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Networking, partnerships and tools to enhance *in situ* conservation of European plant genetic resources

Identifying *in situ* areas with useful adaptive traits

Citation

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https://more.bham.ac.uk/farmerspride/wp-content/uploads/sites/19/2020/10/D3.3_Identifying_in_situ-areas_with_useful_adaptive_traits.pdf

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1. Executive Summary

In the present context of climate change, identifying which landraces or crop wild relative populations might contain the currently most-demanded traits for crop breeding has become an urgent issue.

To determine which crop traits are most needed for satisfying future agricultural and market needs, a questionnaire was prepared using the online tool EuSurvey. The questionnaire was circulated among farmers, breeders and seed companies. From the survey results, predictive characterisation techniques were used to identify crop wild relative populations with a higher probability of containing the identified desired traits than if randomly selected. Two different approaches were followed by predictive characterisation analyses: the environmental filtering method and the calibration method. Targeted crop wild relative populations were those native to Europe, with occurrence records and evaluation data and whose related targeted crops obtained a high number of responses in the survey.

An evidence-based approach was also used to identify landraces with the desired traits. This relied on a collection of 105 landrace case studies where information on the most important agronomic traits, was retrieved from landrace descriptions given by those who cultivate or have deep knowledge of them. For this approach, landraces of both European native and introduced crops were considered. For the majority of survey respondents, tolerance/resistance to abiotic and biotic stress were the most demanded groups of traits, the results for traits related to good nutritional quality were also relevant.

Populations predictively containing abiotic stress resistance/tolerance traits (i.e. drought tolerance, salinity tolerance or waterlogging tolerance) were found in crop wild relatives of wheat (*Aegilops* spp.), lens (*Lens* spp.) and lupin (*Lupinus* spp.). Populations predictively containing nutritional value traits (i.e. acyanogenic) were found in crop wild relatives of white clover (*Trifolium repens*). Abiotic stress resistance/tolerance, biotic stress resistance, and valuable nutritional traits were reported by those who described the landraces for 19, 9 and 15 landraces of different crops respectively.

Both approaches used allowed the identification of plant genetic resources that can be targeted in breeding and pre-breeding studies where *ad hoc* trials should be carried out to confirm the presence of useful traits.

2. Introduction

Landraces and crop wild relatives (CWR) are valuable genetic resources for breeding modern cultivars due to the large genetic diversity characterising these materials (e.g., Vaughan, 1994; Maxted et al., 1997; van de Wouw et al., 2001; Hajjar and Hodgkin, 2007; Heywood et al., 2007; Millet Manisterski and Ben-Yehuda, 2008; Yahiaoui et al., 2008; Russell et al., 2016 Winfield et al., 2018; Raggi et al., 2019). Having evolved under semi-natural (landraces) and natural (CWR) conditions, they are expected to contain useful traits determining adaptations to different selective pressures (Hawtin et al., 1996). On the contrary, most modern cultivars have little or no genetic diversity, as they have been intensively selected for certain characteristics (e.g. high yield or synchrony in their fruition).
Landraces are important sources of traits for crop breeding and are widely used for this purpose due to their adaptation to different environments and the easy transfer of genes (Camacho Villa et al., 2005). They are priceless genetic resources for breeding modern cultivars, but also to realise the agricultural production, especially in marginal areas and in under more sustainable models. Adapting landraces to present agricultural conditions represents a challenging opportunity to facilitate their use in modern sustainable agriculture (Casañas *et al.*, 2017). On the other hand, the use of crop wild relatives in plant breeding has gained relevance over the last decades and their use is becoming more popular among plant breeders (Hajjar and Hodgkin, 2007).

In the current context of climate change, identifying which landraces or crop wild relative populations might contain the currently most-demanded traits for crop breeding has become an urgent issue. The evaluation of agronomic traits is an intensive task that involves the implementation of cultivation trials in different locations under varying environmental conditions. Therefore, different approaches are being developed to anticipate the CWR populations and landraces that are more likely to contain the desired traits. Advances in the knowledge of the set of genes involved in the expression of a particular phenotype are enabling the prediction of the phenotype of a CWR population or a landrace from genetic characterisation studies. Thus, genome-wide association studies (GWAS) are used in genetics research to associate specific genetic variations with particular phenotypes. The method involves scanning the genomes from many different plants and looking for genetic markers that can be used to predict the presence of a particular trait. Once such genetic markers are identified, they can be used to understand how genes contribute to the phenotype and to predict the phenotype of a plant genetic resource through the analysis of the genetic markers. The identification of such populations may provide new sources of genetic variation that can enhance crop responses to pests and diseases or abiotic stresses, such as droughts or frosts. However, the number of natural CWR populations and landrace accessions conserved *ex situ* (mainly in genebanks) or *in situ* (in the habitats where they evolved) is in most cases too large to use a genomic analysis approach. Nowadays, it is unrealistic, in terms of economic and human resources, to genomically characterise thousands of natural populations and seed accessions. In this sense, predictive characterisation based in ecogeographic information can be an alternative approach that may be useful to make an initial selection of plant genetic resources that are more likely to have a desired particular trait. Then, this selection can be used to conduct genomic studies and/or evaluation assays to identify the new sources of genetic variation of interest.

The objective of this study was to pinpoint the agronomic traits that are currently sought by farmers and breeders in Europe and to implement a pilot study to identify populations, of both crop wild relatives and landraces, that are more likely to have some of these useful traits, by applying predictive characterisation techniques – based on species distribution data and thematic maps containing environmental data (Thormann *et al.* 2014) – and an evidence based approach.

3. Methodology

3.1 Most needed traits for satisfying future agricultural and market needs

To determine which crop traits are needed most to satisfy future agricultural and market needs, a questionnaire was prepared using the online tool EuSurvey (Appendix A). The survey was made available online for six months: from December 2018 to June 2019. The questionnaire was disseminated by all the Farmer's Pride project partners and Farmer's Pride Ambassadors to the main target audience (i.e. farmers and plant breeders), trying to reach the greatest number of stakeholders and encouraging them to complete it. Initially prepared in English, the survey was then translated into seven different languages: Spanish, French, Turkish, German, Dutch, Croatian, and Swedish.

The survey was designed to feature two different parts: one focused on contact data and the other on crop information. In the first section, the name, affiliation, and address of the respondent were requested, as well as the willingness to be contacted. To help with the compilation of the second part, a list of 63 crops was provided to the respondent including the option of "other" (crop). The target farming system was requested with two different options: "Conventional" and "Low input/Organic". Eight categories were established so traits could be easily addressed: Yield, Tolerance/resistance to abiotic stress, Tolerance/resistance to biotic stress, Plant architecture, Technological quality, Nutritional quality, Environmental quality and Other. A rank of relevance (from 1 to 5) was requested per trait group; further details were required for those traits with a relevance of: 3 (medium), 4 (high) and 5 (very high). The analysis of the top 10 crops (i.e. crops that got the highest number of answers) allowed the generation of a list of the most useful traits to be considered for the predictive characterisation approaches.

3.2 Predictive characterisation

Predictive characterisation techniques are based on the Focused Identification of Germplasm Strategy methodology (Mackay and Street 2004), initially described and applied to cultivated plants. This methodology selects populations with a higher probability of containing the desired traits than if randomly selected (Thormann *et al.*, 2014). We also addressed the potential genetic diversity of adaptive value of the populations with the use of Ecogeographic Land Characterisation maps (ELC maps). These type of maps are built through the combination of bioclimatic, edaphic and geophysic information that describe the territory and are available as GIS layers (Parra-Quijano *et al.*, 2012a; b). Considering that the different environmental pressures found in the territory of study may provide populations with divergent genetic diversity of adaptive value, the use of ELC maps in combination with the predictive characterisation methodologies may be convenient to increase the genetic diversity held by the selected populations. There are two different approaches followed by predictive characterisation analyses: the environmental filtering method and the calibration method. The first one links available environmental information to the localities of CWR or landrace populations, and selects amongst them those that, according to their environmental conditions and thresholds set by the user, may have greater possibilities of having the targeted trait as a result of adaptation processes (e.g., selecting populations occurring in places with the lowest minimum monthly temperatures may point to populations with frost tolerance) (Figure 1). The use of ELC maps can maximise the potential genetic diversity amongst the selected populations. On the other hand, the calibration method takes into account previously evaluated material (populations or genebank accessions) for a given trait. By linking environmental conditions to the trait-assessed populations, the algorithm can select, among non-evaluated populations, those with higher probabilities of containing the targeted trait according to their environmental conditions (Figure 2). Once again, through ELC maps, the potentially divergent genetic diversity among populations can be taken into account to arrange the selection.

3.2.1 Targeted taxa and distribution data

Targeted crops were selected from those that obtained a high number of responses in the survey, had crop wild relatives native to Europe and occurrence records and evaluation data, and when the callibration method was used, were readily available. We also considered it appropriate to balance the selection to include both human and animal food crops. The predictive characterisation studies were, thus conducted on wheat, lentil, blue lupin and white clover.

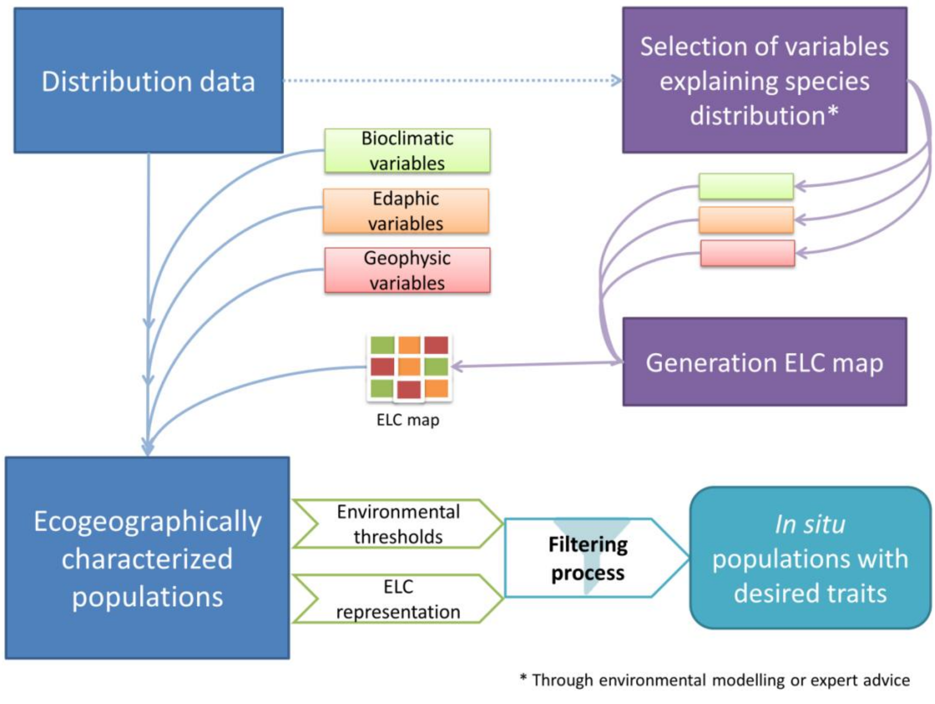

Figure 1. Process followed to apply the environmental filtering method. Populations are selected according to environmental conditions of their inhabiting sites, maximising the probability of finding desired tolerances to abiotic stresses.

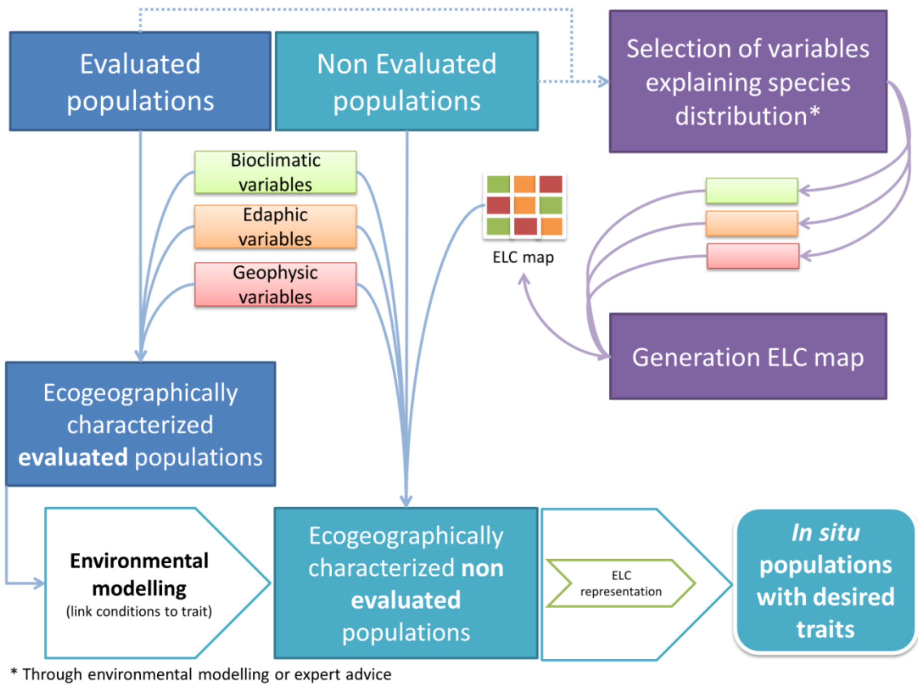

Figure 2. Predictive characterisation process using the calibration method. On the basis of a group of evaluated accessions/populations for a given trait, an environmental model is built. This model can then be applied to non-evaluated populations to identify those with higher probabilities of containing the desired trait, according to their environmental conditions.

The first two are ancient crops that are widely cultivated and have been present in agriculture for thousands of years (Sandhu and Singh 2007; Shewry 2009). On the other hand, blue lupin is a forage crop and a promising human food crop in Europe, as it is relatively more tolerant to abiotic stresses than other legumes and constitutes a source of high-quality proteins that could diminish Europe's dependency on soya bean importations (Lucas et al., 2015). Finally, white clover is considered a high-quality forage (Ulyatt 1981) with good persistence under grazing (Caradus et al., 1995) and is the most widely-grown temperate forage legume and the most common legume in pastures grazed by cattle and sheep (Frame and Newbould 1986). It is ranked the third most used legume pasture species after lucerne (Medicago sativa L.) and red clover (Trifolium pratense L.) (Mather et al., 1996). Targeted CWR taxa (Appendix B) were taxa listed in the Inventory of Priority European CWR (Kell unpublished results) that were: i) wild relatives of wheat in Aegilops genus (33 taxa), close relatives of wheat that probably contributed to its domestication and evolution and that have been used in breeding programmes (Kilian et al., 2011), ii) wild relatives of lentils (five taxa), iii) wild relatives of blue lupins (six taxa), and wild populations of white clover. In addition, landrace genebank accessions of white clover were also considered.

Distribution data used for these analyses were extracted from a high quality database of crop wild relatives occurrences generated for deliverable 1.2 "*In situ* plant genetic resources in Europe: crop wild relatives" of the Farmer's Pride project (www.farmerspride.eu). This database contains high quality occurrence data with high probability of current *in situ* occurrence. Data were downloaded from GBIF and Genesys databases using R packages 'rGBIF' (Chamberlain & Boettiger, 2017) and genesysr (Obreza 2019) and subjected to a strict process of filtering and cleaning data, that includes deleting records without coordinates or low accuracy coordinates (less than 10x10 km resolution), deleting records that coincide with centroids of countries and capitals, deleting records where the country data does not match with the given coordinates, selecting only records from 1950 onwards, deleting records occurring in water bodies, permanent ice or snow or urban areas according to a land-use map (ESA CCI Land Cover project 2017), and deleting records of the same taxa found to be in a less than 1 km radius. All these filtering and selection processes were performed using R statistical environment (R Core Team, 2013). Further details can be found in the Farmer's Pride project report "I*n situ* plant genetic resources in Europe: crop wild relatives" (Rubio Teso et al., 2020). While the geographic scope of the study on *Aegilops spp., Lens spp*. and *Lupinus spp*. was Europe plus Turkey, the study on *Trifolium repens* was performed at the world level. The particularities of occurrence data compilation for the later are detailed in García and colleagues (2019).

3.2.2 Generation of Ecogeographic Land Characterisation maps

The generation of the Ecogeographic Land Characterisation maps (ELC map) for each genus was performed taking into account environmental variables explaining their distribution, according to an objective process of environmental modelling. This process was performed through an adapted R script developed for the SelecVar tool of the Capfitogen software (Parra-Quijano et al., 2016). A total of 122 bioclimatic, geophysic and edaphic (topsoil) variables were included in the analysis (Appendix C). Variables information was extracted per population at a 2.5 arc-min resolution. The model used to analyse variable importance was Random Forest (RF), which classifies variables according to two different indexes, the Mean Decrease Accuracy (MDA) and Mean Decrease Gini (MDG) (Cutler et al., 2007). On the other hand, correlations among variables were analysed through Bivariate Correlations analyses. Following Garcia and colleagues (2017), top 15 variables, according to their MDA value (higher values) from RF analyses, were selected and correlated variables within the same group (bioclimatic, edaphic or geophysic) were removed (Pearson correlation coefficient >0.50 and p-value <0.05).

Non-correlated variables of each group were chosen for the generation of one ELC map per each targeted genus, which potentially represents the different adaptive scenarios for their wild populations. The ELC maps, with cell resolution of 2.5 arc-min (around 5x5 km), were built following the R script developed for the ELC mapas tool of Capfitogen software (Parra-Quijano et al., 2016). The geographic scope was Europe and following Capfitogen developers' recommendations, the maximum number of clusters per group of variables was six. The elbow method, suggested for large extensions of territory, was the statistical procedure chosen to determine the number of groups in the clustering analyses.

In addition to the bioclimatic, edaphic and geophysic variables associated to the populations occurrences, ELC categories of resulting maps per genus were also added to the dataset. The distribution of ELC categories among populations was made using an adapted R script developed for the Representa tool of Capfitogen software (Parra-Quijano et al., 2016). This way, the potential genetic diversity among populations due to environmental differences was taken into account.

3.2.3 Target traits and predictive characterisation through environmental filtering

According to the survey respondents' answers, abiotic stress tolerances were some of the most demanded characteristics. Abiotic stress is one of the major causes for losses in crop yield (see Wang et al., 2003 and references therein), and two of the most limiting conditions for crops are drought and soil salinity (Cattivelli et al., 2008; Hamdia and Shaddad 2010). In addition, waterlogging tolerance is an abiotic stress that severely decreases lentil performance and yield (Islam et al., 2009). Thus, these three abiotic tolerances were selected for the application of predictive characterisation using the environmental filtering method.

Drought tolerance

The De Martonne aridity index (De Martonne 1926) was calculated per each occurrence record as a proxy of the drought selective pressures that are experienced by the populations under study. The De Martonne aridity index ($I_{ar}DM$) was calculated as $I_{ar}DM = P/(T+10)$, where P is the annual mean precipitation, T the annual mean temperature and 10 is a constant to avoid negative values. One of the most critical periods of plant development is the flowering season, which can be severely affected by drought (Kazan and Lyons 2016), especially in the Mediterranean region. Thus, it may be appropriate to focus on the drought period experienced by plants during their flowering season. The months associated to the flowering period for *Aegilops* were May, June and July (Kilian et al., 2011) and for *Lens* and *Lupinus*, March, April, May and June. To focus the analyses on the flowering period, De Martonne aridity indexes targeting the flowering months ($I_{ar}DM_m$) were calculated for the populations linked to each crop ($I_{ar}DM_m= 12*P_m/(T_m+10)$, where P_m and T_m are the precipitation and mean temperature of the corresponding month, respectively). Finally, the monthly values were averaged to generate a Flowering De Martonne index ($I_{ar}DM_f$), where:

$$I_{ar}DM_f= (I_{ar}DM_{m1} + I_{ar}DM_{m2} + ... + I_{ar}DM_{mn})/n$$

According to De Martonne, sites can be classified into six categories according to their $I_{ar}DM$ (Table 1).

Table 1. Classification of sites according to De Martonne's Aridity index

De Martonne Index	Classification
$0 \leq I_{ar}DM <5$	Deserts. Extremely arid
$5 \leq I_{ar}DM <10$	Semi-desert. Arid
$10 \leq I_{ar}DM <20$	Drought Mediterranean countries. Semi-arid
$20 \leq I_{ar}DM <30$	Sub-humid
$30 \leq I_{ar}DM <60$	Humid
$I_{ar}DM \geq 60$	Per-humid

Once all study populations were characterised with the De Martonne aridity indexes ($I_{ar}DM$ and $I_{ar}DM_f$), the criteria applied to select populations with higher probabilities of containing adaptations to drought were:

1) Select populations with an $I_{ar}DM$ lower than 15 (lowest range of semi-arid sites and drier).
2) Select among those populations, the 50 populations with the lowest values of $I_{ar}DM_f$ (and in any case with $I_{ar}DM_f$ below 15). This second criterion provides a reduced and manageable subset of populations, potentially adapted to drought during the flowering period that can be further explored, collected and screened.

In this process, the ecogeographic classification of the populations according to the generated ELC maps was taken into account applying an algorithm modified from Van Etten and colleagues (pers. comm.) by which the subset of selected populations maximised the ecogeographic representation.

Salinity tolerance

According to Abrol and colleagues (1988) soils can be classified into five categories according to their conductivity (Table 2), which may affect crop yields. It is largely known that most crops are affected by soil salinity, and that their yields are reduced under saline conditions (soil conductivity above 4 dS/m (Panta et al., 2014; Zörb et al., 2018)). Thus, the criterion applied to select populations potentially tolerant to soil salinity consisted in choosing those populations that occurred in sites with soil conductivity above this threshold. In addition, populations occurring in slightly saline soils (soil conductivity >2 dS/m < 4 dS/M) were also searched for. Once again, the representativeness of selected populations in terms of the ecoegeographic units resulting from the ELC maps was also taken into account.

Table 2. Classification of soils according to the conductivity of the saturation extract (dS/m) and their effects of crops (Abrol et al., 1988)

Type of soil	Conductivity (dS/m)	Effect on crop plants
Non saline	0 – 2	Salinity effects negligible
Slightly saline	2 – 4	Yields of sensitive crops may be restricted
Moderately saline	4 – 8	Yields of many crops are restricted
Strongly saline	8 – 16	Only tolerant crops yield satisfactorily
Very strongly saline	> 16	Only a few very tolerant crops yield satisfactorily

Waterlogging tolerance

The approach followed to select wild *Lens* populations potentially tolerant to waterlogging included the incorporation of soil texture data to the sites where the study populations are found, and its combination with the De Martonne aridity index. Soils can be classified into different categories according to their composition in silt, sand and clay (Figure 3). Using the USDA Soil texture calculator (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167), all population occurrence sites were classified according to their corresponding soil texture. Criteria used for the environmental filtering were:

1) Considering that the least permeable soils are those with soils texture classified as Clay, Silty Clay, Sandy Clay or Silty Clay Loam, populations associated to soils in any of these categories were selected.
2) Subsequently, from this selection, the populations occurring under more humid conditions were searched for, using the De Martonne aridity index. In order to generate a manageable subset of populations for prospecting, the top 50 populations with the highest De Martonne aridity annual indexes (the most humid populations) were selected.

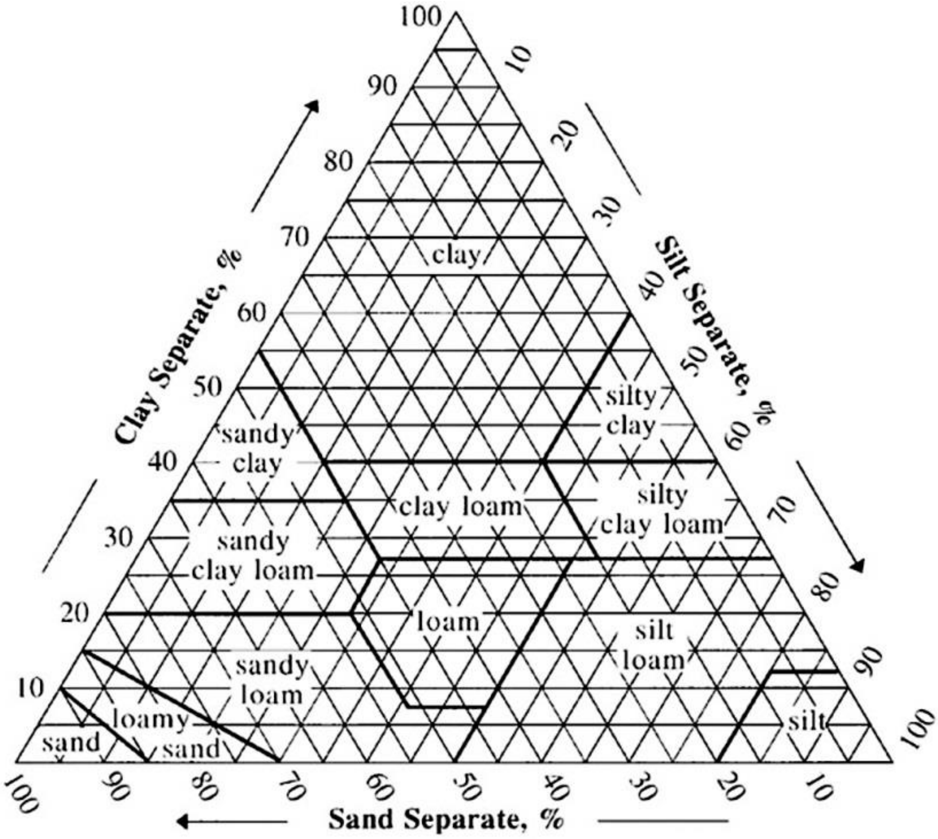

Figure 3. USDA Soil classification according to its content in sand, clay and silt. (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167)

3.2.4 Target traits and predictive characterisation through the calibration method

This methodological approach was applied to white clover and cyanogenic acid content. Cyanogenesis is a metabolic process that generates antiquality compounds in some Trifolium species. It is a matter of concern because it has a negative effect on large herbivores. This trait and crop were chosen because we had the evaluation data needed to conduct the calibration method and, as such, the trait is given consideration in several breeding programmes (Crush and Caradus 1995). Although they were not among those most highlighted in the survey, it was a suitable case to implement the calibration method of predictive characterisation.

The cyanoglucosides present in some cultivars of white clover form free hydrogen cyanide (HCN) when ingested by ruminants (Caradus et al., 1995). Although there are no recorded instances of mortality due to cyanide toxicity in livestock (Caradus et al., 1995), indirect effects on metabolism of iodine (Greer et al., 1966), selenium (Gutzwiller 1993) and sulfur (Caradus et al., 1995) in animals may have serious consequences for nutrient availability. Because of this, there is a growing interest in acyanogenic germplasm.

A questionnaire was sent to 10 researchers involved in white clover breeding. Considering the scientific literature available on this matter and taking into account other potential factors, researchers were asked to select the ecogeographic variables that have greater effect on the expression of cyanogenesis. The responses of the expert survey identified five potentially influential ecogeographical variables: sun radiation, annual mean temperature, annual precipitation, elevation and soil pH. Because a global cover layer with sun radiation data was not available when the layers were compiled, the global layers for slope, northness and latitude were used as a proxy for sun radiation. The experts were also asked to select a threshold value to discern accessions with desirable low levels of cyanogenesis. The threshold proposed by the breeders to discern desirable and undesirable levels of cyanogenesis was 0% cyanogenesis. The cyanogenesis trait was predicted by the calibration method of the predictive characterisation approach. To this end, desirable low levels of expression were assigned a value of 1, and undesirable levels a value of 0. The binarised variable was used as the dependent variable, and the selected ecogeographical variables were used as explanatory variables in the construction of several alternative models.

The evaluated set was partitioned into two subsets: one set containing 75% of the data points, which was used to calibrate all models (training data), and a second set containing 25% of the data points, which was used to evaluate the model (test data). Eight modelling techniques implemented in the 'biomod2' R package (Thuiller et al., 2014) were used in this analysis: artificial neural networks, classification tree analysis, flexible discriminant analysis, generalised additive model, generalised boosted model, generalised linear model (GLM), multivariate adaptive regression splines, and random forest. The "biomod2" package was originally conceived for species distribution modelling, but in this study it was used to model the presence–absence of a trait in a population. Using the function "BIOMOD_Modelling" in the "biomod2" package, 100 models were run for each of the eight techniques. In each model, the distribution of the data points for the training and test sets was randomly assigned; however, the original proportion of the number of 1s and 0s of the entire evaluated set was maintained. The predictive power of each model was evaluated with the true skill statistic (TSS). TSS ranges from –1 to +1, where +1 indicates perfect agreement and values of zero or less indicate a performance no better than random. The average TSS for 100 runs was calculated for each of the eight techniques. The function "variables_importance" in "biomod2", which assigns to each variable a value from 0 (no influence on the model) to 1, allowed us to identify the most influential variables on the model.

The run with the highest TSS value from the modelling approach with the highest average TSS value was used to predict the levels of cyanogenesis in the non-evaluated set with the function "BIOMOD_Projection" ("biomod2" package, Thuiller et al., 2014). The predictions for the populations of the non-evaluated set were obtained in the form of their probability (0–1,000) of having low levels of cyanogenesis according to the selected model. The populations were then ranked according to their probability of having low levels of cyanogenesis. Thus, a priority set of populations of white clover that may have desirable low levels of cyanogenic plants was identified.

Because the populations that are of greatest interest for the breeders are those that are acyanogenic, only accessions ranked highest for probability of having low levels of cyanogenesis were considered for evaluation. Thus, 18 accessions, from the first 40 USDA accessions ranked highest for probability of having low levels of cyanogenesis, were evaluated to determine the percentage of plants that were cyanogenic, following the same method applied in the initial evaluation of the USDA accessions (Pederson et al., 1996). To guarantee the comparability of the evaluation of this subset with the previous evaluation tests, five completely cyanogenic and five completely acyanogenic accessions from the original evaluated set were included in the trial. Seeds of each accession were scarified with sandpaper and germinated on water agar. Details on the procedure followed for the evaluation assay are found in García and colleagues (2019).

3.3 Evidence-based approach on *in situ* landraces

A second approach was also used to identify areas where landraces characterised by important agricultural traits are potentially grown. This approach considered only landraces that are still maintained *in situ* and for which traits of interest were mentioned. In contrast from the predictive characterisation approach used for CWR, in the evidence-based approach crops are considered regardless of whether they have European native CWR or not.

A collection of landrace case studies of different crops was developed by asking Farmer's Pride Partners and Ambassadors to provide information about landraces they were aware of. The information sought included data on cultivation locations, basic characteristics and how, where, and why such resources are still conserved, kept in cultivation (i.e. used) and marketed (see Farmer's Pride Deliverable D2.4 *In situ landrace propagation management and access guidelines*). All the information on the collected case studies was used to develop keywords referring to different landrace value traits (Raggi *et al.*, submitted). Among them those related to traits of agricultural, processing and nutritional interest were also recorded (i.e. easy cultivation, precocity or lateness, lodging resistance, high yield, stable yield, suitable for organic agriculture, tolerant to abiotic stresses, tolerant to biotic stresses, special taste, special colour, high storability, processing value, special nutritional value). Keyword indexing was then used to identify and locate those landraces with most needed traits for satisfying future agricultural and market needs, as obtained from stakeholder survey results.

4. Results

4.1 Most needed traits for satisfying future agricultural and market needs

The survey was answered by 64 participants from 24 countries (Appendix D). Stakeholders from Spain (12), The Netherlands (9) and United Kingdom (7) provided most answers. Through the questionnaire, a total of 1,492 trait details were collected of 61 different crops (Appendix E). Soft wheat was the crop that received the highest number of answers by far, followed by tomatoes, beans, apples and potatoes (Table 3). From all the answers, including detailed crop needs, 52% regarded the conventional farming system while the remaining 48% the low input/organic (Figure 4).

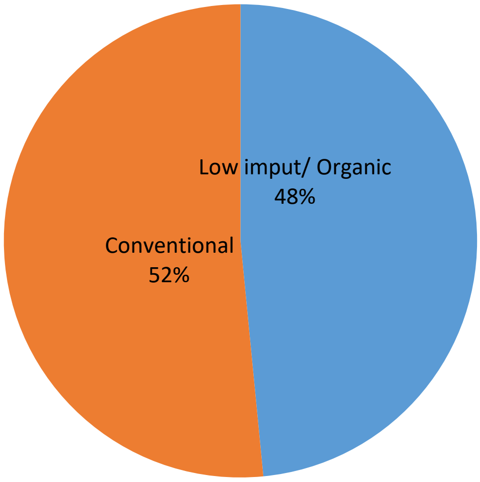

Figure 4. Relative frequency of target farming systems in the answers of the survey.

Tolerance/resistance to biotic stress was the most demanded group of traits (23% of the answers) followed by tolerance/resistance to abiotic stress (19%) (Figure 5), although this differed for each crop (Appendix F). However, the level of importance assigned to the desired traits provided a somewhat different picture, with tolerance/resistance to biotic stress and nutritional quality as the traits of greatest importance (score 5, very high) (Figure 6).

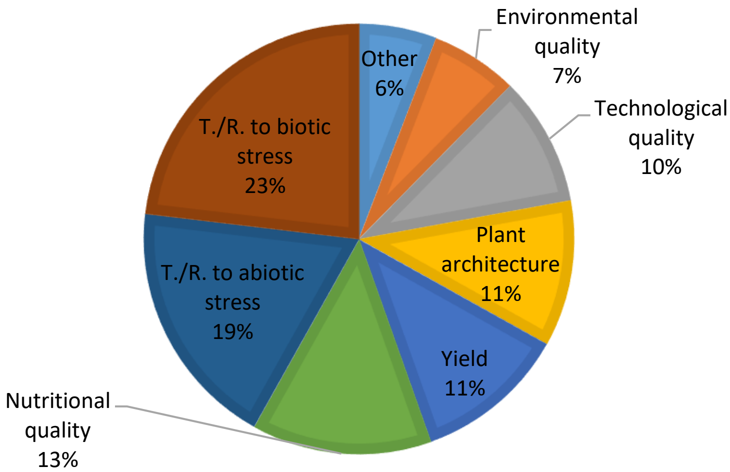

Figure 5. Relative frequency of target desired traits in the answers of the survey.

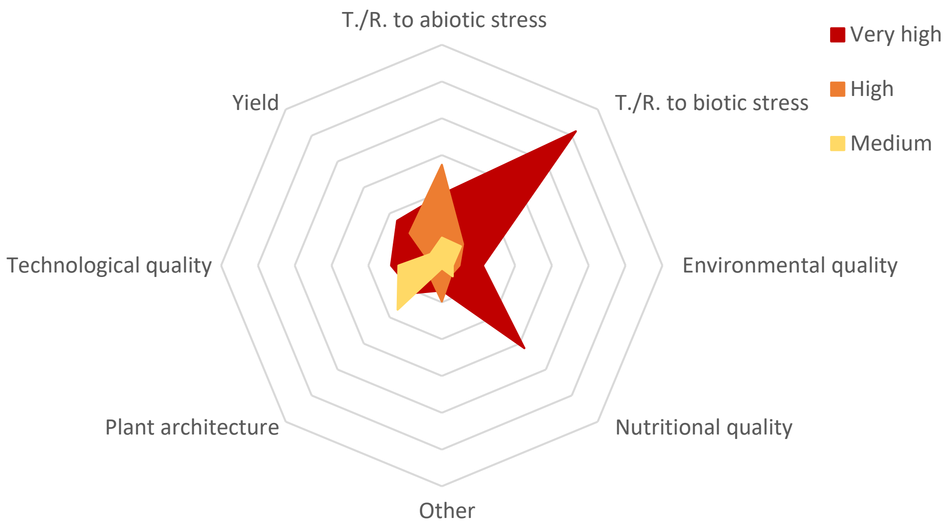

Figure 6. Level of importance given to the different groups of desired crop traits.

4.1.1 Most demanded crops and their desired traits

The 10 crops that received the largest number of answers of desired traits were analysed separately. These were: soft wheat, tomatoes, beans, apples, potatoes, durum wheat, Brassica complex, barley, faba beans and lentils. For all these crops —except for the Brassica complex, lentil and faba bean— the two most selected desired traits were tolerance/resistance to abiotic and biotic stress (Table 3). For the Brassica complex, the environmental quality and the tolerance/resistance to abiotic stress were the most desired traits. The faba bean received the greatest number of preferences for traits of tolerance/resistance to biotic stress, followed by both plant architecture and environmental quality. Finally, lentil received the most answers for tolerance/resistance to abiotic stress and environmental quality.

Table 3. Top ten crops highlighted by survey respondents. Total number of trait details (Tot.) and number of trait details by groups of interest.

Crop	Tot.	Abiotic stress*	Biotic stress*	Environmental**	Nutritional**	Technological**	Yield	Plant architecture	Other
Bread wheat (*Triticum aestivum*)	136	45	24	16	16	8	5	10	12
Tomato (*Solanum lycopersicum*)	76	28	14	5	5	3	1	12	8
Bean (*Phaseolus vulgaris*)	66	14	14	10	7	2	4	9	6
Apple (*Malus* spp.)	65	11	12	10	8	4	5	8	7
Potato (*Solanum tuberosum*)	67	12	18	8	8	5	4	8	4

Durum wheat (*Triticum durum*)	61	13	10	5	7	9	1	6	10
Brassica complex (*Brassica* spp.)	55	18	8	18	1	2	0	2	6
Barley (*Hordeum vulgare*)	51	12	11	5	5	5	5	2	6
Faba bean (*Vicia faba*)	47	7	10	8	5	2	4	8	3
Lentil (*Lens culinaris*)	47	7	11	8	6	2	4	6	3

*Related to resistance/tolerance traits; **Related to quality traits.

4.1.2. Most demanded crops for each type of desired trait

The 10 crops that were the most demanded for each desired crop trait and their status regarding the presence of native European plants related to them were obtained (Table 4). Soft wheat was the most demanded crop in six of the eight crop trait categories. It is worth noting that some of the most demanded crops do not have close CWR native to Europe (e.g. potatoes, tomatoes, common beans, peppers and corn). The Brassica complex was the most demanded crop regarding nutritional quality, whereas plant architecture was most demanded for tomatoes.

Table 4. The ten most demanded crops for each type of desired trait and presence of CWR native to Europe for each crop.

Crop	Tolerance/ resistance to biotic stress	Native European relative	Crop	Tolerance/ resistance to abiotic stress	Native European relative
Triticum aestivum	45	Yes	*Triticum aestivum*	24	Yes
Solanum lycopersicum	28	No	*Solanum tuberosum*	16	No
Brassica spp.	18	Yes	*Solanum lycopersicum*	14	No
Phaseolus vulgaris	14	No	*Phaseolus vulgaris*	14	No
Capsicum spp.	14	No	*Malus* spp.	12	Yes
Solanum tuberosum	14	No	*Hordeum vulgare*	11	Yes
Triticum durum	13	Yes	*Lens culinaris*	11	Yes
Hordeum vulgare	12	Yes	*Triticum durum*	10	Yes
Malus spp.	11	Yes	*Vigna unguiculata*	10	No
Beta vulgaris var. *cicla*	9	Yes	*Vicia faba*	10	Yes
Crop	**Yield**	**Native European relative**	**Crop**	**Nutritional Quality**	**Native European relative**
Triticum aestivum	16	Yes	*Brassica* spp.	18	Yes
Solanum tuberosum	8	No	*Triticum aestivum*	16	Yes
Malus spp.	8	Yes	*Phaseolus vulgaris*	10	No
Phaseolus vulgaris	7	No	*Malus* spp.	10	Yes
Triticum durum	7	Yes	*Solanum tuberosum*	8	No
Lens culinaris	6	Yes	*Vicia faba*	8	Yes

Zea mays	6	No	*Lens culinaris*	8	Yes
Solanum lycopersicum	5	No	*Vigna unguiculata*	8	No
Hordeum vulgare	5	Yes	*Pisum sativum*	8	Yes
Vigna unguiculata	5	No	*Zea mays*	7	No
Crop	**Plant architecture**	**Native European relative**	**Crop**	**Technological quality**	**Native European relative**
Solanum lycopersicum	12	No	*Triticum aestivum*	12	Yes
Triticum aestivum	10	Yes	*Triticum durum*	10	Yes
Phaseolus vulgaris	9	No	*Solanum lycopersicum*	8	No
Solanum tuberosum	9	No	*Prunus* spp.	8	Yes
Malus spp.	8	Yes	*Malus* spp.	7	Yes
Vicia faba	8	Yes	*Hordeum vulgare*	6	Yes
Triticum durum	6	Yes	*Phaseolus vulgaris*	6	No
Lens culinaris	6	Yes	*Brassica* spp.	6	Yes
Vigna unguiculata	6	No	*Capsicum* spp.	5	No
Pisum sativum	6	Yes	*Solanum tuberosum*	4	No
Crop	**Environmental quality**	**Native European relative**	**Crop**	**Other**	**Native European relative**
Triticum aestivum	8	Yes	*Triticum aestivum*	5	Yes
Triticum durum	7	Yes	*Malus* spp.	5	Yes
Hordeum vulgare	5	Yes	*Hordeum vulgare*	5	Yes
Malus spp.	4	Yes	*Solanum tuberosum*	4	No
Solanum tuberosum	4	No	*Phaseolus vulgaris*	4	No
Beta vulgaris var. *cicla*	4	Yes	*Lens culinaris*	4	Yes
Triticum x *Secale*	4	Yes	*Vigna unguiculata*	4	No
Solanum lycopersicum	3	No	*Vicia faba*	4	Yes
Vitis vinífera	3	Yes	*Pisum sativum*	4	Yes
Avena sativa	3	Yes	*Vitis vinifera*	4	Yes

4.1.3. Specific traits sought in most demanded crops

The database compiled contains an enormous wealth of data regarding the specific demands within each of the eight trait groups for each crop. For instance, in soft wheat, the tolerance or resistance to biotic stress trait group contains 45 records 86% of them were focused on fungi, 10% on virus, 2% on nematodes and 2% on aphids. Among fungi, *Puccinia spp*. and *Fusarium spp*. were the most frequent taxa of concern, followed by *Tilletia spp*. and *Erysiphe spp*. Even if it is not practical to provide in this report a full description of the 1,492 traits recorded in the survey for the 61 crops, the database compiled in an [Excel file] can be consulted.

4.2 Areas with useful adaptive traits

4.2.1 Targeted taxa and distribution data

Occurrence data in the compiled high-quality occurrence database contained 10,199 records for 25 (out of a total of 33) wild relatives of wheat in the *Aegilops* genus; 624 records for four out of the five targeted wild relatives of lentils and more than 2,650 occurrence records for five of the six targeted wild taxa related to blue lupins. Detailed information on the number of occurrences per taxa can be found in Appendix B. In *Trifolium repens*, 3,072 high-quality records were gathered at a world level.

4.2.2 Generation of Ecogeographic Land Characterisation maps

Non-correlated variables among the first 15 variables per group (bioclimatic, edaphic and geophysic) chosen through a Random Forest algorithm were selected for the generation of the ELC maps. A total of nine variables were selected for *Aegilops*, eight for *Lens* and nine for *Lupinus* (Table 5).

Table 5. Variables selected to generate ELC maps per each genus under analysis.

Target genus	Group	Variable
Aegilops	Bioclimatic	Annual Mean Temperature
	Edaphic	Topsoil pH (H2O)
		Topsoil CEC (soil)
		Topsoil Gravel Content
		Topsoil Organic Carbon
		Bulk density (fine earth) in kg / cubic-meter – topsoil
	Geophysic	Elevation (meters above sea level)
		Longitude
		Slope
		Latitude
		Orientation
Lens	Bioclimatic	Annual Mean Temperature
	Edaphic	Topsoil total exchangeable bases
		Topsoil silt fraction
		Topsoil sand fraction
		Topsoil gravel content
		Topsoil organic Carbon
		Topsoil salinity
	Geophysic	Annual solar radiation
		Annual radiation December
		Longitude

Lupinus	Bioclimatic	Annual mean temperature
	Edaphic	Topsoil pH (H2O)
		Topsoil clay content (0-2 micro meter) mass fraction (%)
		Topsoil saturated water content (volumetric fraction) for tS
		Topsoil Organic Carbon
		Topsoil Sand Fraction
		Topsoil Clay Fraction
	Geophysic	Annual solar radiation
		Longitude

Resulting ELC maps had 28 ELC different categories for *Aegilops* (Figure 7a), also 28 for *Lens* (Figure 7b) and 36 for *Lupinus* (Figure 7c). These different categories represent different potentially adaptive scenarios for each genus, based on the variables that better explained their distribution.

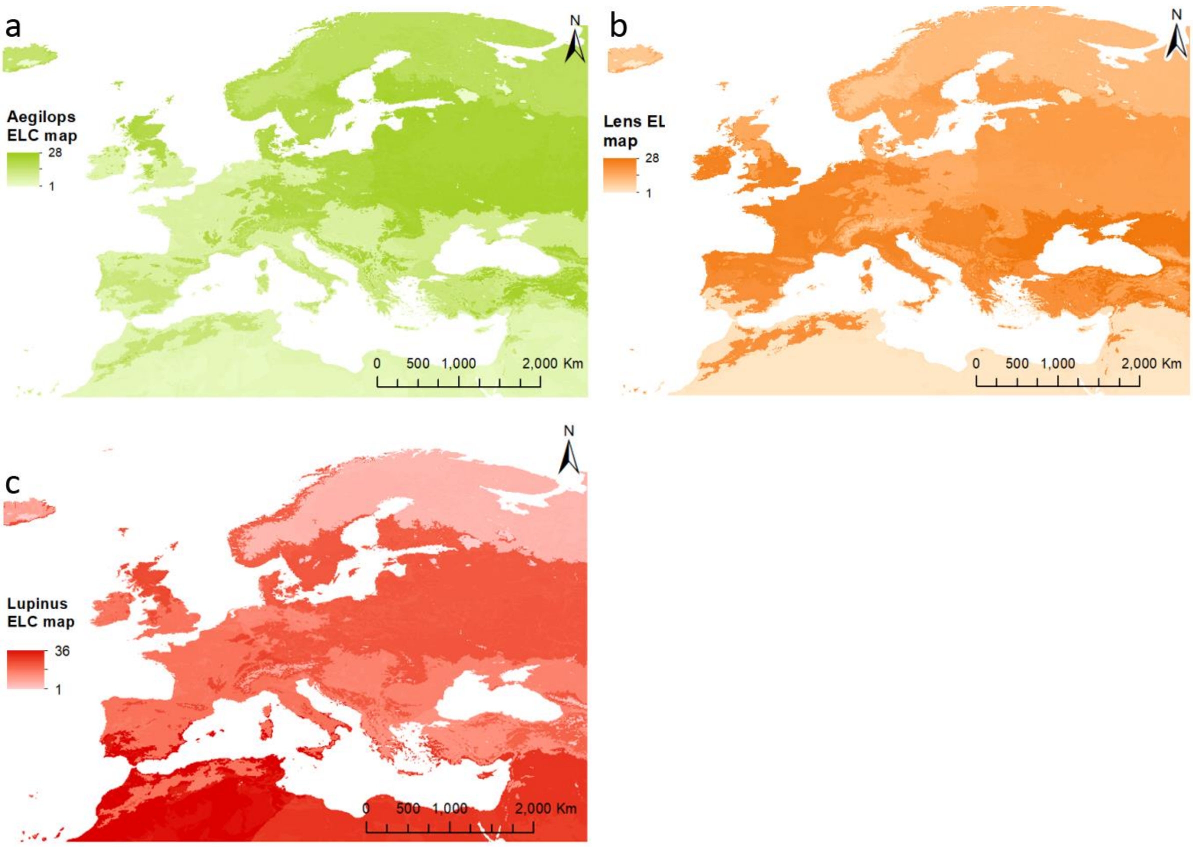

Figure 7 a) Ecogeographic Land Characterisation maps obtained for *Aegilops spp*., b) *Lens spp*., c) *Lupinus* spp.

4.2.3 Targeted traits and predictive characterisation – environmental filtering

4.2.3.1 Drought tolerance

Soft wheat

The selection of *Aegilops* CWR populations occurring in sites with a De Martonne aridity annual index below 15 (mid semi-arid and drier) obtained 521 populations. Subsequently, a further subset of the top 50 with the lowest Flowering De Martonne index ($I_{ar}DM_f$) was selected. The populations were distributed across the Mediterranean region from East (Turkey) to West (Canary Islands) (Figure 8). This subset encompasses seven taxa (*A. biuncialis, A. geniculata, A. neglecta, A. peregrina, A. speltoides, A. triuncialis, A. umbellulata*) distributed in four different ELC categories. Almost half of them were classified as extremely arid (desert) according to the calculated Flowering de Martonne index. The rest of them, were classified in the arid (semi-desert) category, all of them with Flowering De Martonne indices below seven. The taxonomic details, location of the populations and ecogeographical category of the final subset is shown in Appendix G.

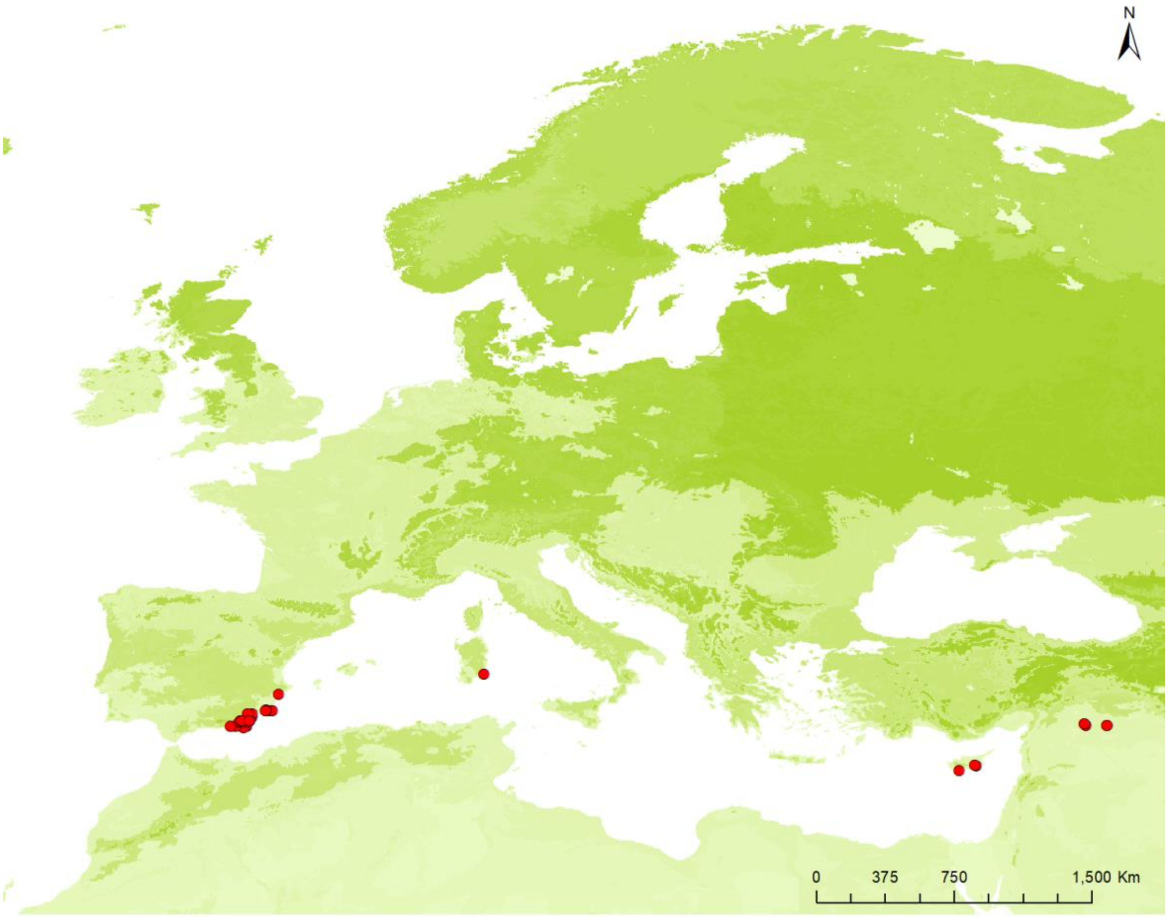

Figure 8. Top 50 *Aegilops spp*. populations most likely to be drought tolerant.

Lentil

The selection of populations with an annual De Martonne indexed below 15, obtained 19 wild CWR populations of *Lens*. From these, six had a Flowering De Martonne index above 15, and thus were removed for the final selection. The final subset encompasses 13 populations of three taxa (*L. ervoides, L. lamottei, L. nigricans*), all of them with Flowering De Martonne aridity indices between 10 and 15. They were found in Spain, Greece and Turkey (Figure 9) and belonged to a single ELC category. Appendix H provides taxonomic, geographic and ecogeographic details for each of them.

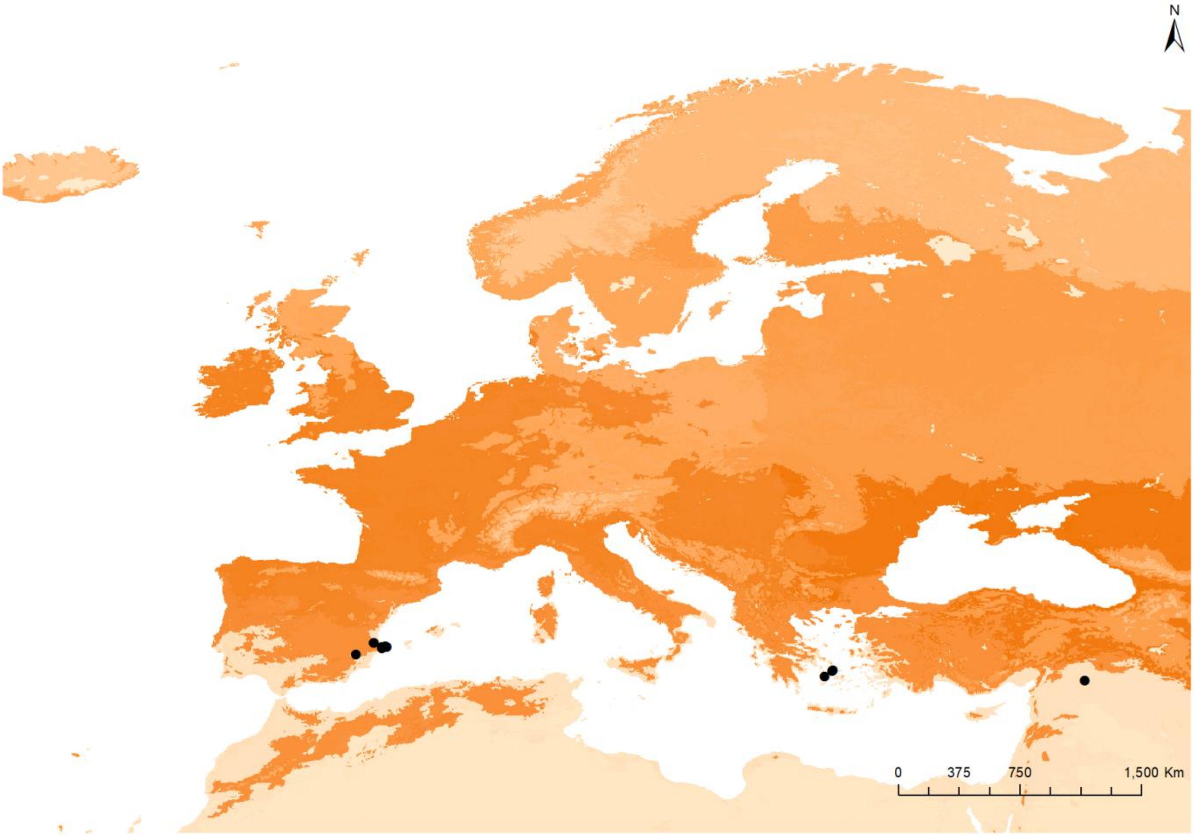

Figure 9. Selection of 13 populations of wild relatives of lentil most likely to be tolerant to drought.

Lupin

The application of the drought tolerance selection criteria to wild *Lupinus spp*. populations obtained 54 populations with an annual De Martonne aridity index below 15. From these, 28 populations presented a Flowering De Martonne aridity index higher than 15, and thus were removed from the dataset, leaving a final subset of 26 populations. This subset encompasses three species taxa (*L. angustifolius, L. hispanicus, L. luteus*) distributed in six ELC categories of the map. Four of them are classified in the arid (semi-desert) category, and the rest of them as semi-arid, during the flowering season (March, April, May and June). The selected populations are distributed across the Mediterranean region, from the Canary Islands to Greece (Figure 10). Taxonomic, geographic and ecogeographic details are provided in Appendix I.

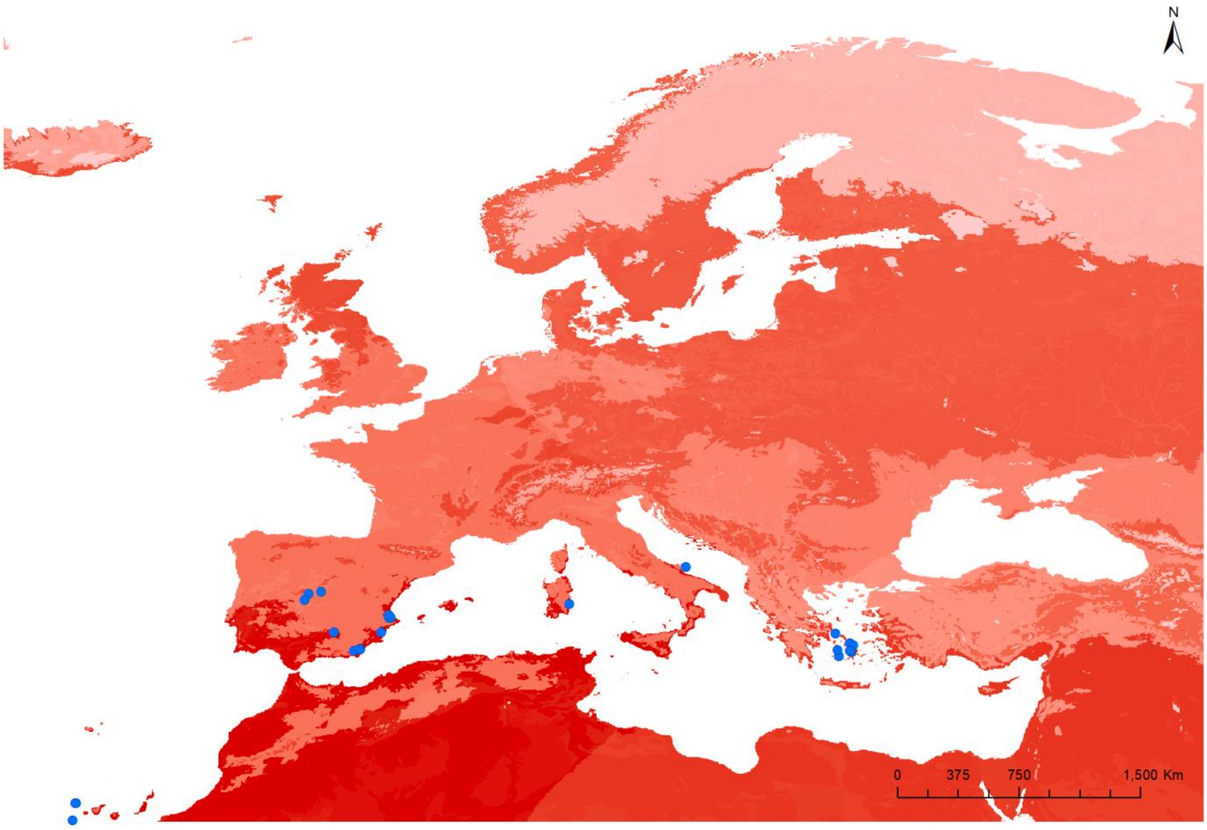

Figure 10. Selection of 26 populations of wild relatives of *Lupinus spp.* most likely to be tolerant to drought.

4.2.3.2 Salinity tolerance

The selection of populations occurring in moderately and strongly saline soils (conductivity above 4 dS/m), obtained three populations of *Aegilops spp*. (two taxa in one ELC category) distributed in Portugal (Figure 11), two populations of *Lupinus spp.* (two taxa in one ELC category) located in Portugal and Spain (Figure 12) and no populations of *Lens spp*. It is worth mentioning that populations selected for *Aegilops* and *Lupinus*, present a soil conductivity higher than 12 dS/m, and thus are occurring in sites classified as strongly saline.

The selection of populations occurring in slightly saline soils (conductivity between 2-4 dS/m), obtained eight populations of *Aegilops spp.* (three taxa, one ELC category) distributed in France and Spain (Figure 11), one population of *Lens spp*. I France (Figure 13) and no populations of *Lupinus spp*. The taxonomic, geographic and ecogeographic details of these populations are found in Appendix J.

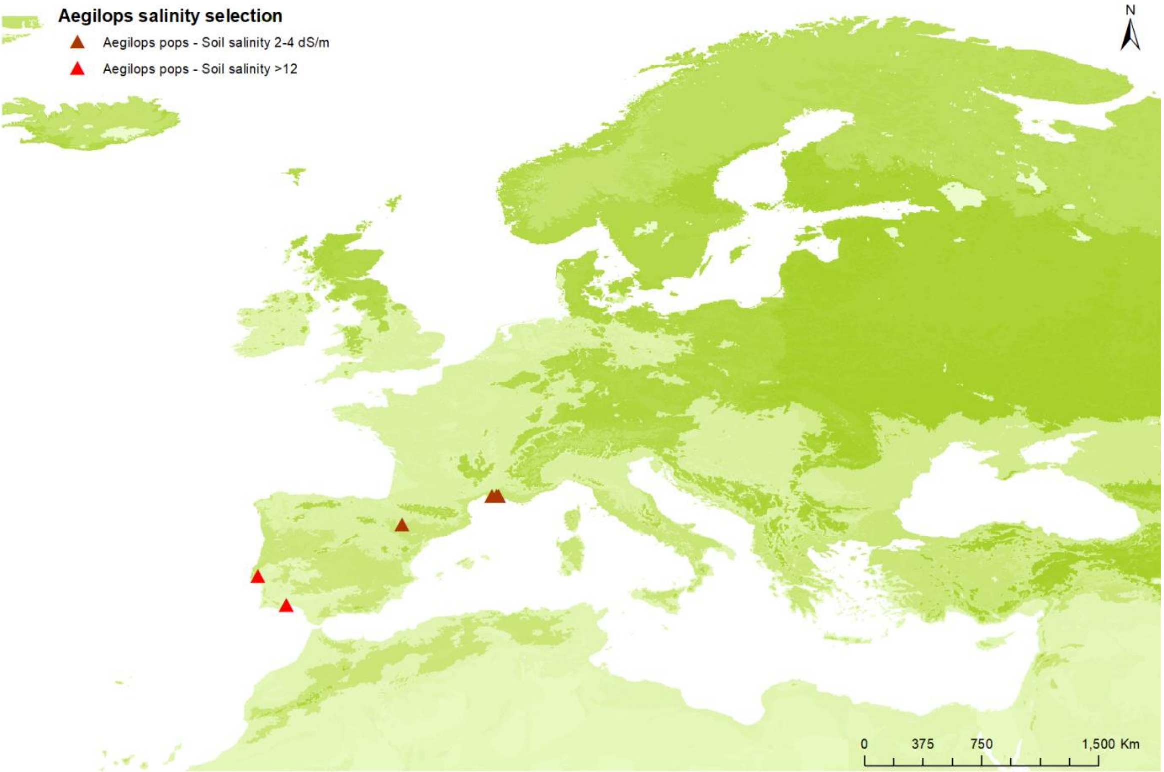

Figure 11. Subset of *Aegilops* populations occurring in saline soils. Red triangles: strongly saline soils, Brown triangles: slightly saline soils.

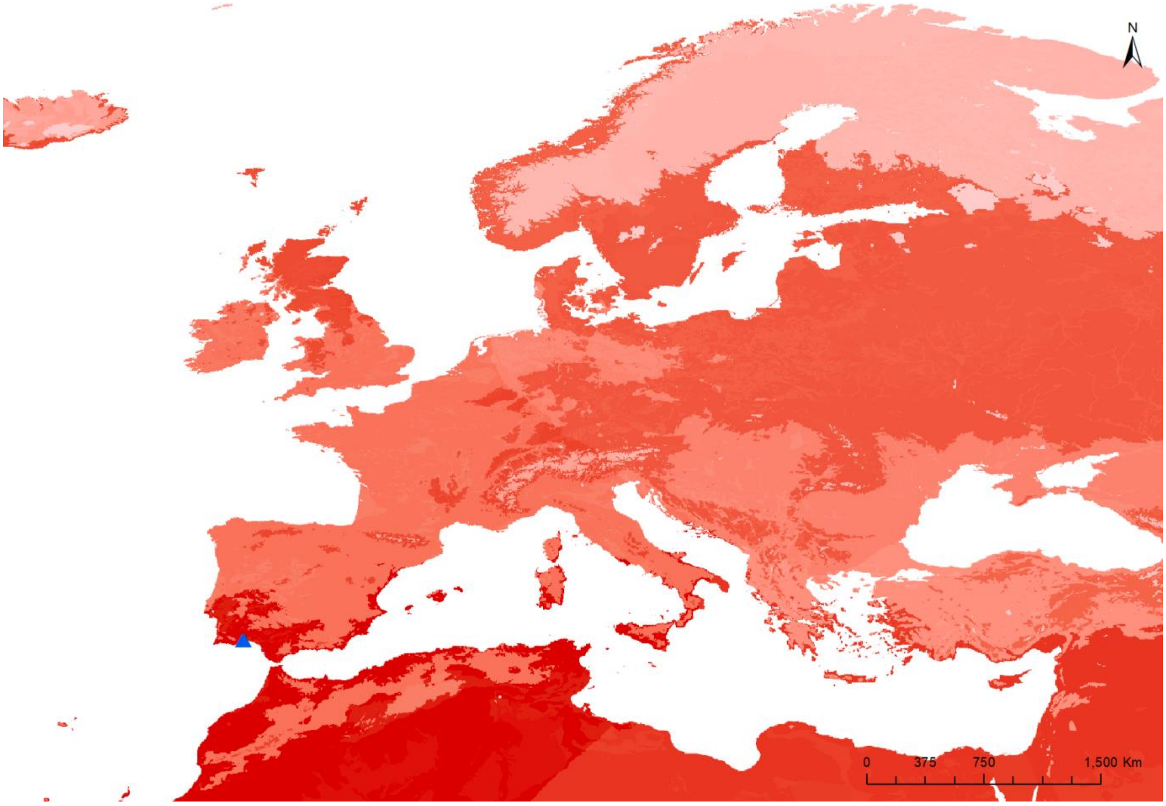

Figure 12. Two selected *Lupinus spp*. populations occurring in strongly saline soils.

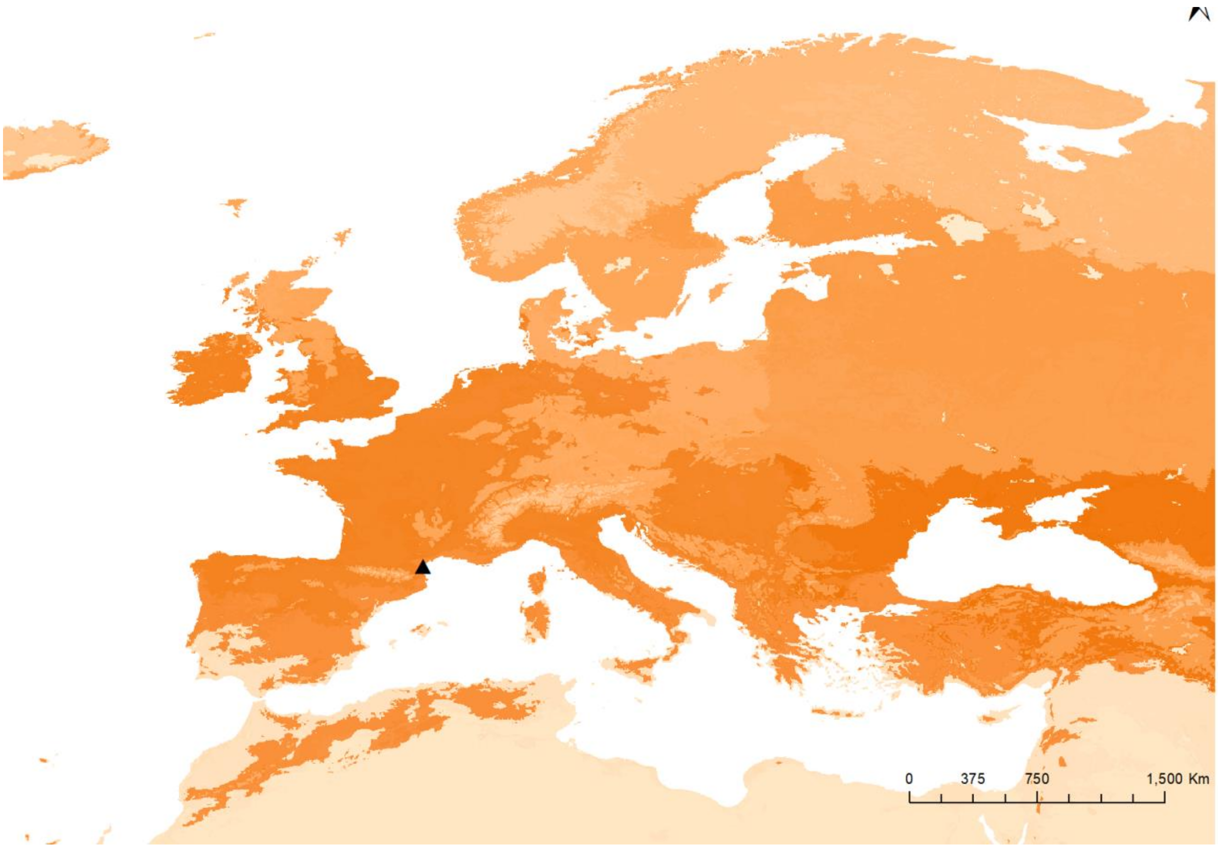

Figure 13. Selected *Lens spp.* population occurring in slightly saline soil

4.2.3.3 Waterlogging tolerance

The selection of populations of wild relatives of lentils occurring in Clay, Silty Clay, Sandy Clay or Silty Clay Loam soils, obtained 69 populations that were found in Clay soils. From these, populations occurring in mid-high subhumid or more humid areas (Annual De Martonne Aridity Index > 25) selected a final subset of 21 populations (Figure 14) that encompasses four taxa (*L. culinaris subsp. Orientalis, L. ervoides, L. lamottei, L. nigricans)* located in four different ELC categories. Detailed taxonomic, geographic and ecogeographic information is found in Appendix K.

4.2.4 Target traits and predictive characterisation through the calibration method

The GLM method yielded the best fit, with the highest TSS value of a run and the highest mean, lower and upper TSS values (Table 6). The most influential variable on the model was annual mean temperature (0.93), followed by annual precipitation (0.43) and altitude (0.13). The other four ecogeographic variables did not have any influence on the model.

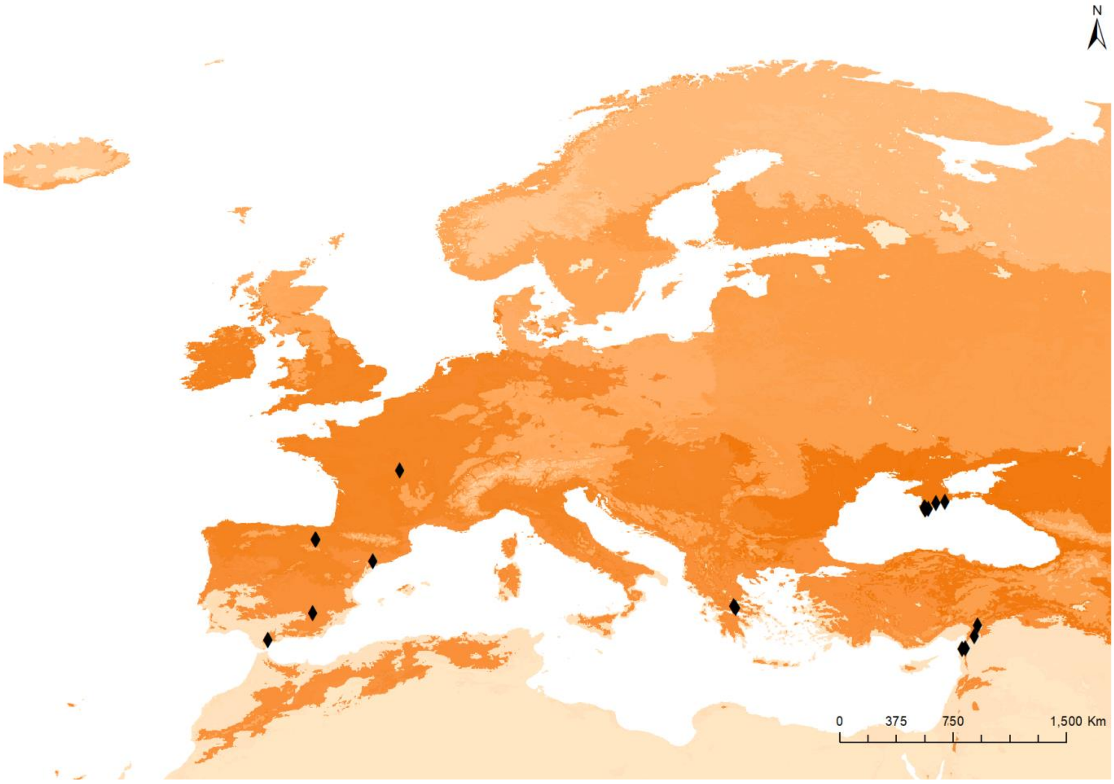

Figure 14. Subset of 21 populations of wild relatives of lentils most likely to present tolerance to waterlogging. They correspond to populations with the highest annual De Martonne aridity indexes – most humid – and occurring in the least permeable soils (Clay soils).

Table 6. Model accuracy values for learning-based techniques used on test data (25%) of the evaluated set over 100 runs of the algorithms. TSS, True skill statistic (García et al., 2019)

Model		TSS
Artificial neural networks (ANN)	Mean	0.38
	Lower	0.00
	Upper	0.82
Classification tree analysis (CTA)	Mean	0.39
	Lower	0.08
	Upper	0.78
Flexible discriminant analysis (FDA)	Mean	0.47
	Lower	0.16
	Upper	0.78
Generalised additive model (GAM)	Mean	0.43
	Lower	0.00
	Upper	0.82
Generalised boosted model (GBM)	Mean	0.49
	Lower	0.23
	Upper	0.79
Generalised linear model (GLM)	Mean	0.52
	Lower	0.27
	Upper	0.85

Multivariate adaptive regression splines (MARS)	Mean	0.49
	Lower	0.04
	Upper	0.78
Random Forest (RF)	Mean	0.48
	Lower	0.18
	Upper	0.79

The projection of the run of the GLM technique with the highest TSS value (0.85) on the non-evaluated set identified 470 populations with a higher probability of being acyanogenic (Figure 15). Central and northern Eurasia, as well as the Southern Cone and areas above the Tropic of Cancer in America, were identified as areas with high probability of occurrence of acyanogenesis (Figure 16).

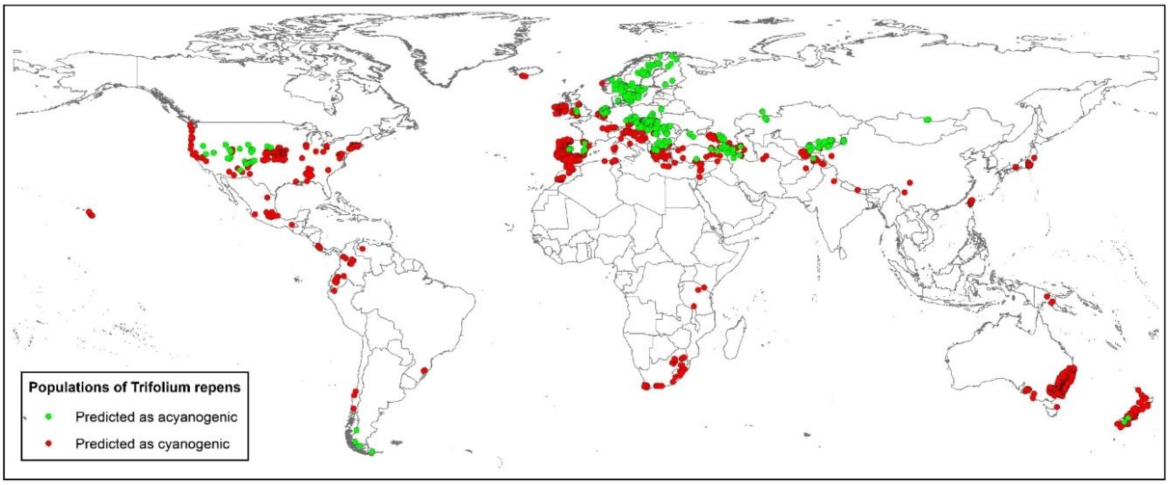

Figure 15. Predicted completely acyanogenic (green) and cyanogenic (red) trait in non-evaluated populations of white clover (*Trifolium repens*) through the calibration method.

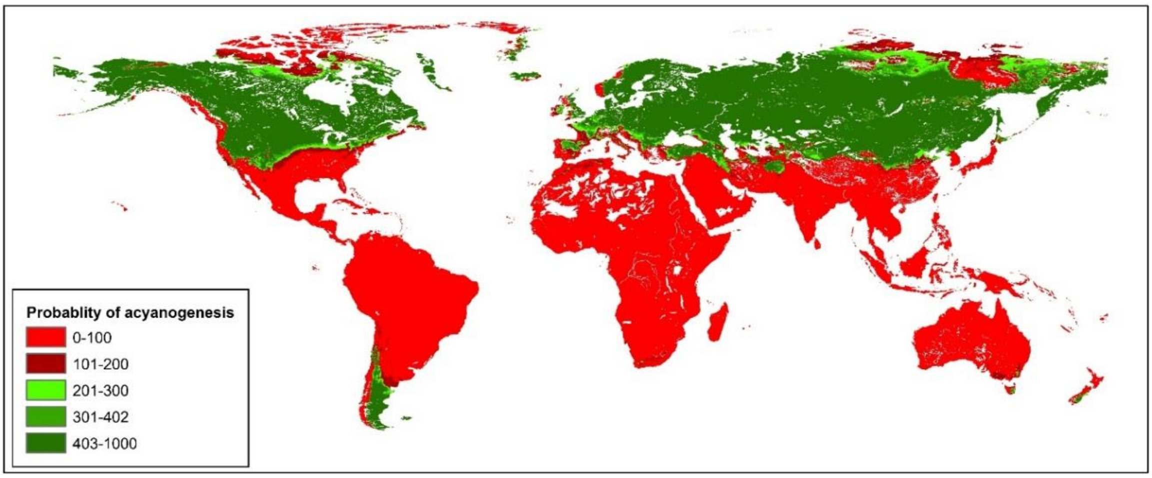

Figure 16. Probability of an area for having the environmental conditions to favor acyanogenesis according to the selected model (0: very low; 1000: very high).

Only a portion of the USDA top-rank predicted acyanogenic accessions could be evaluated owing to limited seed availability. These accessions were located between positions three and 351 in the ranking, and their predicted probabilities of being acyanogenic ranged between 930 and 626 (Appendix L). Of the 18 evaluated accessions, 17 were completely acyanogenic, whereas the other accession, which had the lowest probability of being acyanogenic of the evaluated sample, had 95% of acyanogenic plants (Appendix L).

4.2.5 Areas with useful adaptive traits of in situ landraces obtained from the evidence-based approach

A total of 105 case studies of *in situ* maintained landraces were collected; 104 from 14 European countries and one from a non-European country (Mexico). The full description of each collected case study is available on an ad hoc developed database hosted by the European Cooperative Programme on Genetic Resources (ECPGR) website (https://www.ecpgr.cgiar.org/in-situ-landraces-best-practice-evidence-based-database).

The case studies includes landraces of 53 different species of which the most represented are *Solanum lycopersicum L.* (12 case studies) and *Phaseolus vulgaris L*. (8), followed by cereals belonging to the *Triticum genus* (8) and *Secale cereale L.* (6).

Table 7. List of species, number of case studies by species and country of the 105 case studies of *in situ* maintained landraces)

Species	N	Country	Species	n	Country
Allium ampeloprasum L.	1	ITA	*Malus domestica* Borkh.	3	ITA
Allium cepa L.	4	AUT, GRC, PRT, SWE	*Papaver somniferum* L.	1	HUN
Allium sativum L.	1	ROU	*Phaseolus coccineus* L.	2	ESP, HUN
Apium graveolens L.	1	ITA	*Phaseolus lunatus* L.	1	HUN
Armoracia rusticana Gaertn.	1	FIN	*Phaseolus vulgaris* L.	8	ESP (2), HUN, ITA (3), PRT, SWE
Asparagus officinalis L.	1	DNK	*Phleum pratense* L.	1	GBR
Avena strigosa Schreb.	1	GBR	*Pisum sativum* L.	1	CHE
Beta vulgaris L. var. *rapacea* Koch.	1	DNK	*Pisum sativum* L. subsp. *sativum* var. *arvense*	3	DEK, ITA, SWE
Brassica napus L. var. *napobrassica*	2	SWE	*Prunus domestica* L.	1	ITA
Brassica oleracea L. subsp. *Capitata*	1	GBR	*Prunus persica* L.	1	ITA
Brassica oleracea L. var. *acephala*	1	PRT	*Pyrus communis* L.	2	ITA
Brassica oleracea L. var. *italica* Plenck	2	ITA	*Secale cereale* L.	6	FIN (3), PRT (2), GBR
Brassica rapa L. subsp. *Rapa*	2	CHE, ESP	*Solanum lycopersicum* L.	12	AUT, GRC, HUN (6), ITA, ESP (3)

Brassica rapa L. subsp. *sylvestris* var. *esculenta*	1	ITA	*Solanum melongena* L.	1	ESP
Capsicum annuum L.	2	GRC, HUN	*Solanum tuberosum* L.	3	CHE, FIN, GBR
Cichorium intybus L.	1	CZE	*Trifolium pratense* L.	1	FIN
Citrullus lanatus (Thunb.) Matsum & Nakai	2	ESP, HUN	*Trifolium repens* L.	1	GBR
Cucurbita pepo L.	1	ESP	*Triticum aestivum* L. subsp. aestivum	3	AUT, GBR, ITA
Cynara cardunculus L. subsp. C*ardunculus*	1	CHE	*Triticum aestivum* L. subsp. *spelta*	1	GBR
Daucus carota L.	3	CHE (2), ROU	*Triticum monococcum* L. subsp. *monococcum*	2	GRC, ROU
Helianthus tuberosus L.	1	CHE	*Triticum turgidum* L. subsp. *dicoccum*	1	ITA
Hordeum vulgare L.	2	GBR, ITA	*Triticum turgidum* L. subsp. *durum*	1	GRC
Ipomea batatas (L.) Lam.	1	ESP	*Vicia faba* L.	1	ITA
Lactuca sativa L.	3	ESP (2), HUN	*Vigna unguiculata* (L.) Walp.	1	ITA
Lathyrus clymenum L.	1	GRC	*Vitis vinifera* L.	2	PRT, SRB
Lathyrus sativus L.	1	GRC	*Zea mays* L.	4	CHE, ITA, MEX, PRT
Lens culinaris Medik.	2	AUT, GRC	-	-	-

For 65 out of the 105 collected case studies, tolerance/resistance to biotic or abiotic stress or a particular nutritional value was recorded. In some cases, more than one trait of interest was recorded for the same landrace (e.g. *Tomataki Santorinis* tomato from Greece, *Markóci bean* from Hungary, *Bözödi* and *Kaploutzas einkorn* wheats from Romania and Greece). The list of landraces characterised by tolerance/resistance to biotic or abiotic stress is reported in Table 8 and Table 9, respectively, while those with a particular nutritional value are reported in Table 10. It should be noted that these are the most important traits according to the survey results. The exact location of cultivation of each landrace (shown in a detailed map) can be retrieved using the above cited tool available at the ECPGR website and by clicking on the landrace name.

Table 8. Landraces for which an abiotic stress resistance/tolerance trait has been recorded in the case study collection. Crop, landrace/s' name and landrace origin country are shown

Crop scientific name	Landrace name	Country Code	Trait of interest
Allium cepa L.	*Laaer Zwiebel*	AUT	Drought tolerance
Allium cepa L.	*Leksand*	SWE	Drought tolerance
Brassica oleracea L. subsp. *capitata*	*Shetland cabbage*	GBR	Adaptation to harsh weather conditions
Brassica rapa L. subsp. *rapa*	*Bosco Gurin*	CHE	Adaptation to harsh mountain climate
Brassica rapa L. subsp. *rapa*	*Nabo de Morcín*	ESP	Frost tolerance
Cichorium intybus L. var. *sativus*	*Slezská*	CZE	Drought tolerance
Lactuca sativa L.	*Morada de Morella*	ESP	Adaptation to low temperatures
Lens culinaris Medik.	*Faki Eglouvis*	GRC	Drough escape (early maturity)
Lens culinaris Medik.	*Steinfelder Tellerlinse*	AUT	Drought tolerance
Phaseolus vulgaris L.	*Markóci*	HUN	Drought tolerance
Phleum pratense L.	*Scots Timothy*	GBR	High winter hardiness
Secale cereale L.	*Centeios serranos (Serra da Estrela's rye)*	PRT	Rusticity and adaptation to less favourable pedoclimatic conditions
Secale cereale L.	*Hermanni*	FIN	Good winter hardiness
Secale cereale L.	*Iivo*	FIN	Good winter hardiness
Solanum lycopersicum L.	*Máriapócs*	HUN	Magnesium/calcium deficiency tolerance
Solanum lycopersicum L.	*Tomataki Santorinis*	GRC	Drought tolerance
Triticum aestivum L. subsp. *aestivum*	*Solina*	ITA	Cold resistance
Triticum monococcum L. subsp. *monococcum*	*Bözödi*	ROU	Abiotic stress tolerance (general)
Triticum monococcum L. subsp. *monococcum*	*Kaploutzas*	GRC	Drought resistance

Table 9. Landraces for which a biotic stress resistance/tolerance trait has been recorded in the case study collection. Crop, landrace/s' name and landrace origin country are shown.

Crop scientific name	Landrace name	Country code	Trait of interest
Capsicum annuum L.	*Bocskor*	HUN	Biotic stress tolerance (general)
Capsicum annuum L.	*Glikokafteri Mpachovou*	GRC	Excellent resistance to pathogens and harmful insects
Malus domestica Borkh	*Rosa Romana*	ITA	Reduced sensitivity to apple scab
Phaseolus vulgaris L.	*Markóci*	HUN	Resistance to different diseases;
Solanum lycopersicum L.	*Cegléd*	HUN	Low attacks by *Helicoverpa armigera* due to yellow fruits color
Solanum lycopersicum L.	*Máriapócs*	HUN	Fungal diseases tolerance
Solanum lycopersicum L.	*Tomataki Santorinis*	GRC	Biotic stress tolerance (general)
Triticum monococcum L. subsp. *monococcum*	*Bözödi*	ROU	Tolerance to different diseases and pests
Triticum monococcum L. subsp. *monococcum*	*Kaploutzas*	GRC	Amazing resistance to pests and diseases

Table 10. Landraces for which a nutritional value trait has been recorded in the case study collection. Crop, landrace/s' name and landrace origin country are shown.

Crop scientific name	Landrace name	Country code	Trait of interest
Armoracia rusticana Gaertn.	*Piparjuuri Vehmaa*	FIN	High glucosinolate content
Avena strigosa Schreb.	*Black oat*	GBR	Flour suitable for persons affected by wheat allergy
Brassica oleracea L. var. *acephala*	*Couve-Galega*	PRT	High quality of the product
Cucurbita pepo L.	*Bubango*	ESP	Ability to relieve irritations of the urinary tract and diuretic
Lactuca sativa L.	*Morada de Morella*	ESP	High anthocyanin content
Lathyrus clymenum L.	*Arakas for Fava Santorinis*	GRC	Optimal organoleptic qualities
Lathyrus sativus L.	*Fava Feneou*	GRC	Rich in protein, carbohydrates and plant fiber
Malus domestica Borkh	*Rosa Romana*	ITA	Easy 'natural storage' that allows a better smell and aroma to be retained
Phaseolus vulgaris L.	*Tarreste*	PRT	Recognised as functional foods
Phaseolus vulgaris L.	*Ganxet*	ESP	High protein and uronic acids content in the seed-coat
Pisum sativum L. subsp. *sativum* var. *arvense*	*Roveja di Civita di Cascia*	ITA	High quality of the product
Secale cereale L.	*Hebridean rye*	GBR	Product tolerated by some people with a wheat allergy, reduced postprandial insulin response
Solanum lycopersicum L.	*Tomataki Santorinis*	GRC	High ascorbic acid concentration in red ripe fruits, high amount of bioactive compounds with health-promoting properties
Solanum melongena L.	*Almagro*	ESP	High phenolic content
Triticum aestivum L. subsp. spelta	*Zollen spelt*	GBR	Nutritional benefits and unique taste

5. Discussion

5.1 Most needed traits for satisfying future agricultural and market needs

Results obtained from the survey provide a timely account of the main concerns of plant breeders, farmers and other plant genetic resources users regarding traits needs in future cultivars. The factors identified as major constrains for crop production and the preservation of food security are congruent with those found in previous reports. An increasing awareness of the significance of genetic diversity (FAO 2010), both to satisfy expanding needs for a more diverse diet and to address present and future agricultural challenges, emerges from the collected replies. The concern regarding different crop traits here expressed by farmers, plant breeders, and agricultural experts, is also broadly consistent with the growing environmental variability that is arising from climate change, who entrust access to a wider range of plant genetic resources to face the outstanding challenge. The attention paid to a great number of crops reveals the importance given to interspecific diversity, considering that agriculture is nowadays characterised by a sharp decrease in the diversity of cultivated plants (Haussmann et al., 2004). Furthermore, the varying factors that are affecting all crops at different locations and farming systems, highlights the need for different trait adaptations and the urgency to address the lack of available sources of useful genetic diversity at intraspecific level.

5.2 Areas with useful adaptive traits

The genetic diversity of crop wild relatives as a source of genes involved in adaptations useful to breed crops, is largely documented (Hawtin et al., 1996; Inci and Toker 2011; Brozynska et al., 2016; Dempewolf et al., 2017), although it remains fairly unexploited (Ford-Lloyd et al., 2011; Prohens et al., 2017). In addition, the usefulness of genetic diversity conserved in wild *Aegilops* and *Lens* species for wheat and lentil breeding – especially to enhance resistance and tolerance to biotic and abiotic stresses including drought and salinity – is widely recognised (Monneveux et al., 2000; Dwivedi et al., 2007; Ashraf 2010; Coyne and McGee 2013; Chahota et al., 2019). In the case of lupins, the breeding material available in Europe and Australia has limited genetic diversity (Berger et al., 2012) and thus the exploration of wild genetic resources as a source of novel variation should be addressed.

Two of the most important abiotic agents limiting crop yields are salinity and drought (Zhang et al., 2017). Addressing different strategies to improve salt tolerance in crops, Shannon (1997) identified two of them related to the use of crop wild relatives, which involved: i) the introgression of genes or ii) the domestication of wild species inhabiting saline soils. However, targeting adequate wild populations to start breeding and pre-breeding processes might be a challenge, given the large number of populations occurring in the wild. Predictive characterisation can help to identify wild populations with important traits for crop breeding, and, thus, increase the probabilities of success with regard to the alternative option of randomly selecting the populations, thereby, making the most of available resources (Thormann et al., 2014, 2016). Although the populations we present here must be further screened and evaluated through field trials to confirm the presence of the targeted traits, previous works performed with landraces applying similar approaches have shown that this methodology is efficient for the selection of germplasm targeting both biotic and abiotic adaptation traits (Bari et al., 2012, 2016; Khazaei et al., 2013). In the case of CWR, following an evolutionary approach, Egan et al. (2018) assessed genetic variation in wild relatives of the strawberry, testing different traits and successfully relating this information with the mesoclimatic variation, landscape isolation and geographic distance between populations. Furthermore, the predictive characterisation approach, using the calibration method, successfully predicted the acyanogenic status of white clover populations (García Sánchez et al., 2019). Based on the ecogeographic variables involved in the expression of the trait, this approach allowed us to model the expression of cyanogenesis in white clover and to predict which populations might have desired levels of this trait. The evaluation carried out in this study confirmed the reliability of the prediction, given that the 18 accessions selected by predictive characterisation and later evaluated were completely or almost completely acyanogenic.

When searching for desirable traits, one should try to maximize the different sources of genetic diversity, while keeping redundancy to a minimum (Hawtin et al., 1996). The field evaluation of all existing populations of CWR species for the targeted traits is not only unfeasible from an economic point of view, but also in terms of time and human resources. In this sense, the application of ecogeographical land characterisation maps can provide a basis for maximising genetic diversity of adaptive value. Generated through the aggregation of environmental information, ELC maps generate a tentative picture of the different potential adaptive scenarios of a given species and are useful to identify the genetic diversity of adaptive value allocated throughout the distribution range of the species (Parra-Quijano et al., 2012a, b, c). The generation of genus-specific ELC maps for *Aegilops*, *Lens* and *Lupinus*, through the selection of important variables for their distribution through objective processes, provided a manageable number of adaptive scenarios in Europe to look for adaptive traits. The addition of these data into the occurrence records contributed to the outlining of the potential genetic diversity and to maximising it in the selected subset of populations. Thus, the selected subsets of populations will not only potentially contain the desired trait, but will also provide populations under different adaptive scenarios that may have generated the desired traits through different alleles in a certain specific locus or different gene combinations.

This pilot study on the application of predictive characterisation methods has shown that current worldwide data availability of genebank accessions, CWR geographic distribution, climate, soil and topographic information and partial evaluation data, makes it possible to implement this type of analyses with open-source software and limited economic resources. Therefore, this approach provides an efficient tool to make initial screenings of plant genetic resources in pre-breeding studies.
Also the utility of the landrace genetic diversity in crop breeding is largely documented (Lopes et al., 2015; McNally et al., 2009; Strigens et al., 2013; just to cite some of the many references). As Esquinas-Alcazar (1993) writes “The heterogeneous varieties of the past have been and still are the plant breeder’s raw material. They have been a fruitful, sometimes the sole, source of genes for pest and disease resistance, adaptation to difficult environments, and other agricultural traits like the dwarf-type in grains that have contributed to the green revolution in many parts of the world”. Also the many landraces here identified as characterised by biotic, abiotic stress resistance/tolerance and/or nutritional valuable traits by farmers cultivating them, like the CWR populations, need to be further screened and evaluated in ad hoc trials to confirm the presence of the targeted traits in them before being used in crop breeding. This is because many environmental variables condition the performance of a certain landrace, while stable traits across years and environments are needed for ensuring success during introgression breeding or direct selection from a landrace.

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Appendix A: Identify useful in situ traits for Food and Agriculture breeding

Identify useful *in situ* traits for Food and Agriculture breeding

Fields marked with * are mandatory.

Information about the Farmer's Pride Project

Funded by the European Union, the Farmer's Pride project is responding to a call for action to enhance and strengthen in situ conservation of plant genetic resources (PGR) in Europe [1].

The focus of the project is on conserving the diversity that exists in both wild and cultivated populations of species important for food, nutrition and economic security in the region[2].

To that purpose, we aim to build The European Network for *In Situ* Conservation of Plant Genetic Resources that will comprise a network of both stakeholders and sites across Europe. It will establish a mechanism for coordinated action on PGR conservation in situ in the region, with a view to ensuring that the diversity needed for continual crop enhancement and adaptation is available for future use.

Please feel free to distribute the link to this survey among potential respondents in your network.

For further information on the project, please visit www.farmerspride.eu.

[1]In wild species *in situ* conservation involves the management of populations in their natural habitats (which may be in wild, semi-natural, managed, or abandoned habitats). In the case of crops, it involves their management in the locations where they are cultivated (which may be in farms, smallholdings, home gardens, and allotments).

[2] Species known as crop wild relatives (CWR – wild species related to crops which contain important diversity

for crop enhancement) and landraces (LR – diverse, locally adapted crop populations which not only contain diversity for crop enhancement, but are also important for local food and economic security. They are also known as "farmer varieties").

The survey

Welcome to this 'Identification of useful traits for Food and Agriculture breeding' consultation for the development of a European Network for *In Situ* Conservation of Plant Genetic Resources.

With this survey we aim at gathering information on most needed traits for satisfying present and future agricultural and market needs. If you have any knowledge on breeding needs for the future, we would like to hear from you.

Based on answers received from this survey and information from other workpackages we will identify the Landraces and Crop Wild Relatives populations which most likely contain the desired traits. This identification will be performed using predictive characterization approaches based on species distribution data and thematic maps containing environmental data (climate, soil, topography, etc.). The identification of these populations could be of a great importance when searching for the variability needed for breeding programs.

The survey will take 5-10 minutes to complete and comprises two sections:

Section 1: contact information details.

Section 2: information on your crop of interest and traits to be addressed.

Please note that:

- Questions flagged with asterisks (*) are mandatory.
- Any results or publications arising from this survey will contain no identifying information that could associate it with you or the organization you represent.
- At any point in the survey you may go back to the previous question if you wish to change an answer. This action will overwrite the previous answer given.
- Should you have any questions or inquiries please contact Lorenzo Raggi, José M. Iriondo, Clara Álvarez o María Luisa Rubio Teso: lorenzo.raggi@gmail.com; jose.iriondo@urjc.es; clara.alvarez@urjc.es; marialuisa.rubio@urjc.es

In order to carry out the research described in this survey, we will need to collect information about you, and some of this information may be your personal data (if you voluntarily provide it). Under data protection law, we have to provide you with very specific information about what we do with your data and about your rights. We have set out below the key information you need to know about how we will use your personal data.

☐ *By completing this survey you are consenting to the Farmer's Pride project storing the information you provide and which will only be accessed by authorized personnel working in the project. In agreement with Regulation (EU) 2016/679 we will not make your contact details available in the public domain or pass them on to any third parties. You can exercise your rights of access, rectification, cancellation, opposition, treatment limitation, portability, deletion/ forgetting and others recognized in the European Regulation 2916 /679, of April 27, general Data Protection. The information you contribute to this survey will not be used for any other purpose than for the establishment if the European Network for *In Situ* Conservation of Plant Genetic Resources, and for reporting on its establishment. The responsible for the data processing is José María Iriondo Alegría (Universidad Rey Juan Carlos, Tulipán s/n, 28933 Móstoles, Spain). A synthesis of the results will be published in a publicly available document on the Farmer's Pride project website (www. farmerspride.eu) and may also be published in other forms, such as in a journal article. Any such publications arising from this survey will contain no identifying information that could associate it with you or the organization you represent. Your data will be retained for 10 years after the publication of the research outcomes. This privacy notice is effective from September 9th of 2018, and is reviewed when necessary. Any changes will be published here.
The web page https://www.urjc.es/proteccion-de-datos sets out much of this information, including how to ask any questions you may have about how your personal data is used, exercise any of your rights or complain about the way your data is being handled.

This survey is created under the frame of the Farmer's Pride Project funded by the European Commission under the Horizon 2020 programme – Coordination and Support Actions (CSA). Grant Agreement: 774271. This survey has been developed in relation to task 3.2 of the project: Identify useful *in situ* traits.

1. Contact data

These data will only be used for internal project records and to contact you in case any clarification is needed. Personal data will be used according to Regulation EU 2016/679.

1.1 Name

First name and Family name.
Ex: John Smith.

1.2 Affiliation

Please provide the name of the organization to which you are related to.
Ex: Rey Juan Carlos University.

1.3 Address

Please, provide full details of the address of your organization, including city and country.
Ex: C/ Tulipán, s/n. 28933 Móstoles (Madrid) Spain.

* **1.4 Do you allow us to contact you in case we need any clarification?**

- Yes
- No

1.5 Contact

Please, provide a means of contact (preferably your work email account).
In case you prefer to provide a telephone number, please follow this format: Country code (i.e. +34), national destination code (i.e. 91), suscriber number (i.e. 4888288). Format: +34914888288

2. The crop

*

2.1 What is your crop of interest?

between 1 and 1 choices

- Apple (*Malus spp.*)
- Artichoke (*Cynara scolymus*)
- Asparagus (*Asparagus officinalis*)
- Barley (*Hordeum vulgare*)
- Beans (*Phaseolus vulgaris*)
- Beet (*Beta vulgaris*)
- Blueberries, cranberries (*Vaccinium*)
- Brassica complex (*Brassica spp.*)
- Carrot (*Daucus carota*)
- Chestnut (*Castanea spp.*)
- Chickpea (*Cicer arietinum*)
- Chicory (*Cichorium intybus*)
- Cowpea (*Vigna unguiculata*)
- Cucumber (*Cucumis sativus*)
- Currant, gooseberry (*Ribes spp.*)
- Date (*Phoenix dactylifera*)
- Eggplant (*Solanum melogena*)
- Faba bean (*Vicia faba*)
- Fig (*Ficus carica*)
- Forage grasses
- Forage legumes
- Garlic (*Allium sativum*)
- Grapes (*Vitis vinifera*)
- Grass pea (*Lathyrus sativus*)
- Hazelnut (*Corylus spp.*)
- Hempseed (*Cannabis sativa*)
- Hops (*Humulus spp.*)
- Lentil (*Lens culinaris*)
- Lettuce (*Lactuca sativa*)
- Linseed (*Linum usitatissimum*)
- Lupin (*Lupinus spp.*)
- Maize (*Zea mays*)
- Melon (*Cucumis melo*)
- Millet (*Pennisetum glaucum*)
- Myrtle berries (*Myrtus communis*)
- Oat (*Avena sativa*)
- Olive (*Olea europea*)
- Onion (*Allium cepa*)
- Orange, lemon (*Citrus spp.*)
- Other
- Pea (*Pisum sativum*)
- Pear (*Pyrus spp.*)
- Pepper (*Capsicum spp.*)
- Peppermint (*Mentha balsamea*)
- Pistacion (*Pistacia vera*)
- Poppy seed (*Papaver somniferum*)
- Potato (*Solanum tuberosum*)
- Radish (*Raphanus raphanistrum*)
- Raspberry (*Rubus spp.*)
- Rice (*Oryza sativa*)
- Rye (*Secale cereale*)
- Safflower seed (*Carthamus tinctorius*)
- Spinach (*Spinacia oleracea*)
- Squash (*Cucurbita spp.*)
- Stonefruits (*Prunus spp.*)
- Strawberry (*Fragaria spp.*)
- Sugarbeet (*Beta vulgaris*)
- Sunflower (*Heliantus annuus*)
- Tomato (*Solanum lycopersicum*)
- Triticale (*Triticum x Secale*)
- Walnut (*Juglans spp.*)
- Watermelon (*Citrullus lanatus*)
- Wheat, durum (*Triticum durum*)
- Wheat, soft (*Triticum aestivum*)

* 2.1.1 If you have answered 'Other' in question 2.1, please provide the name of your crop (if it is possible, common name and scientific name).

2.2 What is your target farming system?

- Conventional
- Low input / Organic

2.3 To breed your crop of interest, what is/are the most needed traits for which you do not already have access to sources of useful genetic variation?

Please, rank from 1 to 5 (where 1 is not relevant and 5 is extremely relevant) the following traits:

Yield	☆☆☆☆☆
Tolerance/resistance to abiotic stress	☆☆☆☆☆
Tolerance/resistance to biotic stress	☆☆☆☆☆
Plant architecture	☆☆☆☆☆
Technological quality Suitability of the product to be variously transformed. For example: suitability of barley to be used for beer production or suitability of dry beans to be cooked in a short time.	☆☆☆☆☆
Nutritional quality	☆☆☆☆☆
Environmental quality Suitability of the crop for contributing to a healthy environment or providing environmental services. For example: suitability of the crop for providing food/shelter/nesting to pollinators or increasing soil fertility.	☆☆☆☆☆
Other	☆☆☆☆☆

2.4 Trait details

If you have scored 3 to 5 in any of the traits in the previous question (2.3), please complete this table below identifying main targets to be addressed when breeding your trait of interest.

Please, provide as many details as possible. For instance, in the case of **biotic** stress, please provide the scientific name of the plague, pathogen or weed. Common names can be provided separated by a comma and multiple answers separated by semi-colons (e.g. *Mayetiola destructor*, Hessian fly; *Pseudaletia unipuncta*, True armyworm). You may write more than one answer in each field. In case of multiple answers, please separate them with semi-colons.

	Details
Yield	
Tolerance/resistance to abiotic stress	
Tolerance/resistance to biotic stress	
Plant architecture	
Technological quality	
Nutritional quality	
Environmental quality	
Other	

2.5 Please use this space to provide any comments you may have related to this survey

Please provide any comment helping us to better understand the interests for breeding your crop.

Do you have information about another crop of interest?

If you do, please fill the following questions.

If you don't, please press "Submit" at the bottom of the survey.

2.1 What is your crop of interest?

☐ Apple (*Malus spp.)*	☐ Grass pea *(Lathyrus sativus)*	☐ Pistacion *(Pistacia vera)*
☐ Artichoke (*Cynara scolymus)*	☐ Hazelnut *(Corylus spp.)*	☐ Poppy seed *(Papaver somniferum)*
☐ Asparagus (*Asparagus officinalis)*	☐ Hempseed (*Cannabis sativa)*	☐ Potato *(Solanum tuberosum)*
☐ Barley *(Hordeum vulgare)*	☐ Hops (*Humulus spp.)*	☐ Radish *(Raphanus raphanistrum)*
☐ Beans (*Phaseolus vulgaris)*	☐ Lentil *(Lens culinaris)*	☐ Raspberry *(Rubus spp.)*
☐ Beet *(Beta vulgaris)*	☐ Lettuce *(Lactuca sativa)*	☐ Rice *(Oryza sativa)*
☐ Blueberries, cranberries *(Vaccinium)*	☐ Linseed *(Linum usitatissimum)*	☐ Rye *(Secale cereale)*
☐ Brassica complex *(Brassica spp.)*	☐ Lupin *(Lupinus spp.)*	☐ Safflower seed *(Carthamus tinctorius)*
☐ Carrot *(Daucus carota)*	☐ Maize *(Zea mays)*	☐ Spinach *(Spinacia oleracea)*
☐ Chestnut *(Castanea spp.)*	☐ Melon *(Cucumis melo)*	☐ Squash *(Cucurbita spp.)*
☐ Chickpea *(Cicer arietinum)*	☐ Millet *(Pennisetum glaucum)*	☐ Stonefruits *(Prunus spp.)*
☐ Chicory *(Cichorium intybus)*	☐ Mirtle berries *(Myrtus communis)*	☐ Strawberry *(Fragaria spp.)*
☐ Cowpea *(Vigna unguiculata)*	☐ Oat *(Avena sativa)*	☐ Sugarbeet *(Beta vulgaris)*
☐ Cucumber *(Cucumis sativus)*	☐ Olive *(Olea europea)*	☐ Sunflower *(Heliantus annuus)*
☐ Currant, gooseberry *(Ribes spp.)*	☐ Onion *(Allium cepa)*	☐ Tomato *(Solanum lycopersicum)*
☐ Date *(Phoenix dactylifera)*	☐ Orange, lemon *(Citrus spp.)*	☐ Triticale *(Triticum x Secale)*
☐ Eggplant *(Solanum melogena)*	☐ Other	☐ Walnut *(Juglans spp.)*
☐ Faba bean *(Vicia faba)*	☐ Pea *(Pisum sativum)*	☐ Watermelon *(Citrullus lanatus)*
☐ Fig *(Ficus carica)*	☐ Pear *(Pyrus spp.)*	☐ Wheat, durum *(Triticum durum)*
☐ Garlic *(Allium sativum)*	☐ Pepper *(Capsicum spp.)*	☐ Wheat, soft *(Triticum aestivum)*
☐ Grapes *(Vitis vinifera)*	☐ Peppermint *(Mentha balsamea)*	

2.1.1 If you have answered 'Other' in question 2.1, please provide the name of your crop (if it is possible, common name and scientific name).

2.2 What is your target farming system?

- Conventional
- Low input / Organic

2.3 To breed your crop of interest, what is/are the most needed traits for which you do not already have access to sources of useful genetic variation?

Please, rank from 1 to 5 (where 1 is not relevant and 5 is extremely relevant) the following traits:

Yield	☆☆☆☆☆
Tolerance/resistance to abiotic stress	☆☆☆☆☆
Tolerance/resistance to biotic stress	☆☆☆☆☆
Plant architecture	☆☆☆☆☆
Technological quality Suitability of the product to be variously transformed. For example: suitability of barley to be used for beer production or suitability of dry beans to be cooked in a short time.	☆☆☆☆☆
Nutritional quality	☆☆☆☆☆
Environmental quality Suitability of the crop for contributing to a healthy environment or providing environmental services. For example: suitability of the crop for providing food/shelter/nesting to pollinators or increasing soil fertility.	☆☆☆☆☆
Other	☆☆☆☆☆

2.4 Trait details

If you have scored 3 to 5 in any of the traits in the previous question (2.3), please complete this table below identifying main targets to be addressed when breeding your trait of interest.

Please, provide as many details as possible. For instance, in the case of **biotic** stress, please provide the scientific name of the plague, pathogen or weed. Common names can be provided separated by a comma and multiple answers separated by semi-colons (e.g. *Mayetiola destructor*, Hessian fly; *Pseudaletia unipuncta*, True armyworm). You may write more than one answer in each field. In case of multiple answers, please separate them with semi-colons.

	Details
Yield	
Tolerance/resistance to abiotic stress	
Tolerance/resistance to biotic stress	
Plant architecture	
Technological quality	
Nutritional quality	
Environmental quality	
Other	

9

2.5 Please use this space to provide any comments you may have related to this survey

Please provide any comment helping us to better understand the interests for breeding your crop.

Thank you for completing the survey

We appreciate your participation and contributions.

Your answers will be used to improve knowledge about farmers' and breeders' needs for the improvement of valuable crops for Europe.

With the information you have provided we will be able to perform predictive characterization analyses in a selected group of relevant crops for food security and economic estability in Europe.

In addition, we will be able to gain knowledge for the construction of a European network for the *in situ* conservation of plant genetic resources for food, nutrition and economic security.

Appendix B: Number of high quality occurrence records per target wild taxa

Target crop	Wild relative taxa	Num pops
Wheat	*Aegilops bicornis* (Forssk.) Jaub. & Spach	5
	Aegilops biuncialis Vis.	628
	Aegilops biuncialis subsp. *archipelagica* (Eig) Raus	0
	Aegilops biuncialis Vis. subsp. b*iuncialis*	0
	Aegilops caudata L.	147
	Aegilops caudata L. subsp. *caudata*	0
	Aegilops caudata subsp. *polyathera* (Boiss.) Zhuk.	0
	Aegilops columnaris Zhuk.	23
	Aegilops comosa Sm.	200
	Aegilops comosa Sm. subsp. *comosa*	11
	Aegilops comosa subsp. *heldreichii* (Boiss.) Eig	24
	Aegilops crassa Boiss.	1
	Aegilops cylindrica Host	481
	Aegilops geniculata Roth	4,102
	Aegilops juvenalis (Thell.) Eig	1
	Aegilops kotschyi Boiss.	4
	Aegilops neglecta Bertol.	1,702
	Aegilops peregrina (Hack.) Maire & Weiller	33
	Aegilops peregrina subsp. *cylindrostachys* (Eig & Feinbrun) Maire & Weiller	0
	Aegilops peregrina (Hack.) Maire & Weiller subsp. peregrina	0
	Aegilops speltoides Tausch	66
	Aegilops speltoides subsp. *ligustica* (Savign.) Zhuk.	35
	Aegilops speltoides Tausch subsp. *speltoides*	9
	Aegilops tauschii Coss.	55
	Aegilops tauschii Coss. subsp. *tauschii*	0
	Aegilops triuncialis L.	2,352
	Aegilops triuncialis subsp. *persica* (Boiss.) Zhuk.	9
	Aegilops triuncialis L. subsp. *triuncialis*	5
	Aegilops umbellulata Zhuk.	89
	Aegilops uniaristata Vis.	14
	Aegilops vavilovii (Zhuk.) Chennav.	2
	Aegilops ventricosa Tausch	201
	TOTAL AEGILOPS POPULATIONS	**10,199**
Lentil	*Lens culinaris* subsp. *odemensis* (Ladiz.) M. E. Ferguson & al.	0
	Lens culinaris subsp. *orientalis* (Boiss.) Ponert	7
	Lens ervoides (Brign.) Grande	145
	Lens lamottei Czefr.	29
	Lens nigricans (M. Bieb.) Godr.	443
	TOTAL LENS POPULATIONS	**624**
Blue Lupin	*Lupinus angustifolius* L.	1,542

	Lupinus angustifolius L. subsp. *angustifolius*	82
	Lupinus angustifolius subsp. *reticulatus* (Desv.) Arcang.	82
	Lupinus hispanicus Boiss. & Reut.	188
	Lupinus hispanicus var. *bicolor* (Merino) Gladst.	0
	Lupinus luteus L.	756
	TOTAL LUPINUS POPULATIONS	**2,650**

Appendix C: Environmental variables used for SelecVar process

Type of variable	Variable description	Variable unit	Source	Link to source
Bioclimatic	Annual Mean Temperature	°C	Worldclim	http://worldclim.org
	Mean Diurnal Range (Mean of monthly (max temp - min temp))			
	Isothermality (BIO2/BIO7) (* 100)			
	Temperature Seasonality (standard deviation *100)			
	Max Temperature of Warmest Month	°C		
	Min Temperature of Coldest Month			
	Temperature Annual Range (BIO5-BIO6)			
	Mean Temperature of Wettest Quarter			
	Mean Temperature of Driest Quarter			
	Mean Temperature of Warmest Quarter			
	Mean Temperature of Coldest Quarter			
	Max Temperature January			
	Max Temperature February			
	Max Temperature March			
	Max Temperature April			
	Max Temperature May			
	Max Temperature June			
	Max Temperature July			

	Max Temperature August
	Max Temperature September
	Max Temperature October
	Max Temperature November
	Max Temperature December
	Mean Temperature January
	Mean Temperature February
	Mean Temperature March
	Mean Temperature April
	Mean Temperature May
	Mean Temperature June
	Mean Temperature July
	Mean Temperature August
	Mean Temperature September
	Mean Temperature October
	Mean Temperature November
	Mean Temperature December
	Min Temperature January
	Min Temperature February
	Min Temperature March
	Min Temperature April
	Min Temperature May
	Min Temperature June

	Min Temperature July		
	Min Temperature August		
	Min Temperature September		
	Min Temperature October		
	Min Temperature November		
	Min Temperature December		
	Annual Precipitation	Mm	
	Precipitation of Wettest Month		
	Precipitation of Driest Month		
	Precipitation Seasonality (Coefficient of Variation)		
	Precipitation of Wettest Quarter		
	Precipitation of Driest Quarter		
	Precipitation of Warmest Quarter		
	Precipitation of Coldest Quarter		
	Mean Precipitation January		
	Mean Precipitation February		
	Mean Precipitation March		
	Mean Precipitation April		
	Mean Precipitation May		
	Mean Precipitation June		
	Mean Precipitation July		
	Mean Precipitation August		
	Mean Precipitation September		

	Mean Precipitation October			
	Mean Precipitation November			
	Mean Precipitation December			
Edaphic	Reference depth of the soil unit	Code	HWS Database	http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/
	Topsoil base saturation	%		
	Topsoil sodicity			
	Topsoil calcium carbonate content	% weight		
	Topsoil calcium sulphate (gypsum) content			
	Topsoil clay fraction			
	Topsoil organic Carbon			
	Topsoil sand fraction			
	Topsoil silt fraction			
	Topsoil gravel content	%vol.		
	Topsoil CEC due to clay fraction	cmol/kg		
	Topsoil CEC (soil)			
	Topsoil total exchangeable bases			
	Topsoil salinity	dS/m		
	Topsoil pH (H2O)	-log(H+)		
	Topsoil reference bulk density	kg/dm3		
	Sodic soil grade	grade	Soilgrids	https://soilgrids.org
	Available soil water capacity (volumetric fraction) for h1 – topsoil	%		
	Available soil water capacity (volumetric fraction) for h2 – topsoil			
	Available soil water capacity (volumetric fraction) for h3 – topsoil			

	Saturated water content (volumetric fraction) for tS – topsoil Probability of occurrence of R horizon Clay content (0-2 micro meter) mass fraction in % - topsoil Coarse fragments volumetric in % Sand content (50-2000 micro meter) mass fraction in % Silt content (2-50 micro meter) mass fraction in % Available soil water capacity (volumetric fraction) until wilting point			
	Depth to bedrock (R horizon) up to 200 cm	cm		
	Bulk density (fine earth) in kg / cubic-meter - topsoil	kg / cubic-m		
	Soil organic carbon density in kg per cubic-m			
	Cation exchange capacity of soil in cmolc/kg - topsoil	cmol / kg		
	Soil organic carbon content (fine earth fraction) in g per kg	g / kg		
	Soil organic carbon stock in tons per ha	tonnes / ha		
	Soil pH x 10 in H2O Soil pH x 10 in KCl	index*10		
Geophysic	Elevation (meters above sea level)	m	Worldclim	http://worldclim.org
	Orientation Slope	º	Derived from SRTM DEM	Not available
	Eastness . Values close to 1 if East trend orientation, - 1 if West trend orientation, 0 if North or South trend	-		
	Northness. Values close to 1 if North trend orientation, - 1 if South trend, 0 if East or West trend			
	Longitude (cell centroid)			Not available

	Latitude (cell centroid)	Decimal degrees	Not available	
	Solar radiation January Solar radiation February Solar radiation March Solar radiation April Solar radiation May Solar radiation June Solar radiation July Solar radiation August Solar radiation September Solar radiation October Solar radiation November Solar radiation December Annual solar radiation	MJ m-2	Worldclim2	http://worldclim.org

Appendix D: Origin of the answers of all the participants that provided information in the survey.

Country	Number of answers
Spain	12
Netherlands	9
United Kingdom	7
Hungary	6
Unknown	4
Estonia	4
Austria	2
Italy	2
Latvia	2
Germany	1
Argentina	1
Armenia	1
Azerbaijan	1

Country	Number of answers
Croatia	1
Greece	1
France	1
Lithuania	1
Nigeria	1
Portugal	1
Czech Republic	1
South Africa	1
Sweden	1
Switzerland	1
Ukraine	1
Zambia	1

Appendix E: List of all the crops that received answers in the survey and number of traits detailed for each one.

Crop	Number of traits detailed
Soft wheat (*Triticum aestivum*)	136
Tomato *(Solanum lycopersicum*)	76
Potato (*Solanum tuberosum*)	67
Beans (*Phaseolus vulgaris*)	66
Apple (*Malus* spp.)	65
Durum wheat (*Triticum durum*)	59
Brassica complex (*Brassica* spp.)	55
Barley (*Hordeum vulgare*)	51
Faba bean (*Vicia faba*)	47
Lentil (*Lens culinaris*)	47
Cowpea (*Vigna unguiculata*)	46

Crop	Number of traits detailed
Soybeans (*Glycine max*)	13
Forage grasses	12
Amaranthus spp.	11
Rice (*Oryza sativa*)	11
Blueberries, cranberries (*Vaccinium* spp.)	10
Cleome spp.	10
Corchorus spp.	10
Currant gooseberry (*Ribes* spp.)	10
Raspberry (*Rubus* spp.)	10
Sunflower (*Heliantus annuus*)	10
Colocasia esculenta	9

Pepper (*Capsicum* spp.)	45		Orange lemon (*Citrus* spp.)	9
Pea (*Pisum sativum*)	44		Chestnut (*Castanea* spp.)	8
Maize (*Zea mays*)	42		Chickpea (*Cicer arietinum*)	8
Forage legumes	39		Fig (*Ficus carica*)	8
Lupin (*Lupinus* spp.)	36		Kentucky bluegrass (*Poa pratensis*)	8
Millet (*Pennisetum glaucum*)	36		Pistacion (*Pistacia vera*)	8
Grapes *(Vitis vinífera*)	35		Rye (*Secale cereale*)	8
Stonefruits (*Prunus* spp.)	33		Sugarbeet (*Beta vulgaris* var. *altissima*)	8
Beet (*Beta vulgaris* var. *cicla*)	32		Carrot (*Daucus carota*)	8
Triticale (*Triticum* x *Secale*)	26		Chicory (*Cichorium intybus*)	7
Cucumber (*Cucumis sativus*)	23		Watermelon (*Citrullus lanatus*)	7
Oat (*Avena sativa*)	22		Asparagus (*Asparagus officinalis*)	5
Garlic (*Allium sativum*)	21		Pear (*Pyrus* spp.)	4
Onion (*Allium cepa*)	20		Celery (*Apium graveolens*)	3
Strawberry (*Fragaria* spp.)	18		Fennel (*Foeniculum vulgare*)	3
Lettuce (*Lactuca sativa*)	18		Grass pea (*Lathyrus sativus*)	3
Eggplant (*Solanum melogena*)	15		Melon (*Cucumis melo*)	3
Olive (*Olea europea*)	15		Radish (*Raphanus raphanistrum*)	3
Squash (*Cucurbita* spp.)	15		Safflower seed (*Carthamus tinctorius*)	2
Hazelnut (*Corylus* spp.)	13			

Appendix F: Number of answers of desired traits per crop.

Crop	**Environmental quality**	**Nutritional Quality**	**Plant architecture**	**Technological quality**	**Other**	**Yield**	**T./R. to abiotic stress**	**T./R. to biotic stress**
Amaranthus spp.	1	2	0	2	1	1	2	2
Apple (*Malus* spp.)	4	10	8	7	5	8	12	11
Asparagus (*Asparagus officinalis*)	0	0	2	0	0	1	1	1
Barley (*Hordeum vulgare*)	5	5	2	6	5	5	11	12
Beans (*Phaseolus vulgaris*)	2	10	9	6	4	7	14	14
Beet (*Beta vulgaris* var. *cicla)*	4	3	3	3	1	4	5	9
Blueberries, cranberries (*Vaccinium* spp.)	0	1	2	2	0	1	2	2
Brassica complex (*Brassica* spp.)	2	18	2	6	0	1	8	18
Carrot (*Daucus carota*)	0	0	1	1	0	1	0	5
Celery (*Apium graveolens*)	0	0	1	0	0	1	0	1

Chestnut (*Castanea* spp.)	1	1	1	1	1	1	1	1
Chickpea (*Cicer arietinum*)	1	1	1	1	1	1	1	1
Chicory (*Cichorium intybus*)	1	1	1	1	0	1	1	1
Cleome spp.	1	2	0	1	1	1	2	2
Colocasia esculenta	1	2	0	1	1	0	2	2
Corchorus spp.	1	2	0	1	1	1	2	2
Cowpea (*Vigna unguiculata*)	2	8	6	3	4	5	10	8
Cucumber (*Cucumis sativus*)	2	2	3	2	2	4	3	5
Currant gooseberry (*Ribes* spp.)	1	1	1	1	1	2	1	2
Eggplant (*Solanum melogena*)	1	2	2	1	1	2	1	5
Faba bean (*Vicia faba*)	2	8	8	3	4	5	10	7
Fennel (*Foeniculum vulgare*)	0	0	0	1	0	0	0	2
Fig (*Ficus carica*)	1	1	1	1	1	1	1	1
Forage grasses	0	3	0	0	0	3	3	3
Forage legumes	2	7	5	2	3	5	10	5
Garlic (*Allium sativum*)	2	2	2	2	2	4	3	4
Grapes (*Vitis vinífera*)	3	5	3	3	4	4	6	7
Grass pea (*Lathyrus sativus*)	0	1	0	0	0	1	1	0
Hazelnut (*Corylus* spp.)	1	1	2	2	1	2	2	2
Kentucky bluegrass (*Poa pratensis*)	0	0	1	1	1	1	2	2
Lentil (*Lens culinaris*)	2	8	6	3	4	6	11	7
Lettuce (*Lactuca sativa*)	2	2	2	1	0	0	7	7
Lupin (*Lupinus* spp.)	1	7	5	2	3	4	9	5
Maize (*Zea mays*)	1	7	6	2	3	6	10	7
Melon (*Cucumis melo*)	0	0	1	0	0	0	1	1
Millet (*Pennisetum glaucum*)	1	7	5	2	3	4	9	5
Oat (*Avena sativa*)	3	2	3	2	0	2	3	7
Olive (*Olea europea*)	2	2	2	2	1	2	2	2
Onion (*Allium cepa*)	2	2	2	3	2	3	2	4
Orange lemon (*Citrus* spp.)	1	1	1	1	0	1	1	3
Pea (*Pisum sativum*)	2	8	6	3	4	5	10	6
Pear (*Pyrus* spp.)	1	1	0	1	0	0	0	1
Pepper (*Capsicum* spp.)	2	4	6	5	2	3	9	14
Pistacion (*Pistacia vera*)	1	1	1	1	1	1	1	1
Potato (*Solanum tuberosum*)	4	8	9	4	4	8	16	14
Radish (*Raphanus raphanistrum*)	0	0	1	0	0	1	0	1
Raspberry (*Rubus* spp.)	1	1	1	1	1	2	1	2
Rice (*Oryza sativa*)	1	1	4	1	0	1	2	1
Rye (*Secale cereale*)	1	1	1	1	1	1	1	1
Safflower seed (*Carthamus tinctorius*)	0	0	0	1	0	1	0	0
Soybeans (*Glycine max*)	1	1	0	0	0	2	5	4
Squash (*Cucurbita* spp.)	1	1	0	1	0	2	3	7

Stonefruits (*Prunus* spp.)	1	6	2	8	1	4	3	8
Strawberry (*Fragaria* spp.)	2	2	2	2	2	3	2	3
Sugarbeet *(Beta vulgaris* var. *altissima)*	1	1	1	1	1	1	1	1
Sunflower (*Heliantus annuus*)	1	1	1	1	1	1	2	2
Tomato (*Solanum lycopersicum*)	3	5	12	8	1	5	14	28
Triticale (Triticum x Secale)	4	2	1	4	1	4	4	6
Watermelon (*Citrullus lanatus*)	0	0	0	0	0	2	3	2
Wheat durum (*Triticum durum*)	7	5	6	10	1	7	10	13
Wheat soft (*Triticum aestivum*)	8	16	10	12	5	16	24	45

Appendix G: *Aegilops spp.* populations potentially adapted to drought in Europe and, especially, during the flowering season

Ordered by Flowering De Martonne Aridity Index (Flowering season = May, June, July). $I_{ar}DM$ = Annual De Martonne Aridity Index; $I_{ar}DM_f$ = Flowering De Martonne Aridity Index; ELC cat = Ecogeographical Land Characterisation Category.

	Taxa	Unique ID	$I_{ar}DM_f$	$I_{ar}DM$	Latitude	Longitude	Country	Collecting site information	ELC cat
1	*Aegilops geniculata* Roth	ID_17332	1.17	10.81	28.133333	-17.316667	Spain	Gomera	4
2	*Aegilops peregrina* (Hack.) Maire & Weiller	GE_9696	1.25	12.94	34.67778	32.78583	Cyprus	Limassol District Paramali. Just outside the village to the road from Avdimou	2
3	*Aegilops geniculata* Roth	ID_12789	1.88	11.69	34.9	33.630556	Cyprus	Not available	4
4	*Aegilops peregrina* (Hack.) Maire & Weiller	GE_9693	2.35	12.28	34.94417	33.57222	Cyprus	Larnaca District Aradipou. Rizoelia forest park	4
5	*Aegilops biuncialis* Vis.	GE_1779	3.41	12.40	36.85	40.0333333	Turkey	On state farm at Ceylanpinar	4
6	*Aegilops speltoides* Tausch	GE_474366	3.41	12.40	36.85	40.0333333	Turkey	On state farm at Ceylanpinar	4
7	*Aegilops speltoides* subsp. *ligustica* (Savign.) Zhuk.	GE_924366	3.41	12.40	36.85	40.0333333	Turkey	On state farm at Ceylanpinar	4
8	*Aegilops triuncialis* L.	GE_18687	3.41	12.40	36.85	40.0333333	Turkey	On state farm at Ceylanpinar	4
9	*Aegilops geniculata* Roth	ID_17329	3.57	7.60	36.8442	-2.3283	Spain	Almería; El Alquian	2
10	*Aegilops geniculata* Roth	ID_13824	3.58	7.70	36.847784	-2.332342	Spain	Almería	4
11	*Aegilops triuncialis* L.	ID_40129	3.60	10.96	39.375073	9.553939	Italy	Not available	4
12	*Aegilops umbellulata* Zhuk.	GE_19232	3.78	12.13	36.8667	39.0167	Turkey	3 km N Hilvan	4
13	*Aegilops biuncialis* Vis.	GE_1776	3.81	12.84	36.9333333	38.9166667	Turkey	29 km south of Urfa	4
14	*Aegilops speltoides* Tausch	GE_474362	3.81	12.84	36.95	38.9166667	Turkey	7 km northeast of Harran ruins-Urfa junction	4
15	*Aegilops speltoides* subsp. *ligustica* (Savign.) Zhuk.	GE_924359	3.81	12.84	36.9333333	38.9166667	Turkey	29 km south of Urfa	4
16	*Aegilops speltoides* subsp. *ligustica* (Savign.) Zhuk.	GE_924358	3.81	12.84	36.95	38.9166667	Turkey	7 km northeast of Harran ruins-Urfa junction	4
17	*Aegilops geniculata* Roth	ID_15268	3.87	8.27	36.849	-2.041	Spain	Níjar; P.N. Cabo de Gata-Níjar, Rodalquilar; Almería province	3
18	*Aegilops geniculata* Roth	ID_15160	3.99	8.61	36.811748	-2.091007	Spain	Níjar, Almería province	3

19	*Aegilops geniculata* Roth	ID_13451	4.27	9.35	36.830896	-2.63638	Spain	Vícar, Almería province	4
20	*Aegilops geniculata* Roth	ID_17044	4.29	9.17	36.766667	-2.183333	Spain	Níjar, Cabo de Gata, Níjar camping, Almeria province	4
21	*Aegilops neglecta* Bertol.	ID_27376	4.57	9.49	36.825	-2.58	Spain	Sª de Gádor, Cerro Los Lobos, Almería province	4
22	*Aegilops neglecta* Bertol.	ID_26241	4.75	8.97	37.299579	-1.799847	Spain	Cuevas del Almanzora, Almería province	4
23	*Aegilops geniculata* Roth	ID_12883	4.85	9.75	37.020711	-2.097439	Spain	Lucainena de las Torres, Almería province	3
24	*Aegilops geniculata* Roth	ID_15452	5.42	9.71	37.583	-0.956	Spain	El Calvario (Cartagena), Murcia	2
25	*Aegilops geniculata* Roth	ID_15721	5.54	10.30	37.133333	-2.05	Spain	1.8 km E of Los Castanos on Sorbas to Vera road (N340). Almeria province	4
26	*Aegilops geniculata* Roth	ID_13814	5.57	10.66	37.088761	-2.087226	Spain	Sorbas, Almería province	4
27	*Aegilops geniculata* Roth	ID_17076	5.62	10.02	37.61	-0.79	Spain	Cabo de Palos, route El Algar - Los Velones (Cartagena, Murcia)	4
28	*Aegilops triuncialis* L.	ID_41087	5.71	10.90	37.09	-2.04	Spain	Río Aguas, Almería province	4
29	*Aegilops geniculata* Roth	ID_12382	5.74	10.24	37.273604	-2.007285	Spain	Antas, Almería province	4
30	*Aegilops neglecta* Bertol.	ID_26231	5.75	10.86	37.089028	-1.909685	Spain	Turre, Almería province	4
31	*Aegilops triuncialis* L.	ID_38785	5.81	10.12	37.424261	-1.790139	Spain	Pulpí, Almería province	4
32	*Aegilops geniculata* Roth	ID_11289	5.95	10.37	37.621	-1.091	Spain	Closeto Perín, Cartagena (Murcia)	3
33	*Aegilops geniculata* Roth	ID_13335	6.09	11.52	37.135197	-1.940534	Spain	Turre, Almería province	4
34	*Aegilops triuncialis* L.	ID_38772	6.09	11.52	37.135114	-1.940378	Spain	Turre, Almería province	4
35	*Aegilops geniculata* Roth	ID_11850	6.19	10.73	37.5797	-1.1242	Spain	sierra de la Muela, Morro de los Garabitos (Cartagena, Murcia)	3
36	*Aegilops geniculata* Roth	ID_15471	6.20	13.10	36.825	-2.849	Spain	Sª de Gádor, Fuente Nueva (Almería province)	4
37	*Aegilops neglecta* Bertol.	ID_26996	6.23	11.84	37.022	-2.41	Spain	Tabernas; East from La Sartenilla; Almería province	13
38	*Aegilops geniculata* Roth	ID_13317	6.26	11.17	37.202558	-2.015981	Spain	Lubrín, Almería province	4
39	*Aegilops triuncialis* L.	ID_38767	6.26	11.17	37.200073	-1.998052	Spain	Bédar, Almería province	4

40	*Aegilops geniculata* Roth	ID_13267	6.31	11.88	37.112014	-2.34252	Spain	Tabernas, Almería province	4
41	*Aegilops neglecta* Bertol.	ID_27396	6.31	11.88	37.112	-2.342	Spain	Tabernas; Sª de Los Filabres, Los Retamares, Rambla de Los Nudos; Almería province	4
42	*Aegilops geniculata* Roth	ID_13269	6.33	11.93	37.084665	-2.335972	Spain	Tabernas, Almería province	13
43	*Aegilops geniculata* Roth	ID_13279	6.33	11.93	37.093095	-2.339432	Spain	Tabernas, Almería province	13
44	*Aegilops geniculata* Roth	ID_13266	6.33	11.93	37.074966	-2.347329	Spain	Tabernas, Almería province	13
45	*Aegilops geniculata* Roth	ID_13285	6.33	11.93	37.082218	-2.349787	Spain	Tabernas, Almería province	13
46	*Aegilops neglecta* Bertol.	ID_26240	6.33	11.93	37.08543	-2.337259	Spain	Tabernas, Almería province	13
47	*Aegilops geniculata* Roth	ID_13788	6.45	11.14	37.43	-2.01	Spain	Huércal-Overa; El Palomar; Almería province	3
48	*Aegilops neglecta* Bertol.	ID_26543	6.53	12.31	37.084405	-2.292634	Spain	Tabernas, Almería province	13
49	*Aegilops neglecta* Bertol.	ID_27257	6.58	10.95	38.38	-0.47	Spain	Lomas del Garbinet, close highway (Alicante province)	4
50	*Aegilops geniculata* Roth	ID_13292	6.66	12.25	37.08435	-1.935516	Spain	Turre, Almería province	13

Appendix H: Lens spp. populations potentially adapted to drought in Europe and, especially, during the flowering season

Selection of 26 populations of wild relatives of lentil with higher probability of being tolerant to drought troughout the year and, especially, during the flowering period (March, April, May, June). $I_{ar}DM_f$ = Flowering De Martonne Aridity Index; $I_{ar}DM$ = Annual De Martonne Aridity Index; ELC cat = Ecogeographical Land Characterisation map Category.

	Taxa	Unique ID	IarDMf	IarDM	Latitude	Longitude	Country	Collecting site information	BGcat
1	*Lens nigricans* (M. Bieb.) Godr.	ID_6954734	10.72	13.94	37.133333	24.5	Greece	Serifos. 1-2 km S to SW of Livadion. Ep. Keas; Nom. Kikladon	2
2	*Lens nigricans* (M. Bieb.) Godr.	ID_6954730	10.79	13.83	37.4	24.9	Greece	Siros. The mt N of Finikas. Ep. Sirou, Nom. Kikladon	2
3	*Lens nigricans* (M. Bieb.) Godr.	ID_6954729	10.88	14.07	37.45	24.933333	Greece	Siros. Mt. Siringas. Ep. Sirou; Nom. Kikladon	2
4	*Lens lamottei* Czefr.	GE_222367	11.43	12.01	38.7775	0.11889	Spain	Close to Petronor gas station and carob trees, Javea, Alicante province	2
5	*Lens lamottei Czefr.*	ID_6953881	12.07	12.15	38.74	0.18	Spain	La Granadella, Xabia, Alicante province	2
6	*Lens lamottei Czefr.*	GE_222365	12.07	12.15	38.75583	0.16	Spain	Tossal del Rebaldi, Javea, Alicante province	2
7	*Lens nigricans* (M. Bieb.) Godr.	GE_222437	13.62	11.75	38.3333	-1.5	Spain	Hozel del Lino, Murcia	2
8	*Lens lamottei* Czefr.	GE_222366	14.21	13.28	38.74028	-0.01694	Spain	Calvari, Jalon, Alicante province	2
9	*Lens lamottei* Czefr.	GE_222343	14.42	13.63	38.983333	-0.516667	Spain	Castle hillside, Xativa, Valencia province	2
10	*Lens nigricans* (M. Bieb.) Godr.	ID_6954675	14.42	13.63	38.983337	-0.516666	Spain	Jativa, Valencia province	2
11	*Lens nigricans* (M. Bieb.) Godr.	ID_6954474	14.44	13.40	38.77	-0.07	Spain	Jalón; Calvari, Alicante province	2
12	*Lens ervoides (*Brign.) Grande	ID_6953173	14.59	12.55	36.9	38.916667	Turkey	29 km South of Urfa on road to Akcakale, In pine woodland. Koruklu, Urfa	2
13	*Lens nigricans (*M. Bieb.) Godr.	ID_6954230	14.74	13.36	38.66	-0.05	Spain	Jalon, Alicante province	2

Appendix I: Lupinus spp. populations potentially adapted to drought in Europe and, especially, during the flowering season

Selected 26 populations according to the lowest values in aridity indices, annual and during the flowering season (March, April, May, June). $I_{ar}DM_f$ = Flowering De Martonne Aridity Index; $I_{ar}DM$ = Annual De Martonne Aridity Index; ELC cat = Ecogeographical Land Characterisation map category.

	Taxa	Unique ID	$I_{ar}DM_f$	$I_{ar}DM$	Latitude	Longitude	Country	Collecting site information	ELC cat
1	*Lupinus angustifolius* L.	ID_8246017	5.31	5.06	41.765629	16.061583	Italy	Monte Sacro Wegstück nördlich des Weihers	18
2	*Lupinus angustifolius* L.	ID_8245938	7.49	11.77	28.657183	-17.776276	Spain	Miranda und Umgebung, Brena Alta, La Palma (Canary Islands)	36
3	*Lupinus angustifolius* L.	ID_8248167	7.49	11.77	28.666943	-17.807121	Spain	2.4 km W major tunnel on Santa Cruz de la Palma, El Paso road; La Palma (Canary Islands)	36
4	*Lupinus angustifolius* L.	ID_8248178	8.86	12.79	27.72973	-17.976894	Spain	1.8 km N of Las Casa on road to San Andreas; El Hierro (Canary Islands)	36
5	*Lupinus angustifolius* L.	ID_8249358	10.31	13.93	36.816667	24.566667	Greece	Kimolos: Ormos Vroma; Nom. Kikladon	30
6	*Lupinus angustifolius* L.	ID_8248123	10.74	14.24	37.0383	25.25	Greece	S of Lefkes at junction to Aspro Chorio (Nomos Kikladhon, Eparchia Parou, island of Paros); Nótion aiyaíon	29
7	*Lupinus angustifolius* L.	ID_8249342	10.92	14.60	37.416667	25.35	Greece	Mikonos: Lino; Nom. Kikladon	29
8	*Lupinus luteus* L.	ID_8256070	10.93	10.56	38.1401	-0.83726	Spain	San Roque, Cadiz province	36
9	*Lupinus angustifolius* L.	ID_8249355	10.96	14.66	37.1	25.2	Greece	Above Parikia, below the monastery. Nom. Kikladon	30
10	*Lupinus angustifolius* L.	ID_8249357	10.98	14.27	37.15	24.5	Greece	Serifos: between Livadion and the town; Nom. Kikladon	30
11	*Lupinus angustifolius* L.	ID_8248431	11.02	14.42	37.55	25.166667	Greece	Tinos Island	29

12	*Lupinus angustifolius* L.	ID_8248461	11.26	14.92	37.1	25.15	Greece	Paros Island	28
13	*Lupinus angustifolius* L.	ID_8248315	11.48	13.83	39.710189	9.590089	Italy	Not available	36
14	*Lupinus angustifolius* L.	ID_8248473	11.82	14.48	38.05	24.366667	Greece	Marmari; Evia	30
15	*Lupinus angustifolius* L.	ID_8247273	11.99	11.17	37.2	-2.01	Spain	Lubrín; Sierra de Bédar, towards Bédar, Almeria province	36
16	*Lupinus angustifolius* L.	ID_8247288	11.99	11.17	37.209	-2.014	Spain	Sª de Bédar, Cerro de la Cerca, Almería province	36
17	*Lupinus angustifolius* L. subsp. *angustifolius*	ID_8245241	12.77	11.88	37.112	-2.342	Spain	Tabernas; Llanos de Tabernas, ctjo. de Las Majadas; Almería province	36
18	*Lupinus angustifolius* L.	ID_8247276	13.63	12.45	37.20283	-2.018299	Spain	Lubrín, Almería province	18
19	*Lupinus hispanicus* Boiss. & Reut.	ID_8253743	13.90	14.12	38.130001	-3.46	Spain	Arquillos, Jaen province	36
20	*Lupinus angustifolius* L.	ID_8248433	14.19	13.76	39.05	-0.4	Spain	Plà de Suros, Barx, Valencia province	36
21	*Lupinus angustifolius* L.	ID_8248707	14.28	14.11	39.1	-0.42	Spain	Carcaixent, Valencia province	36
22	*Lupinus hispanicus* Boiss. & Reut.	ID_8253630	14.52	13.46	40.2581	-4.85667	Spain	Road to Gavilanes, Valle del Tietar, Gavilanes, province of Avila	16
23	*Lupinus angustifolius* L.	ID_8249374	14.74	13.86	38.95	-0.29	Spain	Surar de Pinet, Pinet, Valencia province	36
24	*Lupinus angustifolius* L.	ID_8248439	14.81	13.91	38.96	-0.4	Spain	Barx (Safor), Pla de Suros, Valencia province	36
25	*Lupinus angustifolius* L.	ID_8249167	14.87	14.56	39.933333	-5.1	Spain	Between Calera and Chozas, road N-V, km 142; Toledo province	18
26	*Lupinus angustifolius* L.	ID_8249213	14.98	13.56	40.383333	-4.2	Spain	Chapinería, road C501, km 37.8, Madrid province	16

Appendix J: Populations of wild relatives of wheat, lentil and blue lupin potentially tolerant to salinity in Europe

Selected populations according to the highest soil conductivities (=higher soil salinity). Soil salinity expressed in dS/m (deciSiemens per meter); ELC cat = Ecogeographical Land Characterisation map category.

Taxa	Unique ID	soil salinity	Latitude	Longitude	Country	Collecting site information	ELC cat
Aegilops geniculata Roth	ID_16849	12.6999998	37.216667	-7.433333	Portugal	Faro, Castro Marim	4
Aegilops triuncialis L.	ID_37877	12.6999998	38.89386	-9.05766	Portugal	Vila Franca de Xira, Lisboa	4
Aegilops triuncialis L.	ID_40908	12.6999998	37.216667	-7.433333	Portugal	Faro, Castro Marim	4
Aegilops geniculata Roth	ID_11315	2.09999991	43.47478	4.42079	France	Not available	13
Aegilops geniculata Roth	ID_17354	2.09999991	43.47126	4.66781	France	Not available	13
Aegilops geniculata Roth	ID_17319	2.09999991	43.46929	4.79131	France	Not available	13
Aegilops neglecta Bertol.	ID_24740	2.09999991	43.47478	4.42079	France	Saintes-Maires-de-la-Mer	13
Aegilops neglecta Bertol.	ID_28250	2.09999991	43.47126	4.66781	France	Arles	13
Aegilops neglecta Bertol.	ID_28205	2.09999991	43.46929	4.79131	France	Arles	13
Aegilops triuncialis L.	ID_41334	2.09999991	43.47126	4.66781	France	Arles	13
Aegilops triuncialis L.	ID_39346	2.09999991	41.832	-0.754	Spain	San Mateo de Gállego, close to the Hermitage; Zaragoza province	13
Lens lamottei Czefr.	ID_6953872	2.09999991	42.96808	2.98863	France	La Palme [INSEE:11188], Aude	21
Lupinus angustifolius L.	ID_8247575	12.6999998	37.212522	-7.363922	Spain	Ayamonte, Huelva province	36
Lupinus angustifolius subsp. *reticulatus* (Desv.) Arcang.	ID_8245615	12.6999998	37.218597	-7.457904	Portugal	Reserva in Castro Marim	36

Appendix K: Populations of wild lentils potentially tolerant to waterlogging in Europe

Subset of 21 populations occurring in clay soils and with annual De Martonne aridity indexes above 25, that point to mid-high subhumid or more humid areas. IarDM = Annual De Martonne Aridity Index; ELC cat = Ecogeographical Land Characterisation map category.

	Taxa	Unique ID	Soil texture	IarDM	Latitude	Longitude	Country	Collecting site information	ELC cat
1	*Lens culinaris* subsp. *orientalis* (Boiss.) Ponert	ID_6952438	CLAY	40.11	38.523891	22.502781	Greece	Fokídos, Parnassidhos, NW Ag. Triada	21
2	*Lens ervoides* (Brign.) Grande	ID_6953356	CLAY	35.77	38.633333	22.366667	Greece	The Amvlema-pass, N of Amphissia. Ep. Parnassidos. Nom. Fokidos	21
3	*Lens ervoides* (Brign.) Grande	GE_222062	CLAY	34.38	36.1333	36.1667	Turkey	Harbiye edge of village on road leading south	2
4	*Lens ervoides* (Brign.) Grande	GE_222085	CLAY	33.21	36.1	35.95	Turkey	2 km from Samandagi on road to Kaburluk	2
5	*Lens nigricans* (M. Bieb.) Godr.	ID_6954642	CLAY	33.07	42.61	-2.5	Spain	Bernedo; Peña Alta. At the foot of a limestone rocky place. Rocky flat area, organic matter. Álava province	24
6	*Lens nigricans* (M. Bieb.) Godr.	ID_6954569	CLAY	33.07	42.616005	-2.507488	Spain	Peña Alta, Bernedo, Alava province	24
7	*Lens nigricans* (M. Bieb.) Godr.	ID_6954460	CLAY	32.85	46.6907	2.51218	France	La Groutte	24
8	*Lens nigricans* (M. Bieb.) Godr.	ID_6954619	CLAY	31.97	44.433333	33.783333	Ukraine	near Orlinoye sett.	27
9	*Lens culinaris* subsp. *orientalis* (Boiss.) Ponert	ID_6952604	CLAY	29.43	44.483333	33.716667	Ukraine	Shirokoye sett., Chernaya river valley	27
10	*Lens ervoides* (Brign.) Grande	ID_6953026	CLAY	29.43	44.483333	33.716667	Ukraine	Sevastopol	27
11	*Lens nigricans* (M. Bieb.) Godr.	ID_6954771	CLAY	29.37	41.31	0.91	Spain	Cornudella de Montsant; Albarca. Tarragona province	21

12	*Lens nigricans* (M. Bieb.) Godr.	ID_6954710	CLAY	29.01	44.75	34.4	Ukraine	Demerdzhi mntn, road to top	27
13	*Lens ervoides* (Brign.) Grande	ID_6953338	CLAY	28.98	44.4	33.766667	Ukraine	near Foros sett.	27
14	*Lens lamottei* Czefr.	ID_6953903	CLAY	28.91	36.625	-5.3273	Spain	Cortes de la Frontera: Sierra de los Pinos. Málaga province	21
15	*Lens nigricans* (M. Bieb.) Godr.	ID_6954618	CLAY	28.91	36.632	-5.321	Spain	Cortes de la Frontera; Sierra de los Pinos. Elevation 700-1000 m. Malaga province	21
16	*Lens ervoides* (Brign.) Grande	ID_6953339	CLAY	28.01	44.416667	33.933333	Ukraine	near Opolznevoye sett.	27
17	*Lens nigricans* (M. Bieb.) Godr.	ID_6954246	CLAY	27.61	44.466667	33.761111	Ukraine	Sevastopol	27
18	*Lens nigricans* (M. Bieb.) Godr.	ID_6954658	CLAY	25.80	38.2337	-2.6699	Spain	Segura de la Sierra: Forest path to Yelmo. Jaén province	21
19	*Lens ervoides* (Brign.) Grande	GE_222075	CLAY	25.62	36.85	36.6667	Turkey	44 km W of Kilis on Kilis to Wkhiye	2
20	*Lens ervoides* (Brign.) Grande	ID_6953347	CLAY	25.34	44.857451	34.934721	Ukraine	gorodskoi okrug Sudak. Crimea	27
21	*Lens ervoides* (Brign.) Grande	GE_222086	CLAY	25.16	37.5	36.8667	Turkey	Heyelan 16 km from Kozan on road to Feke	2

Appendix L: Populations of *Trifolium repens* that are most likely to be acyanogenic according to the model and results of the evaluation for cyanogenesis

Cyanogenic response: 1, no cyanogenic reaction; 4, most intense cyanogenic reaction.

Accession identifier	Country of origin	Latitude	Longitude	Predicted probability of being acyanogenic	Percentage of plants with cyanogenic response 1/2/3/4
PI 634094	Mongolia	49.875000	107.722500	930	100/0/0/0
PI 634097	Mongolia	49.772220	107.149720	922	100/0/0/0
PI 634116	Kazakhastan	49.824440	56.890830	920	100/0/0/0
PI 634148	Kazakhastan	50.555560	56.263610	918	100/0/0/0
PI 634157	Kazakhastan	50.207780	56.471670	917	100/0/0/0
PI 611660	China	42.999440	81.110830	811	100/0/0/0
PI 634071	China	43.235830	81.190280	743	100/0/0/0
PI 611661	China	42.743330	81.037220	721	100/0/0/0
W6 37078	Armenia	40.338890	44.273330	698	100/0/0/0
W6 37079	Armenia	40.345830	44.702780	689	100/0/0/0
PI 641346	Bulgaria	42.033330	23.516670	677	100/0/0/0
PI 597575	Bulgaria	42.150000	23.383330	667	100/0/0/0
PI 655807	Russia	44.443890	42.877500	667	100/0/0/0
PI 611656	China	43.255000	81.132220	666	100/0/0/0
PI 494745	Romania	45.583330	25.450000	653	100/0/0/0
PI 655907	Armenia	39.873060	45.409720	639	100/0/0/0
PI 655911	Armenia	39.651670	45.297780	629	100/0/0/0
PI 655891	Armenia	40.501390	44.589440	626	95/5/0/0