — *Aegilops tauschii* Cossi possessing genes that increase resistance to Hessian fly impact, and a peach relative *Prunus ferganensis* (Kostov & Rjabov) Kovalev & Kostov showing drought resistance (Vincent et al. 2013). One study (Keusgen et al. 2006) reported that local people cultivate *Allium* species (common onion and garlic) and also collect related wild taxa for food (spices, vegetables) and medicinal purposes. Another study (Kassam et al. 2010) listed 58 plants used in the Pamirs for food and/or medicinal purposes. Of these, 27 were considered CWR species, 26 of which are present in our list. *Rumex confertus* Willd. listed by Kassam et al. (2010) is not considered a native species by Nowak et al. (2020b).

3.6 Plant genetic resource activities in Tajikistan

Given the diversity and importance of crops in this region, a number of measures have been undertaken for their conservation, breeding and management. Of particular interest is the review of international and local work carried out between 2006 and 2013 in Tajikistan, presented by Turok et al. (2013), which focused on conservation and evaluation of genetic resources. It should be noted that the efforts were mainly aimed at crop improvement, using existing, introduced and crossbred varieties, with no mention of the use of CWR in this process. The main objective was to achieve greater food security through increased yields, disease and pest control, improved drought tolerance and other traits. Nevertheless, these activities also included wild fruit trees. During this period, Turok et al. (2013) reported significant achievements. For example, germplasm of cereals, potatoes, food legumes, sorghum, pearl millet and various vegetable crops was enriched. Improved crop varieties with higher productivity and stress tolerance were developed and commercialized, including four new varieties of wheat, two of potato, one of barley, three of chickpea, one of pearl millet and many vegetable varieties, using new plant genetic material that has been introduced, tested and adapted to local conditions.

To preserve plant genetic resources, a national gene bank was opened in 2002 at the Research Institute of Crop Husbandry of Tajikistan, and the National Centre for Plant Genetic Resources was established in 2007 (Turok et al. 2013). In addition, 55 traditional varieties of fruit plants have been conserved in the national orchard in Sughd region with an area of 493 ha (Turok et al. 2013). For training and capacity building, a regional training centre for apricot genetic resources has been established in the Sughd branch of the Tajik Institute of Horticulture, where 180 varieties of apricot trees are grown and two national training centres for fruit trees have been established in the Tajik Institute of Horticulture in Dushanbe and the Pamir Biological Institute in Khorog (Turok et al. 2013). In terms of policy, a national law on "Conservation and sustainable use of crop genetic resources" has been developed (Turok et al. 2013).

One project coordinated by Bioversity International and funded by the Global Environment Facility Trust Fund, and implemented by UNEP in 2005, aimed to provide farmers, institutes and local communities with knowledge, methodologies and policies for in situ/on-farm conservation of horticultural crops and wild fruit species in Middle Asia, including Tajikistan (UNEP 2005). Through this project, it was evident that many valuable local populations and old varieties of peach, quince, cherry, pomegranate, persimmon and others are still grown in home gardens and small farms. The project identified 122 varieties and forms of apricots, 79 apples, 27 grapes, 22 pears, 9 walnuts, 7 mulberries, 6 pistachios and 3 peaches maintained by farmers in Tajikistan. Most of them have unique characteristics such as drought and frost resistance, excellent taste, fruit size and appearance (Turok et al. 2013).

Other noteworthy projects conducted by Bioversity International in Tajikistan include "Reviving biocultural heritage: Strengthening the socioeconomic and cultural basis of agrobiodiversity management for development in Kyrgyzstan and Tajikistan" in 2005–2009 funded by The Christensen Fund; "Conservation for diversified and sustainable use of fruit tree genetic resources in Middle Asia" initiated in 2013 jointly with Centre de Recherche Public Gabriel Lippmann (CRPGL), Luxembourg; and "Regeneration of Barley and Wheat Collections in Tajikistan", implemented by the Tajik National Centre for Genetic Resources with financial support from the Global Crop Diversity Trust in 2008-2011 (Turok et al. 2013).

3.7 Conservation concerns

An estimated 90% of fruit and nut forests in Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan have been destroyed in the last 50 years (Hunter 2012). For a long time, there was no reliable information on exactly how many vascular plant species, including CWR, are threatened in Tajikistan. Since the publication of Nowak et al. (2020b), the extent of the gradual decline in species diversity, mainly caused by threats from agriculture, urbanization and climate change, is better known. Unfortunately, there are still no reliable data on how many species are currently legally protected, due to the fact that there is still no law protecting flora in Tajikistan (Nowak et al. 2020a).

Habitat protection in 34 of the world's 825 ecoregions with the highest levels of agrobiodiversity was found to be significantly lower than the global average (Stolton et al. 2006). Ten of these have highly inadequate protection (less than 4% of protected areas). One of these areas is the

Alai-Western Tian Shan steppe zone (Kazakhstan, Uzbekistan, Tajikistan) (Stolton et al. 2008). On a brighter note, in recent decades, large protected areas have been established in the Pamir-Alai, now covering about 22% of the country (Safarov 2003). Among them are four strict nature reserves: Tigrovaya Balka, Romit, Dashtidjum and Zorkul nature reserves. Other protected areas that have been established, partly to protect juniper forests, are Dashtijum, Saivotin, Kusavlisai and Childukhtaron reserves. Zeravshan reserve has been established to conserve river valley vegetation. In addition, several agrobiodiversity management and conservation strategies and programmes have been developed in protected areas. Under the aforementioned UNEP project (2005), 11 nurseries were established on an area of 3.37 ha, which produced 87 local varieties including 22 apple varieties, 25 apricots, eight pears, eight peaches, six walnuts, nine grapevines, six mulberries and three pistachios (Turok et al. 2013). In addition, 135 local varieties including 41 apple, 35 apricot, 14 pear, 12 grape, 12 walnut, seven mulberry, six peach, four almond and four pistachio varieties were established in 15 demonstration sites covering 26.33 ha of land in farmers' orchards (Turok et al. 2013). Wild walnut, pistachio, apple and pear varieties were also established in three demonstration points of forestry companies covering 6.05 ha (Turok et al. 2013). In terms of protected areas for crop plant genetic diversity in Tajikistan, the IUCN Category Ia Dashtidjum State Nature Reserve covers 53,400 ha to protect stands of juniper, pistachio, almond, pomegranate and wild fig forests and open woods. The Zeravshansky (Sarezmsky) Reserve is also known to be rich in CWR (Stolton et al. 2006). In addition to the above, there are 19 specially protected areas; the best known include the Tigrovaya Balka, Romit, Dashtijum and Zorkul reserves (Muminjanov 2008).

However, inadequate management of protected areas continues to have a negative influence on plant diversity conservation. Many protected areas in Central and Middle Asia were established under Soviet rule and still apply historical (and in our opinion inadequate) standards. It is also important to note that the density of protected areas in Middle Asia is mainly concentrated in mountainous regions, which tend not to coincide with overall plant species richness, nor with our current understanding of CWR richness. Moreover, government institutions are still unable to manage and monitor all valuable vegetation types and plant populations. Due to the lack of legal guidelines for plant conservation even in strict nature reserves, threats from human activities such as road construction and mining in the Romit Valley continue to affect plant diversity (Nowak et al. 2020a). Improving the effectiveness of nature conservation in the Pamir-Alai requires urgent development of action plans with specific priorities for hotspots of this diversity.

Our research shows that the location of current conservation areas will not provide sufficient protection for Tajik CWR. To confirm the most effective locations of CWR protected areas based on our research, further geobotanical surveys will need to be conducted in selected areas, and new protected areas will probably need to be established, especially in the southwestern regions.

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Code availability Not applicable.

Declarations

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Consent for publication Not applicable.

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