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Importance of agriculture for crop wild relatives conservation in Switzerland

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A R T I C L E I N F O

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A B S T R A C T

While considered an essential part of the genetic diversity of plants, Crop Wild Relatives (CWR), are rarely the primary focus of conservation strategies. Despite this, a large portion of wild flora shares genetic relationships with cultivated species. The conservation of CWR presents not only a challenge to conservationists but also an opportunity to engage other sectors, such as agriculture, in a collaborative effort towards biodiversity preservation. Here, we quantified the association between agricultural areas and the distribution of CWR in Switzerland. To achieve this, we compiled a comprehensive checklist of Swiss CWR representing 2′227 taxa, identifying 285 taxa as priority CWR for Switzerland. Following a taxa-specific ecogeographic analysis, we analysed the extent to which priority CWR are already contained in existing protected areas as well as their distribution in the agricultural area. The observed species richness of priority CWR was compared to the modelled priority CWR richness to identify potential conservation gaps. Among the 285 priority CWR, 64 taxa (22.5%) are not significantly better covered by existing protected areas than a random species. However, 28.8% and 15.5% of these priority taxa are more frequently distributed in agricultural and summer grazing areas respectively than random expectations. A clear deficit of species richness of these priority CWR was inferred on lowlands, possibly related to a lower sampling effort. We further identified a minimal network of 39 complementary sites that contains all Swiss priority CWR and that could be used as a primary conservation infrastructure. Our results support better consideration of CWR in agricultural areas, an important “reservoir” for expanding specific measures of conservation.

1. Introduction

Crop diversity, across and within species, is a major driver of agricultural resilience. However, it is estimated that seventy-five per cent of crop diversity was lost globally during the 20th century (FAO, 2010). The loss of allelic diversity in crops is partly inherent to the breeding process but also due to a wide range of other socio-economic factors that gradually led to crop genetic erosion (Hajjar and Hodgkin, 2007; Khoury et al., 2022). Indeed, most crops originate from the domestication of wild ancestors (Engels and Thormann,

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2020). Therefore, attempts to identify and save Crop Wild Relatives (CWR, Maxted et al., 2007) appear as a priority. Safeguarding genetic diversity will allow access to key traits for the next generations of farmers and breeders and, in turn, may improve food security. More generally, CWR often represent a very significant portion of the wild flora (Maxted et al., 2006). A better focus on their conservation may raise unexplored ways to limit genetic erosion.

Many breeding programs increase their genetic diversity by integrating CWR: for example, the resistance to late blight (*Phytophthora infestans* (Mont.) de Bary) from the wild potato *Solanum demissum* Lindl. or the stem rust resistance (*Puccinia graminis* Pers.) from wheat's CWR *Aegilops tauschii* Coss. (Hajjar and Hodgkin, 2007; Dempewolf et al., 2017). Since the genepool concept was described in the seventies (Harlann and Wet, 1971), growing international momentum for the conservation of CWR has emerged, side-by-side with the efforts aimed at global biodiversity conservation (Maxted et al., 2006). Recently, global (Maxted et al., 2012; Castañeda-Álvarez et al., 2016; Vincent et al., 2019) as well as national inventories of CWR, revealed an urgent need for measures to preserve CWR diversity (e.g. Rubio Teso et al., 2021). Many countries performed their own CWR checklist, for example, Portugal (Magos Brehm et al., 2008), Norway (Phillips et al., 2016), the Czech Republic (Taylor et al., 2017), the UK (Jarvis et al., 2015), Netherlands (Treuren et al., 2017), Turkey (Tas et al., 2019), the USA (Khoury et al., 2013), mostly pursuing similar aims but slightly divergent methodologies. The procedure typically comprises several successive steps: checklist, prioritisation and identification of potential sites for their conservation, often referred to as gap analysis (Maxted et al., 2007). In addition, metrics representative of the relative importance of crops for agriculture could be scored, as it has been performed globally, to inform food security policy (Castañeda-Álvarez et al., 2016).

In Switzerland, a national action plan to conserve crops in situ and ex situ has been implemented since 1999. It is not primarily focusing on CWR and has only partially succeeded in counteracting the decrease in agrobiodiversity (Guntern et al., 2013). Swiss agriculture covers about a third of the country's surface and therefore represents major pressure on ecosystems (FOAG and FOEN, 2013; Guntern et al., 2013). The most recent data showed that more than half of the habitats and 36% of all species are threatened or near-threatened (Guntern et al., 2013). Interestingly, Swiss farmers are entitled to agri-environmental subsidies, in the form of direct payment following a "cross-compliance" scheme. These subsidies are conditioned to a set of practices and provide proof of ecological performance (Jarrett and Moser, 2013). Briefly, this entails limited fertilization and pesticide use, crop rotation, animal welfare measures and 7% of the land allocated as ecological compensation areas.

Because CWR are intrinsically related to crops, they may exhibit similar habitat preferences, assuming the concept of phylogenetic niche conservatism (PNC; Harvey and Pagel, 1991). PNC is the tendency of lineages to retain their niche-related characteristics throughout speciation events and across macroevolutionary timescales (e.g. Crisp and Cook, 2012; Losos, 2008; Pyron et al., 2015; Wiens et al., 2010). This pattern has been supported by a wealth of evidence (Peterson, 2011). Methods to test for such niche conservatism typically employ randomization tests on species distributions (e.g. Broennimann et al., 2012; Glor and Warren, 2011). They have been used to quantify varying amounts of PNC among the CWR of grapevine *Vitis* (Callen et al., 2016), sunflower *Helianthus* (Kantar et al., 2015) and olive *Olea* (Ashraf et al., 2023). If CWR present some PNC with their related crops, it can be assumed that a significant portion of these wild relatives would thrive in habitats associated with agricultural areas where most of the crops are grown.

Given the significant impact of agricultural activities on wild ecosystems and the possible niche conservatism between crops and their wild relatives, we aimed to explore the association between agricultural areas and the distribution of CWR. To address this, we compiled a list of priority CWR for Switzerland and conducted an extensive ecogeographical analysis of their distribution using observed and modelled species distributions. We then assessed the extent to which these priority CWR are already protected under various types of protected areas. Subsequently, we determined the overlap between the distribution of priority CWR and agricultural land and identified a minimal network of sites that encompass all the priority CWR across Switzerland. By combining data on the state of CWR conservation with their overlap with agricultural areas in Switzerland, we draw conclusions on how to improve conservation policies by involving stakeholders from the agricultural sector. We believe our approach can be generalized to other countries or regions and can enhance the consideration of the link between land management and public action in supporting CWR conservation and biodiversity more broadly.

2. Methods

2.1. List of crops with relevant use in Swiss agriculture

First, a list of 129 agricultural crops that are grown in Switzerland was built (Table S1). It contains major and minor crops as defined by Khoury et al. (2013). This comprises all species from Annex 1 of the International Treaty on Plant Genetic Resources for Food and Agriculture and all crops contained in the Swiss national databank for cultivated plants (FOAG, 2022a) and trade data (FOAG, 2022b). In addition, a list of the most common forage species was obtained using the latest Swiss forage crop recommendations (Suter et al., 2019) as well as a list of modern medicinal plants from a published ethnobotanical survey (Cero et al., 2014). Species cultivated as aromatics were collated with help from local experts. Eventually, we also considered species with reported use in forestry, ecosystem restoration and industry from the GRIN Global database and other relevant literature (USDA, 2023).

2.2. Swiss CWR checklist and prioritization

A checklist of CWR was created for Switzerland primarily using a floristic approach (Maxted et al., 2015). Information about taxa located in Switzerland was updated and harmonized with the latest version of the checklist of the Swiss Flora (InfoFlora, 2020). The list obtained was then compared and complemented with the Crop Wild Relative Catalogue for Europe and the Mediterranean for any missing taxa (Kell et al., 2008, updated version by Maxted & Kell, personal communication).

We then linked every possible taxon of the CWR from the checklist with a related crop and their reported use in the literature or by experts (Table S1). We documented the primary and, when available, secondary crop uses based on the following categories: food, forage, medicinal, aromatic, industrial, restoration, forestry and ornamental (Table 2 and Table S2). We considered any species contained in a genus having at least one reported crop being used, or being directly cultivated, wild used or wild harvested, as a CWR. This decision was made due to the often-unclear status of species that were traditionally directly used or harvested in the wild but that can be now cultivated (e.g. in forestry or many aromatic and medicinal plants). Compiling data from published checklists from other European countries and the US (e.g. Magos Brehm et al., 2008; Khoury et al., 2013; Fielder et al., 2015; Phillips et al., 2016; Taylor et al., 2017; García et al., 2017; USDA, 2023, Table S2), we analysed the extent of the relationship between crops and their respective CWR, defined by either the Gene Pool (GP) and the Taxon Group (TG) concepts (Harlann and Wet, 1971; Maxted et al., 2006). Importantly, we also included 18 CWR of crops not cultivated in Switzerland, such as crops from the genera *Setaria* and *Hedysarum*. Although Switzerland does not have formal responsibility for these taxa, preserving some of their genepools could be beneficial for other agricultural systems, particularly considering global climate change. In order to keep a reasonable number of taxa in focus, ornamental-only crops were removed as they represent a very large portion of the flora.

We compiled a shorter list of priority CWR, for which conservation measures should be ensured to maintain genetic diversity among populations. Four criteria have been selected and scoring applied on a scale from 0 (low priority) to 4 (high priority): 1. a high priority score of 4 points was assigned to CWR that are associated with currently used crops in Switzerland (panel food and feed in Table S1); 2. if a CWR had a close genetic relationship to a crop, a higher score was attributed (GP1/TG1 >TG2/GP2 >TG3/GP3 >TG4); 3. Threat status was assigned based on the IUCN Red List classification (Bornand et al., 2016), with 4 points to taxa classified as Critically Endangered (CR) and Data Deficient (DD), 3 to Endangered (EN), 2 to Vulnerable (VU), 1 to Near Threatened (NT) and 0 to Least Concerned (LC); 4. Finally, the origin of the taxa was taken into consideration, with a maximum priority score (4) for indigenous and archeophytes (non-native species introduced in “Ancient Times”, i.e. before the 16th century), a score of 1 for European neophytes (non-native species introduced after the 16th century), and a score of 0 for non-European neophytes. The origin status was sourced from InfoFlora (2020), which is the competence centre for information on the wild plants of Switzerland. Scores were summed across the four criteria and taxa with a score equal to or higher than 10 were classified as priority CWR. Furthermore, this list of priority CWR was reviewed by experts, who identified 85 supplementary taxa that were categorized as priority CWR in an initial preliminary study based solely on expert's knowledge (Häner et al., 2009, Table S2). In this initial work, taxa were ranked on a 3-grades scale (from highly likely to unlikely) for potential use in breeding (as CWR) or direct use (as wild-used Species; Häner et al., 2009). Two workshops were held with the experts, followed by targeted questionnaires for each crop group. The list of the priority CWR for Switzerland was then compared to the recently published inventory of priority European CWR (Rubio Teso et al., 2020) and the National Priority Species (NPS) list for conservation measures in Switzerland (FOEN, 2019). It is important to note that the priority CWR list generated in this study should not be conflated with the NPS, as the latter is based solely on criteria only related to threat status and conservation measures.

2.3. Species distribution, protected area and agricultural surface

To identify species richness, observations of priority CWR recorded between 01/01/2002 and 31/12/2019 were extracted from the database of the Swiss national data centre for vascular plants (InfoFlora, 2020). This centre collects all the possible observations of the Swiss flora gathered by researchers, botanists, monitoring programs or citizen scientists, but excluding herbarium records. Cultivated or sub-spontaneous occurrences were removed, so as occurrences with an uncertainty > 250 m. To avoid duplication, species observations were disaggregated keeping a minimal distance of 100 m between occurrences. In total, 567′319 observations were used in the analysis.

To summarize a comprehensive set of protected areas over the country we combined the geographical layers of Federal inventories (FOEN, 2018), the natural reserves managed by Pro Natura, forest reserves (FOEN, 2018) and the Swiss National Park. The agricultural surface has been determined using data from Szerencsits et al. (2018), with a distinction between the actual agriculture surface and the surfaces dedicated to summer grazing being retained.

To assess if the distribution of each priority CWR was significantly overlapping the protected areas, we generated 1′000 random distributions. These random distributions consist of 1′991 points (corresponding to the average number of occurrences among the priority CWR), sampled following the sampling bias found in the InfoFlora database (Fig. 1). For each randomization, we measured the

Table 1
Checklist of CWR in Switzerland. A checklist of CWR has been compiled by merging data from the European CWR list and the latest version of the checklist of the Swiss Flora (InfoFlora, 2020). CWR associated with ornamental-only crops have not been considered for further for prioritization.

	No of CWR taxa
Swiss CWR according to CWRIS (Kell et al., 2008)	4464
Swiss CWR checklist after correction using the checklist of the Swiss Flora (InfoFlora, 2020)	3006 (66.7% of the flora)
Swiss CWR checklist (without neophytes and invasive species and without taxa related to ornamentals only)	**2227**
Priority CWR (incl. expert's opinion, see Methods)	**285**
Priority CWR in the Red List (Bornand et al., 2016)	90
Priority CWR in the list of the National Priority Species (FOEN, 2019)	92

Table 2
List of CWR taxa according to their reported use. This is based on the 2′227 taxa from the CWR checklist and the 285 priority taxa (Table S2), for which results are given between brackets. The number of taxa is indicated according to their use (columns), their degree of relationship to the crop (documented belonging to the gene pool or taxon group of a crop), their documented use (either directly or through breeding), and their threat status on the Red List (IUCN, 2016). A single taxon can belong to multiple categories simultaneously.

Number of CWR taxa	Total	Food	Forage	Medicinal	Aromatic	Industrial Restoration Forestry	Ornamental
In total	2227 (285)	334 (125)	240 (115)	1792 (206)	95 (20)	393 (7)	857 (21)
With documented relationship to crop	358 (183)	192 (99)	140 (89)	244 (127)	30 (3)	6 (2)	20 (7)
With documented use	817 (186)	139 (66)	134 (128)	695 (134)	42 (15)	70 (7)	245 (16)
With threat status (CR, EN, VU, DD)	444 (91)	62 (48)	39 (30)	349 (58)	16 (3)	54 (0)	168 (5)

proportion of the random distributions covered by the protected area, allowing us to test if the taxa were significantly more protected by the existing protection area than expected by chance.

2.4. Species distribution modelling

Species distribution models (SDMs) relate species occurrences to environmental factors. Once this relation is statistically

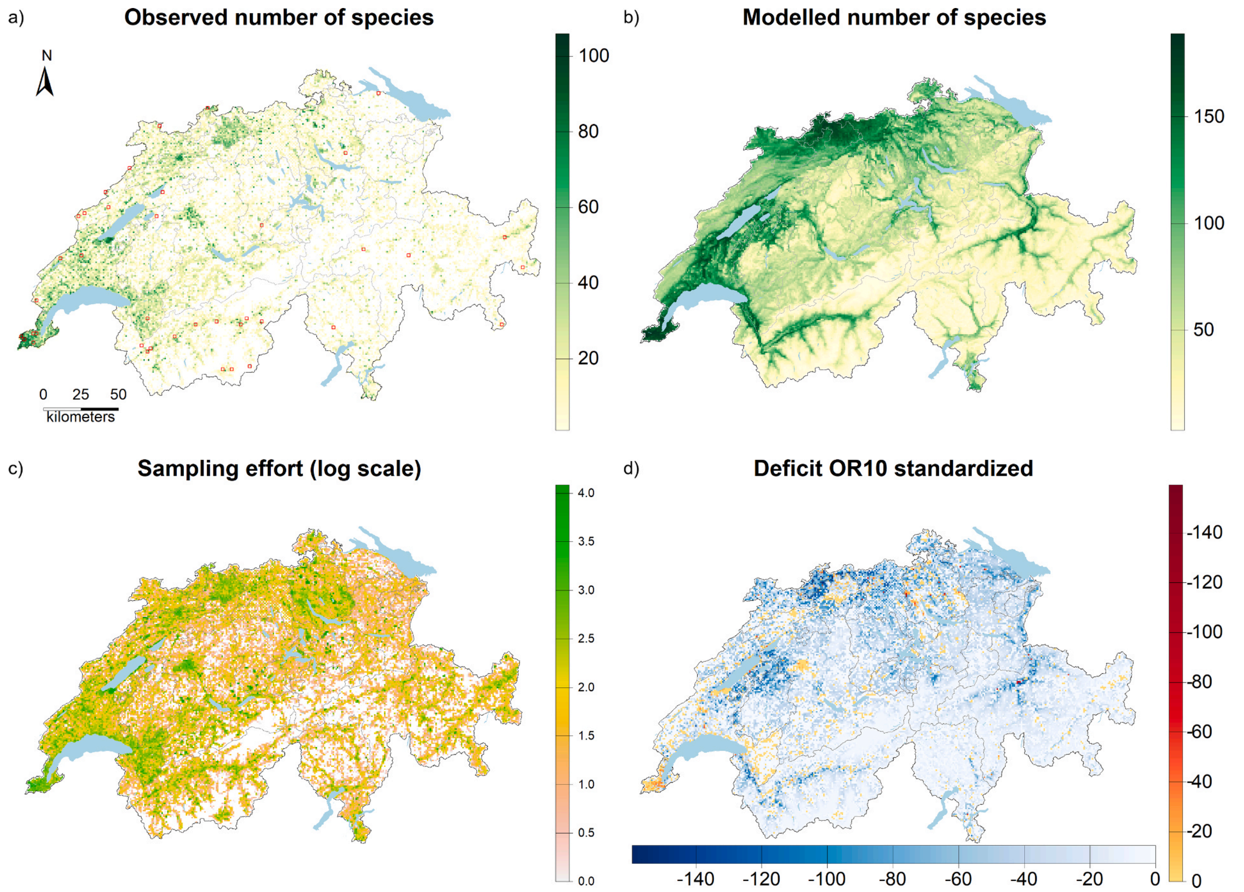

Fig. 1. Distribution of priority CWR in Switzerland. a) Number of priority CWR observed in Switzerland. Red sites represent the minimum number of sites to cover all CWR species in the country. b) Modelled distribution of priority CWR in Switzerland obtained by stacking the potential distribution of each priority CWR in Switzerland. c) Sampling effort represented by logarithm (base 10) of the number of observations for all plant species in the InfoFlora database for the period 2001–2019. d) Deficit area between observed and standardized modelled distribution of priority CWR in areas with a high ($\geq$ 500 observations per km^2; yellow to red) or lower sampling effort ($<$ 500 observations per km^2; light to dark blue).

quantified, it is then possible to derive predictions of species potential distributions if the predictors are spatially explicit (Guisan and Thuiller, 2005; Elith and Leathwick, 2009). SDMs are particularly useful for conservation practices (Guisan et al., 2013). In this study, we built potential distribution maps derived from SDMs for every taxon with enough observations ($n = 10$). For each species, predictors were selected from an initial set of 33 variables including information about the topography, climate, soil and remote sensing (Table S3). A preliminary variable selection was processed for each taxon to reduce the number of predictors and avoid model overfitting. This selection process retained the variables that most effectively discriminated between species observations and the available conditions in the study area (see Appendix 1 for more details). After this initial step, the number of variables varied between two and nine, depending on the species (Appendix A1). These predictors were related to species occurrences by combining three modelling algorithms (general additive models, MaxEnt and gradient boosting model) into an ensemble modelling approach (Thuiller et al., 2004; Araujo and New, 2007), or an ensemble of small models (ESM, Breiner et al., 2015) depending on the number of observations (Appendix A1). Models were evaluated with 4-fold cross-validation with an index combining 4 commonly used indices of accuracy (AUC, TSS_{max}, Sensitivity and continuous Boyce index, Appendix A1). This index is analogous to a correlation varying between -1 (total counter predictions) and 1 (perfect predictions), 0 meaning random predictions.

2.5. Patterns of species richness

We estimated the difference between the modelled and the observed species richness to map the deficit between the observed and the modelled number of priority CWR species. Because the stacking of SDM maps is known to be sensitive to the threshold used to binarize continuous suitability maps (Benito et al., 2013; Calabrese et al., 2014; Schmitt et al., 2017), we applied five different thresholding criteria to reclassify the individual species suitability maps into potential presences and absences (Appendix A1). As modelled species richness obtained by stacking SDM maps tends to be overestimated (Guisan and Rahbek, 2011; Calabrese et al., 2014), we applied a quantile normalization between the map of the observed number of species and the modelled number of species. Quantile normalization was initially developed for the analysis of high-throughput data in molecular biology (Amaratunga and Cabrera, 2001; Bolstad et al., 2003). In our case, it allows standardizing all the distributions of richness (observed and modelled) with the same minimal and maximal values, while keeping their statistical properties (Hicks & Irizarry, 2015). Finally, we included the sampling effort to interpret the deficit between modelled and observed distributions. We gathered all observations for all the plant taxa recorded in the database of InfoFlora between 2001 and 2019 and categorized areas with a high and low sampling effort (respectively ≥ 500 and < 500 observations per km^2).

2.6. Complementary analysis to delimit a minimal conservation network

A complementary analysis was carried out to obtain a spatial network that most efficiently covers priority CWR species. We selected the site (i.e. the cell in a 4 km^2 grid) with the highest number of taxa, excluded these taxa from the analysis and iteratively repeated this process until all taxa were covered (Rebelo, 2014). This analysis was applied to the observations of the 285 priority CWR species distributed on a 4 km^2 grid. All the data analysis was run with a custom R script available on GitHub (Appendix A1; R version 4.0.3; R Core Team, 2020).

3. Results

3.1. Swiss CWR checklist and prioritization

A total initial number of 3′006 taxa were identified as CWR, representing 66.7% of the described Swiss flora (Table 1). Among those, taxa classified as invasive neophytes, as well as taxa related to ornamental-only crops, were removed, leaving 2′227 CWR, of which 2′045 were related to any agricultural use (namely food, feed, medicinal, aromatic and restoration). Noteworthy, while the threat status of various taxa has been extensively documented (Red List, National Priority Species List threats), only a relatively small proportion of CWR relationships have been reported. We found only 358 taxa (16%) for which the genetic relationship to their crop (gene pool or taxon group) could be documented (Tables 2 and S2).

Based on four criteria: the relationship to a species used in the Swiss agroecosystem, the genetic distance to its related crop(s), its threat status, and its origin, 285 CWR were considered as priority CWR. The expert input in the prioritization process allowed for the integration of species such as *Artemisia annua* L. and *Rhodiola rosea* L. into the priority CWR list. These species have been subjects of local research for medicinal applications and breeding (Simonnet et al., 2008; Vouillamoz et al., 2012). Out of the 285 priority CWR, 257 taxa have a national Red List threat status. This includes 148 Least-Concerned (LC; 52%), 21 Near-Threatened (NT; 7%), 49 Vulnerable (VU; 17%), 24 Endangered (EN; 8%), and 15 Critically Endangered (CR; 5%) taxa. Among these priority CWR, 92 taxa (32%) belong to the National Priority Species list requiring conservation measures (FOEN, 2019), and 95 taxa (33%) are included in the European inventory of priority CWR (Table S2). The priority CWR are primarily related to crops with medicinal (206 taxa; 72%), food (125; 44%), and forage (115; 40%) uses. In contrast, fewer are related to crops with ornamental (21; 7%), aromatic (20; 7%), and industrial, restoration, or forestry uses (7; 2%; Table 2). Note that 200 priority CWR (70%) are related to crops that have multiple uses.

3.2. Distribution, richness, and deficit areas of priority CWR in situ

The areas with the highest CWR taxa richness were found in the northwest region of the country at relatively lower altitudes

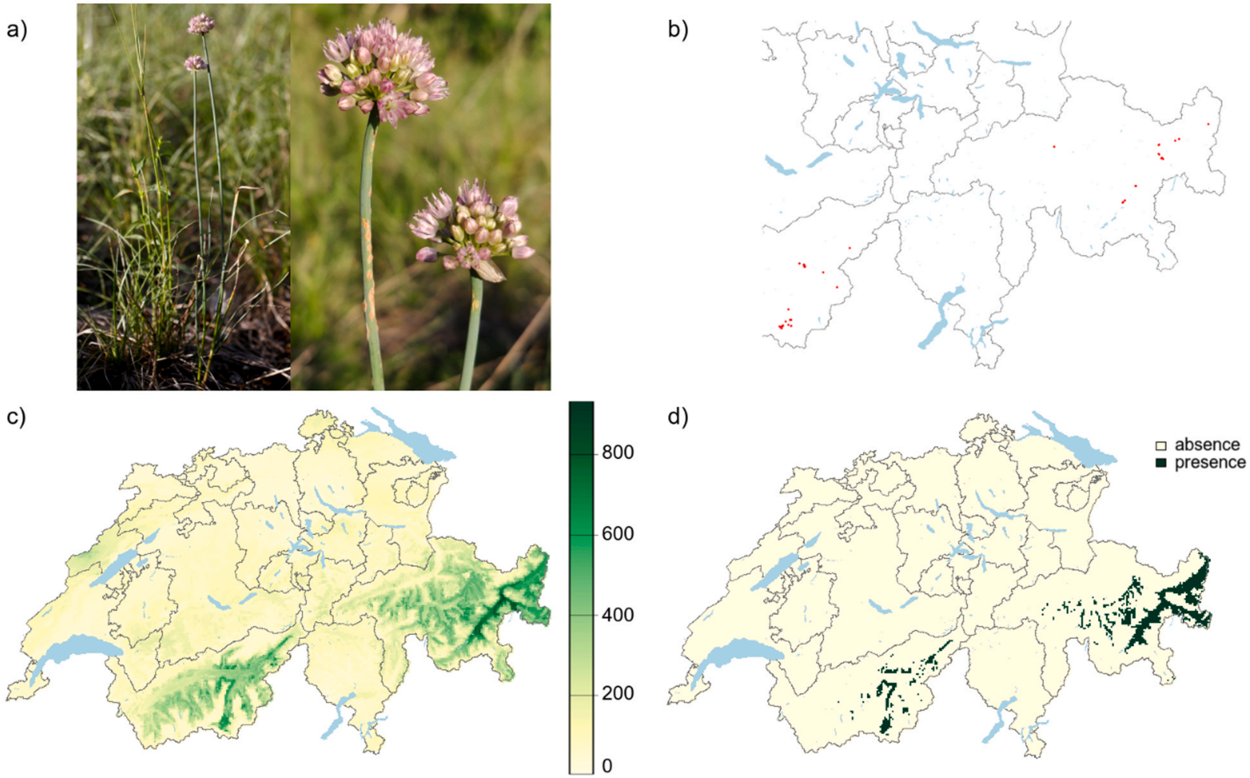

Fig. 2. Distribution of *Allium lineare* in Switzerland. a) Photos of this priority CWR of the onion. Photos by courtesy of Andrea Gygax. b) Red dot represent the known distribution in Switzerland. c) Continuous habitat suitability maps predicted by species distribution models. d) Binarised potential distribution map. Here, we show a potential binary map reclassified with an omission ratio set to 10% (OR10), but four other classification criteria were also used to compute the species richness (Table S4).

(Fig. 1a). The observed richness is correlated with the sampling effort (Spearman correlation between the number of observations and species richness at a 1 km^2 resolution: rs = 0.799, n = 39′961, p-value < 0.001; Fig. 1c).

SDMs were generated for 265 of the 285 priority CWR (Appendix A2). For 20 taxa, the reduced number of observations available from the database (< 10) could not generate reliable modelling. These 20 taxa are composed of 10 known rare species covered by the national Red List belonging to the National Priority Species list, 7 subspecies requiring expert knowledge to reach this determination level and 3 taxa with very few documented observations in Switzerland. The consensus evaluation index varies between 0.4 and 0.968 (with an average of 0.774), supporting that the modelled distributions are accurate. For each priority CWR taxa, like, for example, *Allium lineare* L. (Fig. 2), maps representing observations, habitat suitability and potential distributions were generated (Appendix A2). For *A. lineare*, clear potential distribution was flagged in Wallis and Graubünden (Fig. 2c & d). Only 10 species were modelled with an accuracy below 0.6 (Table S4). These 10 taxa were removed from the analysis of the deficit, in addition to the 20 taxa with insufficient observations. Therefore, the comparison between observed and modelled distributions of the species richness was done with 255 species accurately modelled.

Not surprisingly, the modelled and observed distribution of priority CWR are correlated (Spearman correlation between observed and modelled species richness at a 1 km^2 resolution: average rs across the 5 thresholding methods = 0.491 ± 0.016, n = 39′961, p-value < 0.001; Fig. 1a and b). The modelled richness correlates with the sampling effort much less than the observed species richness (Spearman correlation between the number of observations and the modelled species richness at a 1 km^2 resolution: average rs across the 5 thresholding methods 0.412 ± 0.019, n = 39′961, p-value < 0.001, Fig. 1).

The comparison between observed and potential species richness reveals an important deficit at lower elevations, with pronounced gaps in regions like the Swiss Plateau, Wallis, Ticino, and Graubünden. However, much of this deficit seems to occur in areas with low sampling effort. Conversely, in regions with more intensive sampling, the deficit is less pronounced (Fig. 1d).

3.3. Distribution of priority CWR in protected and agricultural areas

On average, priority CWR have 33% ± 21.4% of their distribution located within protected areas (Table 3). This is significantly more than the distributions of the null model (13.9% ± 0.1%; p-value of a two-sample t-test < 0.001; Table 3). However, 64 species (22.5% of the priority CWR) are not significantly more protected than a random species, with an average protection covering 7.46% ± 4.4% of their distribution (Table S5). Taking advantage of our data, we considered further the probability for priority CWR, as relatives of crop plants, to share some habitats with cultivated plants in the agricultural or summer grazing areas. The eco-geographical analysis reveals that on average 21.9% ± 15.3% of the distribution of the priority CWR are located within the agricultural area (Table 3). This is not significantly more than the distributions of the null model (26% ± 1%; p-value of a two-sample t-test = 1; Table 3) but it is noticeable that 89 species (31.2% of the priority CWR) are significantly more distributed in the agricultural area than expected by chance (Table S5). Finally, priority CWR are not significantly more distributed in summer grazing areas. On average, 4.8% ± 7.8%) of their distribution is located within summer grazing areas, whereas 9.2% ± 0.6% of the random distributions fall within summer grazing areas (p-value of a two-sample t-test = 1; Table 3). Nevertheless, 44 species (15.4% of the priority CWR) are significantly more present in summer grazing areas than expected by chance (Table S5).

3.4. Minimal conservation network of priority CWR for an adapted in situ conservation

The minimal spatial network to cover at least one population of all the 285 CWR taxa consists of 39 2-by-2 kilometres squares, mostly located in South-western Switzerland (Fig. 1a). In these 39 sites, the proportion of protected area ranges from 0% to 51%, with an average of 8% (Table S6). The proportion of agricultural and summer grazing areas dedicated to summer grazing in these “hotspots” ranges from 0.8% to 86%, with an average of 35.2% (Table S6). Interestingly, the proportion of protected area within the hotspots is not correlated with the proportion of agricultural area (Pearson’s correlation P = 0.029; p-value = 0.862), neither with the summer grazing (Pearson’s correlation P = −0.071; p-value = 0.668).

4. Discussion

4.1. Adapting conservation priorities in a changing environment: the Swiss CWR inventory

Following a global effort to improve the conservation effort of CWR globally (Vincent et al., 2013), we took advantage of the recently updated checklist of the Swiss flora (InfoFlora, 2020) to generate a comprehensive country-wide CWR checklist. With an overwhelming 60% of its entire flora being considered as CWR, including a significant number of plants relative to medicinal plants (1′438, Table 2), this checklist had to be prioritized. This process identifies priority CWR and allows a dedicated set of measures

Table 3
Average distribution of priority CWR in protected, agricultural and summer-grazing areas. For comparison, we also provide the average distribution of the 1′000 random distributions of the null model. * ** significantly more than randomly distributed (p-value < 0.001).

	Protected area [%]	Agricultural area [%]	Summer-grazing area [%]
Priority CWR	33.02 ± 21.4 * **	21.9 ± 17.4	5.1 ± 9.2
Random distribution	13.9 ± 0.8	26 ± 1	9.2 ± 0.6

depending on their respective threat status: while the most vulnerable taxa are or will be included in current conservation plans, other less threatened taxa may benefit from some monitoring of their populations. Combining four sets of criteria (relationship to cultivated species, degree of relationship, threat status and origin of the taxa) and validated by experts, we short-listed 285 priority CWR taxa that will be targeted by various dedicated measures, depending on their threat status. This priority list partially aligns with the European priority CWR (Rubio Teso et al., 2020), with only one-third of the species being common to both lists. Although our approach is rooted in a similar framework (Kell et al., 2017), these discrepancies could be attributed to variations in data, methodology to prioritise criteria and regional influences shaping these criteria. For example, we included taxa associated with plants that are locally prized for their aromatic and medicinal properties.

The IUCN Red List and the list of National Priority Species are key resources for identifying taxa that are threatened. However, the list of priority CWR also includes taxa that are not necessarily at risk but are important from a breeding perspective. For instance, *Daucus carota* L. or the various *Festuca* (*rubra, pratensis, ovina*…), are not particularly threatened according to our ecogeographical analysis (Table S4). Nevertheless, these taxa remain an important target for CWR conservation to maintain genetic diversity within the genera of relevant crops (Khoury et al., 2022). CWR genepools may provide traits for pest resistance, drought, salinity and heat stress tolerance and enhanced nutritional quality (Dempewolf et al., 2017). For example, breeding Swiss local CWR of *Lolium* allowed the production of varieties of violet *Lolium*, which are drought resistant and convenient for organic cultures (Suter et al., 2019). *Malus sylvestris* (P.) Mill., another priority CWR, is also utilized in current breeding programs for its fire blight resistance, which has the potential to be incorporated into commercial apple varieties through introgression (Luby et al., 2002). In any case, the modularity of our approach allows the reshuffling of priority criteria to adapt the priority list depending on the specific needs of the different stakeholders, from conservation to breeding and from plant growers to land managers. This work marks the initial step towards recognizing a portion of the biodiversity, namely the relatives of cultivated and wild-used plants, as valuable targets for conservation policies.

4.2. Filling the gaps in existing conservation measures to include national priority CWR

We then used ecogeographic tools to conduct a nationwide assessment of the conservation gaps for each of the priority CWR. We first assessed the extent of protection of priority CWR in existing protected areas. Our analysis reveals that the majority of the priority taxa is well covered by existing protected areas. However, 22.5% of priority CWR are not adequately protected, exhibiting an average distribution protection of less than 10%. This level of protection is not significantly better than what would be expected for a species distributed randomly. It is obvious that for some of these species, prioritization was mostly due to their close relationship to cultivated crops rather than their threat status (e.g. *Capsella bursa-pastoris* L. (Medik.), *Lactuca serriola* L., *Lolium multiflorum* Lam.). However, this list also reveals taxa that are threatened but currently not well covered by existing protection areas (e.g. *Allium rotundum* L., *Alopecurus geniculatus* L., *Chenopodium vulvaria* L, *Fragaria moschata* Duschesne, *Lactuca saligna* L., *Taraxacum pacheri* Sch. Bip.). These species are to be found in habitats that are usually not covered by habitat inventories. For example, most of the dry meadows in Switzerland are in the "dry meadows and pasture" federal inventory where they profit from adequate protection despite occurring usually in environments that are outside protected areas. This conservation gap might be due to the protected areas not necessarily targeting the CWR specifically or to an overall limited distribution and efficiency of the existing protected areas (Guntern et al., 2013). Biodiversity loss is severe in Switzerland, which is far from reaching Aichi's aims nor possibly Montreal-Kunming targets (FOEN, 2017; CBD, 2022). Currently, protected areas cover only 12.5% of the country (FOEN, 2017). More efforts must be performed in the protection of natural habitats in general, including the priority CWR species which are already covered by the current network of protected areas. Globally, similar trends have been observed for the Red List plants "used for human food", with only 47% not covered by protected areas (FAO, 2010). The protection gap observed for priority CWR might therefore benefit from more dedicated actions, like the identification of hotspots relevant for in situ conservation. Few successful examples of CWR-specific protected areas have been documented, for example, the Lizard peninsula in Cornwall (Fielder et al., 2015) or in the Sierra del Rincón, province of Madrid (Rubio Teso et al., 2021). CWR conservation was confronted with various issues related to the required standards and conflicts with local land management policies.

4.3. Agriculture land management fostering CWR conservation

A large portion of the priority CWR populations were found in regions of relatively lower altitudes, mirroring the distribution of their respective deficit regions. The discrepancy between observed and modelled richness may reflect a genuine shortfall in quality habitats for biodiversity, attributable to factors not incorporated in the analysis, such as land use or agricultural intensity. This pattern of diminished species richness in intensively cultivated, lower-altitude areas is corroborated by previous monitoring programs (Meier et al., 2021). In addition, our analysis also indicates that areas with a higher sampling effort exhibit a substantially smaller deficit in priority CWR species richness, suggesting that apparent deficits could partly be due to insufficient observational data. Comparing observed and modelled stacked species distributions is sensitive, as potential distribution stacking is known to consistently overestimate species richness (Benito et al., 2013; Calabrese et al., 2014; Schmitt et al., 2017), thereby artificially inflating the derived deficit.

Our study shows that the quantity of modelled species richness is heavily influenced by the chosen threshold used for binarizing the species' continuous suitability map (Table S3 and Appendix A1). Despite this, the distribution pattern of modelled species' richness remained stable across the different thresholding strategies (Table S3 and Appendix A1). This suggests that a standardisation approach, such as quantile normalization to rescale the modelled species' richness to match the minimum and the maximum of the observed one, might provide a straightforward and conservative method for mapping areas with substantial discrepancies between observed and modelled richness due to methodological bias.

Based on these observations, and again on the assumption that species that are related to cultivated species might share their ecological niche, we wanted to evaluate the extent to which the priority CWR populations were localized on the agricultural land. Although varying levels of phylogenetic niche conservatism have been demonstrated among some CWR genera (Kantar et al., 2015; Callen et al., 2016; Ashraf et al., 2023), to our knowledge, no attempts have been made thus far to evaluate the overlap between cultivated lands and the distribution of priority CWR at a national scale. Our analysis shows that 46.5% of the priority CWR are more frequently distributed in agricultural or summer grazing areas. This pattern could potentially be a sign of phylogenetic niche conservatism, where species retain their ecological characteristics over time due to their close evolutionary history. For a more concrete understanding of the processes leading to such niche conservatism, future research should explicitly consider the phylogenetic distance, the niche, the traits, and the constraints between CWR and their related crops (Crisp and Cook, 2012). This important fraction supports that CWR could be an element to be integrated into the complex set of measures dedicated to the ecological compensation areas to promote farmland biodiversity (Aviron et al., 2009). The current analysis identified an interesting group of taxa, which shows on one hand bad coverage by protected areas, and on the other hand a significant part of their distribution in agricultural or summer grazing areas. For these 33 taxa (11.6% of the priority CWR), agricultural measures and policies may help to better conserve these species. For example, *Valerianella dentata* (L.) Pollich is a characteristic cornfield plant found on lighter, more calcareous arable land, particularly overlying chalk (Appendix A2). Even though this species has a wide global distribution, its populations have diminished considerably, and it is considered a Vulnerable (VU) species on the national Red List (Bornand et al., 2016). This decline has been a result of the intensive use of herbicides and the application of nitrogenous fertilizers to highly competitive modern crop varieties (Lemoine et al., 2018; Waymel et al., 2020; InfoFlora, 2023). *V. dentata* can be successfully aided by adequate management of wheat fields and it is, therefore, a perfect example of an endangered species and close relative to a widely used crop.

In Switzerland, since 2018, an ad hoc plan promotes in situ conservation of some forage crop populations. These measures target an overall surface of 2′750 ha under a dedicated cross-compliance scheme and target specifically 24 priority CWR. Interestingly, when considering forage plants, some conflicting aims could be identified, namely between the short-listing performed by the botanists and the farmer's priorities. For example, *Poa trivialis* L. listed here as a priority CWR, is also considered a common weed of grazing surfaces by many farmers. Such conservation strategies also exist in other countries. Recent initiatives in Malawi and Zambia have shown promising results in incorporating conservation plans dedicated to CWR towards the agricultural areas. These plans also utilize innovative incentives in the form of payments for agrobiodiversity conservation services (Drucker et al., 2023; Wainwright et al., 2019). These are practical examples that highlight the importance to involve all relevant stakeholders, primarily farmers, in the process of designing an effective CWR conservation policy.

To better target potential conservation plans locally, in the last step of our analysis, we identified a network of 39 sites all over the country that allows a comprehensive coverage of all 285 priority CWR (Fig. 1a). Interestingly, the majority of these sites are localized in the hotter and drier climate of Switzerland optimal for agriculture (Holzkämper et al., 2015), suggesting a particularly promising area for implementation of further measures. Again here, about one-third of this conservation network is in agricultural or summer grazing areas, supporting that these surfaces are critical for an efficient conservation strategy of CWR. Because our distribution dataset mainly relies on opportunistic observations without any sampling design, the distribution of this network might be sensitive to the distribution of the sampling effort. If novel areas get better sampled, this can affect the distribution of rare priority CWR and modify the distribution of this complementary network. Such a network dedicated to in situ conservation of priority CWR could integrate information on the modelled species distribution (Guisan et al., 2013; Tulloch et al., 2016) to be less exposed to the influence of sampling effort. Another advantage of SDMs is the possible inclusion of climate or land use scenarios to project potential distributions in the future so that conservation networks could anticipate future distributional changes (Faleiro et al., 2013; Mateo et al., 2019). The current analysis can be used as a first step to synthesise current knowledge about priority CWR. Combining prospective field campaigns and potential distribution analyses integrating global change scenarios would inform how to complete current national monitoring such as the Swiss Biodiversity Monitoring (FOEN, 2014) or the Agricultural Species and Habitats Monitoring Programme (Riedel et al., 2018) to develop efficient monitoring of the priority CWR.

4.4. Raising synergies between conservation and agriculture

The objective of the current study was to set the ground for a comprehensive and sustainable strategy for CWR conservation in Switzerland. Conservation of CWR remains a "grey zone" as much for conservationists as for farmers or policymakers. If we are to meet the target A of the Kunming Montreal Global Biodiversity Framework of the CBD (2022), which states that "the genetic diversity within populations of wild and domesticated species, is maintained, safeguarding their adaptive potential", a synergy between sectors appears urgent. The significant enrichment of priority CWR on the agricultural surface may be a specificity of the Swiss landscape, and the extent to which this can be extrapolated to other agroecosystems remains to be determined. However, the interaction between CWR and agriculture appears largely unexplored. Addressing the rapid loss of biodiversity in the near future, that in turn may directly impact our agroecosystem resilience, will require a cross-sectoral approach (Frison et al., 2011). We believe we provide here a compelling example of how CWR conservation can serve as an effective initial step towards fostering synergies between agricultural practices and biodiversity conservation. This approach could stimulate a transformative change in the way we manage and value agricultural landscapes, leading to more sustainable and diverse environments.

CRediT authorship contribution statement

Blaise Petitpierre: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, software, validation, visualization, writing - original draft preparation, writing - review & editing. **Julie Boserup:** conceptualization, data curation, investigation, methodology, validation, writing - original draft preparation, writing - review & editing (supporting). **Sibyl Rometsch:** conceptualization, data curation, funding acquisition, investigation, project administration, resources, supervision, validation, writing - original draft preparation, writing - review & editing (supporting). **Adrian Möhl:** investigation, validation, writing - original writing - original draft preparation (supporting), writing - review & editing (supporting). **Sylvain Aubry:** conceptualization, data curation, funding acquisition, investigation, methodology, project administration, supervision, validation, writing - original draft preparation, writing - review & editing.

Impact Statement

At least one fifth of the CWR of concern lacks protected areas in Switzerland. Specific management of agricultural areas would benefit these CWR.

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.

Data availability

Data and R scripts are available in the appendix A1 and A2.

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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.2023.e02588.

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