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RESEARCH

Broadening the Base, Narrowing the Task: Prioritizing Crop Wild Relative Taxa for Conservation Action

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ABSTRACT

A broad definition of a crop wild relative is any taxon within the same genus as a crop species, or in the case of some crop genepools, other closely related genera. Given the large number of species cultivated for human and animal food, and medicinal, ornamental, environmental, and industrial purposes, the number of taxa related to these crops is inevitably vast, one estimate being >58,000 species globally. Limited resources for conservation management demands careful planning so that taxa in most urgent need of conservation are given priority. Various prioritization criteria have been used to target wild taxa for conservation action; however, in the case of crop wild relatives, a specific approach is needed to take account of their particular value as potential sources of traits for crop improvement. A surge in conservation planning for crop wild relatives since the turn of the century has resulted in a wide range of different crop wild relative prioritization criteria and methods being applied. This paper reviews those criteria and methods and presents a harmonized, logical, and pragmatic means of assigning priority status to crop wild relative taxa on the basis of three main criteria: (i) the socioeconomic value of crops, (ii) the relative potential value of the wild relatives of socioeconomically valuable crops for variety improvement, and (iii) the relative threat status of the wild relatives of socioeconomically valuable crops.

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Abbreviations: CWR, crop wild relative(s); GP, Gene Pool; IUCN, International Union for the Conservation of Nature; PGR, plant genetic resources; PGRFA, plant genetic resources for food and agriculture; SADC, South African Development Community; SPGRC, South African Development Community Plant Genetic Resources Centre; TG, Taxon Group.

The value of traits derived from crop wild relative (CWR) populations for use in the development of new crop varieties is well documented (e.g., see Hoyt, 1988; Maxted et al., 1997a, 2008, 2012, 2014; Meilleur and Hodgkin, 2004; Hajjar and Hodgkin, 2007; Maxted and Kell, 2009; McCouch et al., 2013; Vincent et al., 2013; Dempewolf et al., 2014), and many researchers and plant breeders recognize the future potential value of CWR diversity, particularly as a source of traits to adapt crop species to the variable and uncertain environmental conditions associated with climate change. There are particular challenges for the plant breeding community in using CWR genetic diversity in breeding programs—for example, overcoming hybridization barriers between species and the problem of linkage drag. However, the wide array of techniques now available (including the use of biotechnological tools), and rapid progress in their continuing development and application, provides increasing options to overcome these challenges, thus opening opportunities for the greater utilization of exotic germplasm in the development of new or improved varieties.

As a prerequisite to the utilization of CWR in crop improvement programs, germplasm needs to be (i) conserved,

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(ii) characterized, and (iii) made available to the plant breeding research and development communities. These are three major challenges that the conservation and plant breeding communities continue to face and which require concerted action at national, regional, and global levels (Maxted et al., 2008, 2012, 2015, 2016; Maxted and Kell, 2009; McCouch et al., 2013; Dempewolf et al., 2014). Since the turn of this century, a number of notable initiatives have raised the profile of CWR and put them firmly on the international conservation agenda; however, conservationists and policymakers are faced with the difficult challenge of how to conserve the vast numbers of CWR taxa and the genetic diversity they contain. If we consider a broad definition of a CWR as any taxon classified in the same genus as a crop species (Maxted et al., 2006), or in the case of some crops, other closely related genera (e.g., the genepool of bread wheat, *Triticum aestivum* L. subsp. *aestivum* encompasses not only taxa in the genus *Triticum* but also in the genera *Aegilops* L., *Agropyron* Gaertn., *Amblyopyrum* Eig, *Elytrigia* Desv., *Leymus* Hochst. and *Elymus* L.), the gross global number of crop and CWR species may account for >58,000 (~21%) of the world's known flowering plant species (Maxted and Kell, 2009; Maxted et al., 2012), and this is disregarding the thousands of subspecific CWR taxa that may contain unique genetic diversity. Clearly it is not feasible to consider conservation interventions for such a large number of taxa; therefore, those in most urgent need of conservation need to be afforded priority for immediate attention.

Many different criteria can be used to prioritize species for conservation action, including socioeconomic use, taxonomic uniqueness, cultural value, endemicity, rarity, intrinsic biological vulnerability, threat of genetic erosion, current conservation status, ecogeographic distinctiveness, and distribution (Maxted et al., 1997b; Heywood and Dulloo, 2005). A wide range of approaches to applying species prioritization criteria have been employed, including scoring and ranking schemes and rule-based systems (reviewed by Magos Brehm et al., 2010). In the case of CWR, however, a specific approach is needed to take account of their particular value as potential sources of traits for crop improvement. A surge in CWR conservation planning since the beginning of the century has resulted in a range of prioritization approaches being applied by different authors of various complexities, depending on the context. In this paper we review the approaches that have been taken to date and consider the question, "which CWR taxa should pragmatically be targeted for immediate conservation action?" We present a harmonized, logical, and efficient means of assigning priority status to CWR taxa that can be applied nationally and regionally as part of a holistic global CWR conservation strategy on the basis of three main criteria: (i) the socioeconomic value of crops, (ii) the potential value of the wild relatives of socioeconomically valuable crops for variety improvement, and (iii) the threat status of the wild relatives of socioeconomically valuable crops. Regardless of the context and scope of the conservation action, these criteria are the most relevant for prioritization of CWR taxa, and in the last 15 yr of concerted action on CWR conservation planning have been widely promoted and consistently applied as the primary basis of taxon selection.

THE CRITERIA EXPLAINED

Criterion 1: The Socioeconomic Value of Crops

The relative socioeconomic value of crops (i.e., their value to society, both in terms of ensuring food and nutrition security and supporting sustainable economic growth) is the most important and fundamental criterion when assigning conservation priority to CWR. The rationale for conserving CWR diversity is to maintain and provide access to it for crop improvement, and while it would be desirable to conserve wild species related to all crops, this option is not realistic at any geographic scale of conservation action. Thus, CWR taxa related to priority crops (i.e., those that are considered to be of highest socioeconomic value) should be given precedence for conservation action because these are the crops with greatest value to human society for food and economic security. Furthermore, because the transfer of traits from CWR to these crops is likely to have significant socioeconomic impact and the cost of prebreeding is more likely to be offset by the additional value of the introgressed traits, the conserved CWR diversity is more likely to be used. The selection of priority crops should therefore logically be the first step in the CWR prioritization process, or if taking a "parallel" approach to prioritization (see explanation provided below), the application of this criterion should be afforded significant weight in the scoring process.

This criterion is founded on the basis of the definition of a CWR proposed by Maxted et al. (2006), which has been widely accepted and adopted by those working in the field of CWR conservation planning worldwide. A CWR taxon is defined by its "indirect use derived from its relatively close genetic relationship to a crop" (Maxted et al., 2006, p. 2680) and, as noted by the authors, includes any taxon within the same genus as a crop taxon. On this basis, it is relatively simple with access to floristic data (i.e., flora checklists) to create complete or partial checklists of CWR (a complete checklist being a list of wild taxa related to crops of all types, and a partial checklist being a list of wild taxa related only to selected crop types, such as human food or forage), and to select those taxa related to the highest priority crops.

The selection of priority crops varies according to geographic scale and the context of the conservation action. For example, whereas the conservation of wild relatives of major food crops such as bread wheat, maize (*Zea mays* L.), and rice (*Oryza sativa* L.) is a priority for global food security, at the regional or national level, minor crops such as cassava (*Manihot esculenta* Crantz), millets [e.g., finger millet, *Eleusine coracana* (L.) Gaertn. and foxtail millet, *Setaria italica* (L.) P. Beauv.], and sweet potato [*Ipomoea batatas* (L.) Lam. var. *batatas*] may be a higher priority. In general, of the main crop use categories (human food, animal food, food additives, materials, fuels, social uses, medicines, and environmental uses; Wiersema and León, 2013), human food crops are of the highest priority due their importance for nutrition and food security (Kell et al., 2015b), and thus their fundamental role in sustaining human life. Crops of high economic value are also of uppermost priority (Kell et al., 2012a) due to their importance for sustainable economic growth, as well as providing important motivation for the establishment of national conservation and sustainable use management plans for plant genetic resources for food and agriculture (PGRFA) (Kell et al., 2015b). There are therefore two main subcriteria on which to base the selection of priority crops: (i) crops of high importance for nutrition and food security, and (ii) crops of high importance due to their economic value. On the basis of these two subcriteria, when planning CWR conservation and sustainable use strategies at the national or regional level, crops in any use category may be afforded priority, depending on the inherent floristic diversity of the country or region and economic value of the CWR diversity within its borders. For example, forage and fodder crops are of particular importance in the Nordic subregion of Europe (Fitzgerald, 2016), where there are fewer human food CWR. At the global level, food security is paramount when considering the selection of priority CWR taxa for active conservation. Thus, wild relatives of human food crops are of critical importance for conservation action at this broad worldwide scale.

The selection of priority crops can be based on a number of crop value statistics (e.g., related to food supply and economic value), which are publicly available via FAOSTAT (www.fao.org/faostat/), the online database of FAO's Statistics Division, as well as by consulting the statistical databases of government agencies, which are publicly available in some countries, and those of regional administrations such as EuroStat (EU, 1995–2016), provided by the European Commission. Value statistics are not available for all crops, but this does not mean that the crops for which these data are not available are unimportant. Other indicators of socioeconomic value can be used to assign relative value to crops—for example, on the bases of (i) expert knowledge of the local, national, or regional socioeconomic value of crops (e.g., for particular nutritional qualities, local market value, or cultural importance); (ii) the number of varieties of a crop cultivated in a country or region; and (iii) the number of accessions of crops held in national or regional genebanks. However, not only do these indicators introduce a degree of subjectivity to the analysis, practitioners should be careful when ranking their importance with respect to other crops, since direct comparisons cannot be made using different indicators. When possible, consultation with the plant breeding community is also important when selecting priority crops, although this approach usually takes only national or regional priorities into account, overlooking the potential value of a nation's or region's CWR diversity for the improvement of crops that are economically valuable in other countries or regions.

Criterion 2: The Potential Value of Wild Relatives for Variety Improvement

In light of recent rapid developments in gene discovery and transfer techniques, it can be argued that all wild species are potential gene donors to crops. However, the use of biotechnology to transfer genes between distantly related species (transgenesis) remains a controversial issue, and the cultivation of crop varieties developed using transgenic techniques is not universally accepted. In addition, biotechnological techniques may work well when considering traits that are regulated by one or few genes but may be more problematic when dealing with traits regulated by many genes or when the genes being transferred are pleiotropic. In the latter case, the transfer of genes from distantly related species may cause the disruption of coadapted gene complexes. Further, the use of biotechnology in plant breeding remains relatively expensive and technically challenging, and the tools and technical knowledge are not available to all plant breeders working on all crops. Therefore, the use of conventional breeding techniques for interspecies gene transfer between closely related species is likely to remain the global norm (Maxted and Kell, 2009; Maxted et al., 2012). In cases where the technology is available, cisgenesis, which involves the use of biotechnology to transfer genes from the same or closely related sexually compatible species, may become more widely accepted as the urgency to speed up the production of new crop varieties to respond to global change gains greater understanding in society. As a general rule, there is therefore a strong argument to assign high priority to the conservation of the wild relatives that are most closely related to crop taxa.

The Gene Pool (GP) concept of Harlan and de Wet (1971) provides the best means of identifying the closest wild relatives, which are taxa in GP1b (wild or weedy forms of the crop that hybridize freely with the crop taxon, also known as "primary" wild relatives) and GP2 (less closely related species with which hybridization is possible but may be more difficult, also known as "secondary" wild relatives). However, GP concepts have only been published for a relatively small number of crops (Maxted et al., 2006)—mainly major food crops such as bread wheat, maize, and rice, or those that are of particular regional economic importance such as sugarbeet (*Beta vulgaris* L. subsp. *vulgaris*) in Europe.

In the absence of this knowledge, taxonomic classifications can be used as a proxy measure for the degree of genetic relationship and therefore the likely interfertility of a taxon to the crop (Maxted et al., 2006). The Taxon Group (TG) concept (Maxted et al., 2006) uses taxonomic distance as a proxy for genetic distance, the assumption being that subspecies or botanical varieties in the same species as the crop (primary wild relatives in TG1b) and taxa in the same series or section as the crop (secondary wild relatives in TG2) are likely to be more easily used than more remote taxa in conventional plant breeding. Although taxonomic distance and genetic distance do not always concur, the concept offers a viable alternative to assessing the degree of relationship of the wild relatives to the crop (and thus potential crossing ability) in the absence of genetic data (Maxted et al., 2006). In cases where the GP concept has not been ascertained and for genera that have not been subdivided into sections and series, the best available information on genetic and/or taxonomic diversity has to be used to make reasoned assumptions about the most closely related taxa, and thus potential crossing ability. For example, in a study conducted by Maxted and Kell (2009), the classification of wild relatives of finger millet into primary, secondary, and tertiary groups was made on the basis of a review of published results of various genetic studies performed on *Eleusine* taxa because a GP classification had not previously been published and the TG concept could not be applied because the genepool contains only nine species, eight of which are in the genus *Eleusine*, which is not subdivided into subgenera, sections, or series. Vincent et al. (2013) later referred to classifications such as this as Provisional GP concepts.

While primary and secondary CWR are of high conservation priority, this does not negate the need to assign conservation priority to taxa in GP3 or TGs 3 and 4 ("tertiary" wild relatives). In this regard, there are two specific considerations when applying Criterion 2 in CWR conservation planning. First, taxa that have already been used in plant breeding or that are known to contain traits of interest for crop improvement (increasing the likelihood of them being used in the future) should be given high priority status (Maxted and Kell, 2009). Examples include the tertiary wild relatives of sugarbeet (*Patellifolia* A.J. Scott et al. spp.), which are donors of beet cyst nematode (*Heterodera schachtii* Schmidt) resistance (now successfully used in sugarbeet production worldwide) and other resistance traits (Prescott-Allen and Prescott-Allen, 1986), and *Hordeum chilense* Roem. & Schult., a tertiary wild relative of barley (*H. vulgare* L. subsp. *vulgare*) that has a number of characteristics of interest for breeding (in particular, resistance to barley leaf rust, caused by *Puccinia hordei* G.H. Otth) and has potential for use in wheat and triticale improvement (Martín and Cabrera, 2005). Second, the particular value of the most closely related species applies to the majority of crops but may be of less importance when prioritizing species related to crops that hybridize relatively freely with their tertiary wild relatives or are routinely bred using advanced techniques. For example, cassava hybridizes naturally with many of the wild species in the genepool and a number of species in GP3 have already been used in breeding programs (Maxted and Kell, 2009), and virtually any wild relative of potato (*Solanum tuberosum* L.) can be utilized in improvement of the crop using ploidy manipulation or somatic fusion to overcome crossing barriers (Bradshaw et al., 2006).

Although narrowing down conservation action to a limited number of CWR taxa is a necessary part of conservation planning, all CWR (regardless of their position in the crop genepool) may be important as gene donors in the future—many taxa remain uncharacterized and the transfer of traits for crop improvement may be facilitated by new breeding techniques (as well as existing techniques that are not yet universally accepted, as mentioned above). Therefore, tertiary wild relatives with no currently known specific use potential should not be overlooked in conservation planning, especially considering that many of these taxa could become more restricted and threatened in the future, particularly in response to climate change. Importantly, species in this category that are known or suspected to be under threat of genetic erosion should be afforded conservation priority (see Criterion 3 below). Further, when the required data are readily available to include a larger number of CWR in diversity and gap analyses to identify populations and sites of conservation priority than have been afforded high priority conservation status, additional tertiary taxa may be targeted for conservation because they coexist with the high priority taxa.

Due to recent concerted efforts in determining and documenting the relationships between taxa in food crop genepools (Maxted and Kell, 2009; Vincent et al., 2013; USDA, ARS, GRIN, 2017), data on the classification of the wild relatives of a wide range of crops into primary, secondary, and tertiary groups are now freely available to aid CWR conservation planning worldwide via the Harlan and de Wet CWR Inventory (Vincent et al., 2013; www.cwrdiversity.org/checklist) and the Germplasm Resources Information Network (USDA, ARS, GRIN, 2017; https://npgsweb.ars-grin.gov/gringlobal/taxon/taxonomysearchcwr.aspx).

As for Criterion 1, consultation with the plant breeding community is worthwhile when selecting priority CWR taxa on the basis of their use potential, especially to gain the support of the user community for their conservation. However, this approach has the same caveat as previously stated: (i) it introduces a degree of subjectivity in the process because not all plant breeders can practically be consulted, and (ii) it usually takes only national or regional priorities into account, overlooking the potential value of a nation's or region's CWR diversity for the improvement of crops that are economically valuable in other countries or regions.

Nonetheless, if consultation with plant breeders is viewed as an additional step in the process (i.e., adding species to the priority list rather than removing them), it is certainly of great value in the CWR conservation planning process.

Criterion 3: The Threat Status of Wild Relatives of Priority Crops

The degree to which species are under threat, relative to other species, is a fundamental criterion for conservation planning. In the case of CWR taxa, however, this criterion should ideally not take precedence over Criteria 1 and 2 unless resources for conservation planning and/or implementation necessarily limit the number of taxa that can be included in the priority list—for example, in cases where the mandate for the conservation requires focus only on a small number of species, or when distribution data are not readily available for all species that would ordinarily be prioritized, including those closely related but with relatively wide distributions. Assigning greatest weight to Criteria 1 and 2 in the CWR conservation planning process increases opportunities to conserve a broad range of genetic diversity of taxa with the most use potential for food and economic security. Following the process of applying the three criteria conceptualized in Fig. 1, CWR taxa of greatest use potential *and* those considered to be worthy of special conservation attention due to their relative threat status (whether closely or distantly related to priority crops) can be prioritized for conservation assessment and possible action, bearing in mind that many threatened species may already be under some level of conservation management because they are listed in legislative instruments such as National Biodiversity Action Plans (NBAPs) or regional conservation initiatives such as the EU Habitats Directive (EU, 1998–2016).

Attributing relative threat status to CWR is no different to any other wild taxa. The primary and most obvious means of achieving this is to categorize taxa according to their Red List status, either based on existing assessments published in national and regional Red Lists, as well as the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species (www.iucnredlist.org), or by undertaking new assessments. Systematic Red List assessment of CWR is now becoming more commonplace through a number of initiatives, particularly under the auspices of the Crop Wild Relative Specialist Group (CWRSG, www.cwrsg.org) of the IUCN Species Survival Commission, which is taking the lead in Red Listing of CWR and has published global assessments for a number of priority CWR in the IUCN Red List of Threatened Species, as well as regional assessments of priority CWR

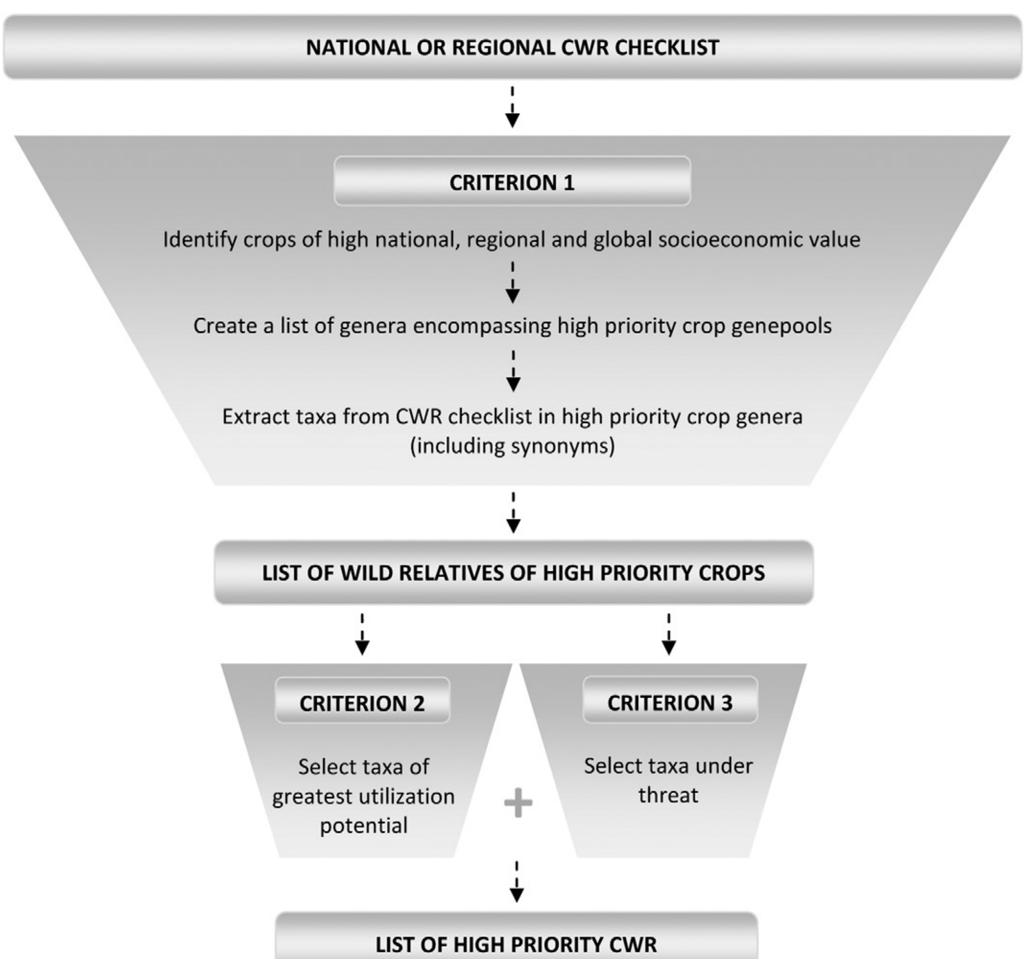

Fig. 1. Conceptual diagram showing a harmonized, logical, and pragmatic approach to crop wild relative prioritization based on three main criteria, which results in a list of taxa that are of greatest use potential for crop improvement and/or considered to be worthy of special conservation attention due to their relative threat status.

in Europe (Bilz et al., 2011). Although Red List assessment of CWR at the national level has not generally been systematically undertaken, some CWR species are included in national Red Lists because of their importance as threatened species per se, rather than as CWR.

If CWR taxa have not been Red Listed, it does not mean that they are not under threat. If a published assessment is not available, a proxy for relative threat may be applied in the prioritization process by categorizing taxa according to their comparative distribution (Ford-Lloyd et al., 2008, 2009) and/or based on knowledge of threats to a species' primary habitat. The comparative distribution of taxa can be seen as an indicator of the relative degree of threat when actual threats to populations or the habitats in which they are found are unknown, on the assumption that the overall populations (i.e., all subpopulations counted together) of taxa with more limited distributions are more likely to be negatively affected by the stresses caused by potential threatening factors. Using this approach, taxa with relatively limited distribution ranges can be afforded higher priority status than those that are more widely distributed. However, this measure should be applied with caution. First, although a taxon may be recorded as occurring in several countries, without knowledge of the actual distribution within those countries, we do not know how widely distributed the taxon actually is across its range. Second, because the aim of CWR conservation is to maximize conservation of infraspecific diversity, populations of taxa that are known to occur both inside and outside the country or region of the CWR conservation action should be actively conserved across their range. Another approach is to use the concept of "taxon vulnerability" (Maxted et al., 2004). In the absence of sufficient data to undertake Red List assessments of African *Vigna* L. spp., the authors combined measures of rarity, breadth of distribution, absolute numbers of ex situ representation, relative ex situ coverage from the breadth of diversity, utility, and extinction assessment to generate an estimate of vulnerability to extinction of each CWR in the study. This approach does, however, include elements of gap analysis (ex situ) in the selection of priority taxa, a step ideally undertaken after taxon prioritization to avoid excluding important taxa in conservation planning.

Importantly, the status of a taxon as endemic should not be confused with its relative distribution. A taxon may be endemic to a country but widely distributed and not threatened, whereas other nonendemic taxa may have narrow ranges and may be threatened. Further, at the regional level, a taxon that is endemic to a small island cannot be compared with one that is endemic to a large continental country. Therefore, although it is understandable that countries and regions assign conservation priority to endemic taxa because of their inherent value to the country as unique national resources, emphasis should be placed on the actual relative distribution of taxa, not to their endemic status per se.

Critically, when prioritizing CWR based on their Red List status, it is not necessarily the case that a species that has been evaluated as Least Concern using the IUCN Red List Categories and Criteria (IUCN, 2012a) is not in need of conservation action. Kell et al. (2012a) argued that three important issues need to be taken into account when interpreting a Least Concern assessment. First, the IUCN Red List assessment process does not take into account genetic diversity within and between populations, only population size and geographic range. As the goal is to maximize the conservation of CWR genetic diversity, it is vital that sufficient populations are actively managed both in situ and ex situ to provide an adequate sample of total genetic diversity (Ford-Lloyd and Maxted, 1993; Maxted et al., 2008, 2012, 2015, 2016; Maxted and Kell, 2009; Kell et al., 2012b). Second, the criteria for assessing a species as threatened (i.e., Critically Endangered, Endangered, or Vulnerable) are very robust, and for species that do not meet the required thresholds, assessors must choose between Near Threatened, Data Deficient, or Least Concern—a choice that is highly subjective. Third, although the regional Red List status of many CWR is likely to be Least Concern, many of these species may be nationally threatened. In Europe, Kell et al. (2012a) estimated that this applies to as many as one third of the species regionally assessed as Least Concern.

When including Red List assessments in the CWR prioritization process, practitioners should also be careful to distinguish between national, regional, and global assessments (note that in this sense "regional" refers to a geographic region such as Europe, not to a regional Red List assessment sensu IUCN [2012b], which includes national assessments), because the Red List status of taxa at these different geographic scales carries different weight depending on the scope of the conservation action. For example, when prioritizing CWR taxa as part of the national CWR conservation strategy planning process, the national Red List Status of species is clearly of upmost importance because prioritization is being undertaken at the national level. National endemic species that are assessed as threatened or Near Threatened are also regionally and globally threatened or Near Threatened, so highlighting this can add weight to the argument for their conservation, even if the regional and global assessments have not been published. On the other hand, for species that are assessed as nationally threatened, Near Threatened, Data Deficient, or Not Evaluated but are not endemic, including their regional and/or global Red List status will not help the cause for their national conservation if they are evaluated as Least Concern at those geographic scales. In a few cases, however, the regional and/or global Red List assessments of non-national endemic species are important to consider in the national prioritization process. For example, in Europe, species regionally and globally assessed as threatened or Near Threatened that occur in more than one country include: *Allium schmitzii* Cout. (Vulnerable) and *Asparagus nesiotes* Svent. (Endangered) (native to Portugal and Spain) (Santos Guerra et al., 2011a, 2011b); *Barbarea lepuznica* Nyár. (Endangered) (native to Romania and Serbia) (Strajeru and Stevanović, 2011); and *Medicago pironae* Vis. (Near Threatened) (native to Croatia, Italy, and Slovenia) (Branca and Donnini, 2011).

A Note about CWR Prioritization and Occurrence Status

Although it is generally accepted that the three criteria presented above are most relevant when prioritizing CWR taxa in the conservation planning process, some authors apply the additional criterion "occurrence status," which in its simplest terms defines whether a taxon is native or introduced to the geographic area delineated in the conservation action, although there are several occurrence status categories defined in the Plant Occurrence and Status Scheme (POSS) (WCMC, 1995). In general, taxa that are considered to be native are afforded conservation priority in any type of biodiversity conservation action plan, although archaeophytes—taxa that have been introduced to an area in ancient times (commonly considered to be before 1500 AD)—are frequently also considered to be of priority. However, since some taxa are able to adapt rapidly to new environments (Ford-Lloyd et al., 2014), populations of neophytes (taxa introduced to an area after 1500 AD) can offer important and unique genetic diversity. Even if they arrive in their non-native habitat with a narrow genetic base, they are likely to rapidly evolve to their new environment and may contain unique diversity not present in the source population.

CWR PRIORITIZATION AT THREE GEOGRAPHIC SCALES

A holistic global approach to CWR conservation involving action at the national, regional, and global levels has been promoted by Iriondo et al. (2008), Maxted et al. (2008, 2012, 2013, 2015, 2016), and Maxted and Kell (2009) and is enshrined in the Convention on Biological Diversity (UN, 1992), the International Treaty on Plant Genetic Resources for Food and Agriculture (International Treaty on PGRFA) (FAO, 2001), and the Second Global Plan of Action on Plant Genetic Resources for Food and Agriculture (FAO, 2012). In recent years, much progress has been made in planning CWR conservation at each of these three geographic scales. To inform ongoing developments, particularly in national CWR conservation planning, it is both relevant and timely to review approaches to CWR prioritization that have been undertaken to date and to highlight some common issues arising in the process.

National Approaches to CWR Prioritization

Due to the sovereign rights of nations over the management and use of the genetic resources within their political borders, the responsibility to conserve those resources also lies at the national level. Therefore, national CWR conservation strategies, which aim for the systematic conservation of priority CWR genetic diversity in situ and ex situ, are fundamental to the effective global conservation of these resources. The surge in projects and research focusing on the conservation of CWR diversity in recent years has resulted in significant progress in the development of national CWR conservation strategies, particularly in the European region, which has been a hub of developments in CWR conservation practice for the last 15 yr. In Europe, a coordinated approach to CWR conservation is being implemented through the auspices of the European Cooperative Programme for Plant Genetic Resources (ECPGR, www.ecpgr.cgiar.org), which has adopted an integrated approach to CWR conservation in the region (Maxted et al., 2015). Three notable projects funded by the EU between 2002 and 2014 (PGR Forum, www.pgrforum.bham.ac.uk; AEGRO, http://aegro.julius-kuehn.de/aegro; and PGR Secure, www.pgrsecure.org) have provided the framework within which knowledge on CWR diversity and planning for its conservation has increased exponentially and enabled concerted efforts in conservation planning (as well as the beginnings of its implementation) in the region based on a range of commonly agreed on and widely tested scientific concepts and techniques. Through the project PGR Secure, training in CWR conservation planning methods (including prioritization) has been provided across the region to build capacity and encourage action at the national level.

Iriondo et al. (2016) and Labokas (2016) reviewed progress in national CWR conservation planning in 26 countries in Europe, Western and Central Asia, and North America, providing useful comparisons between the prioritization methods employed. Notably, both authors highlighted criteria that countries have used which they consider to be supplemental to the three main criteria presented in this paper: (i) stakeholder priorities (especially those of plant breeders), (ii) use categories, (iii) CWR of crops listed in Annex I of the International Treaty on PGRFA, (iv) relative distribution, (v) endemic status (national and regional), (vi) geographical or regional responsibility for certain taxa with restricted worldwide distributions, (vii) rarity of the habitat in which the species grow, (viii) relative abundance, (ix) status in surrounding countries, (x) species listed in the annexes of the EU Habitats Directive, (xi) national protection status, (xii) expected effects of climate change on distribution, (xiii) occurrence status, (xiv) the center of diversity of the crop genepool, and (xv) ex situ and in situ conservation status. In addition, Hunter and Heywood (2011) reviewed the CWR prioritization criteria applied in Armenia, Bolivia, Madagascar, Sri Lanka, and Uzbekistan, noting that the countries "adopted different sets of criteria based on the knowledge, experience, and interests of those involved in the exercise" (p. 130). In addition to the criteria listed above, the following criteria were used: (i) state of knowledge and availability of information, (ii) degree of genetic erosion, (iii) multiple or combined value, (iv) traditional use, and (v) use by local people as a food source.

Untangling this array of different prioritization criteria applied by countries as part of the national CWR conservation strategy planning process is important to assist in future national efforts, both in systematically applying CWR prioritization criteria and in reporting on the methods used. In Table 1, we address each criterion listed above in turn, commenting on those that can be considered integral to or as subcriteria of the three main CWR prioritization criteria presented in this paper, and on their relevance and value for CWR conservation planning. Labokas (2016) also highlighted the categories of crop use that were considered important in the prioritization process, noting that three countries (Norway, Portugal, and Sweden) prioritized taxa related to crops in six use categories: human food, animal food, forestry, medicinal and aromatic, industrial, and ornamental. This emphasizes the point made above that when planning CWR conservation and sustainable use strategies at the national level, crops in any use category may be afforded priority, depending on the inherent floristic diversity of the country and the economic value of the CWR diversity within its borders.

In terms of the methods used in applying the prioritization criteria, there are two primary approaches: (i) the serial method, in which one criterion is applied after another, sequentially reducing the number of taxa to a priority subset; and (ii) the parallel method, in which taxa are scored for all criteria, ranked according to their total scores, and then selected on the basis of their placement in categories according to one or more "cut-off" scores (Maxted et al., 1997b). Sometimes a combination of these two methods may be applied. Both methods are valid but have limitations and potential pitfalls. Using the serial method, the order in which the criteria are applied effectively affords weight to each, and the resulting priority taxon list therefore reflects this weighting. For example, selecting taxa related to priority crops (Criterion 1), followed by selection of a subset based on relative threat status (Criterion 3), results in many taxa that may be of high value for crop improvement being excluded. The same result would occur by selecting taxa based on their relative threat status (Criterion 3), followed by the value of the selected taxa according to the crops to which they are related. Therefore, when using the serial method of applying the criteria, Criterion 1 should always be the first one applied to ensure that the most important taxa are included in terms of their potential to contribute traits to the most socioeconomically valuable crops, and the practical likelihood that trait introgression from CWR is likely to be applied for that crop. After the application of this criterion, the recommended approach is to apply Criterion 2 to identify the first subset of priority taxa, then to apply Criterion 3 to the remaining taxa, thus producing a list of priority taxa that are either of greatest use potential or considered to be worthy of conservation action because they are under threat of genetic erosion, regardless of their current known or potential value for crop improvement. This method is illustrated in Fig. 1.

Using the parallel method, all taxa in a national CWR checklist (whether complete or partial) are scored for each criterion and ranked according to their total scores to identify priority taxa. This approach can be quite robust if very carefully planned and executed. However, there are two major potential pitfalls. First, the decision has to be made whether to afford equal weight to each of the criteria. Experience has shown that some countries tend to lend greater weight to relative threat status than to the socioeconomic value of the related crop or use potential for crop improvement, an approach that results in many taxa that may be of high value for crop improvement being excluded from the priority list. This problem may be compounded by including several subcriteria (as described in Table 1). Giving equal weight to these subcriteria effectively results in unintentionally affording greater weight to one of the three main criteria (usually Criterion 3, because most of the subcriteria being applied relate to relative threat status). Second, the scoring system used is always subjective because it depends on the opinions of the practitioner undertaking the prioritization—although this subjectivity can be reduced to some extent through a process of review and validation involving national stakeholders, experts, and based on previous studies. One solution proposed to reduce bias and subjectivity is to apply a number of different methods to the same set of species and then select the top 50 species in each of the methods to ensure that the priority species identified are those common to most methods (Magos Brehm et al., 2010). However, this approach involves a significant amount of researcher time and may not be possible in most circumstances.

In addition to these pitfalls, the work involved in scoring a large number of species is arduous and time consuming, whereas the more simple serial approach described in this paper can be relatively rapidly achieved by running queries on the base dataset. We therefore conclude that, while there is no single right or wrong way of undertaking CWR prioritization, the approach summarized in Fig. 1 is the simplest and most applicable approach to ensure that all important taxa are included in the priority list and to reduce potential for bias towards relative threat status over the potential value of taxa for the improvement

Table 1. Crop wild relative (CWR) prioritization criteria reported by Hunter and Heywood (2011), Iriondo et al. (2016), and Labokas (2016), with a commentary on their placement within the framework of the three main criteria presented in this paper, as well as on their value in the CWR prioritization process.

Criteria	Supplemental to the three main prioritization criteria?	Placement within the framework of the three main prioritization criteria	Value for prioritizing CWR taxa
Stakeholder priorities, especially those of plant breeders.	No	This can be considered as a subcriterion of both Criteria 1 and 2 because stakeholder priorities can be considered when selecting high priority crops and CWR taxa with the greatest use potential.	Caution should be exercised in assigning weight to this subcriterion because it is unlikely that all relevant stakeholders can practically be consulted and stakeholder priorities are unlikely to take account of the potential socioeconomic value of CWR outside the geographic scope of the conservation action.
Use categories	No	This is integral to Criterion 1, socioeconomic value of crops.	Criterion 1, to which “use categories” belongs, is the most important and fundamental of the three CWR prioritization criteria.
CWR of crops listed in Annex I of the International Treaty on Plant Genetic Resources for Food and Agriculture (International Treaty on PGRFA)	No	This can be considered as a subcriterion of Criterion 1, socioeconomic value of crops, because Annex I of the International Treaty on PGRFA is a list of crops considered important for global food security and interdependence.	Caution should be exercised in assigning weight to this subcriterion because the list is not exhaustive and excludes some crops that are of economic importance in some regions and countries. Nonetheless, it can be valuable to include this subcriterion as justification for CWR conservation due to the obligations of Contracting Parties to implement the provisions of the Treaty.
Multiple or combined value	No	This can be considered as a subcriterion of both Criteria 1 and 2 because multiple values can be taken into account when selecting high priority crop and CWR taxa (some crop species have multiple values and some CWR taxa are related to more than one crop).	Caution should be exercised in assigning weight to this subcriterion because species with multiple use values should not necessarily be given precedence over those with only one use value that is of high socioeconomic importance.
Relative distribution	No	This can be considered as a subcriterion of Criterion 3, relative threat status, because it is based on the premise that the narrower a species’ range, the more likely it is to be subject to genetic erosion.	The value assigned to this subcriterion is applicable to any wild species and thus is important for CWR conservation planning. However, caution should be exercised in applying this subcriterion because assigning significant weight to it can result in more widespread CWR taxa being ignored in conservation planning.
Endemic status (national and regional)	No	This can be considered as a subcriterion of Criterion 3, relative threat status, because it is based on the premise that the narrower a species’ range, the more likely it is to be subject to genetic erosion.	The value assigned to this subcriterion is applicable to any wild species and thus is important for CWR conservation planning. However, caution should be exercised in applying this subcriterion because assigning significant weight to it can result in more widespread CWR taxa being ignored in conservation planning.
Geographical or regional responsibility for certain taxa with restricted worldwide distribution	No	This can be considered as a subcriterion of Criterion 3, relative threat status, because it is based on the premise that the narrower a species’ range, the more likely it is to be subject to genetic erosion.	The value assigned to this subcriterion is applicable to any wild species and thus is important for CWR conservation planning. However, caution should be exercised in applying this subcriterion because assigning significant weight to it can result in more widespread CWR taxa being ignored in conservation planning.
Rarity of the habitat(s) in which a species grows	No	This can be considered a subcriterion of Criterion 3, relative threat status, because it implies that species that occur in rare habitats may be under threat of genetic erosion.	As a subcriterion of Criterion 3, this measure can be important for prioritizing CWR taxa that may be threatened but have not been Red Listed. However, caution should be exercised in applying this subcriterion because assigning significant weight to it can result in more widespread CWR taxa being ignored in conservation planning.

Table 1. Continued.

Criteria	Supplemental to the three main prioritization criteria?	Placement within the framework of the three main prioritization criteria	Value for prioritizing CWR taxa
Relative abundance	No	This can be considered a subcriterion of Criterion 3, relative threat status, because it implies that species with small overall population sizes may be under threat of genetic erosion.	As a subcriterion of Criterion 3, this measure can be important for prioritizing CWR taxa that may be threatened but have not been Red Listed. However, caution should be exercised in applying this subcriterion because assigning significant weight to it can result in more widespread CWR taxa being ignored in conservation planning.
Status in surrounding countries	No	This can be considered a subcriterion of Criterion 3, relative threat status, because it implies knowledge of the threat status of subpopulations in neighboring countries.	As a subcriterion of Criterion 3, this measure can be important for prioritizing CWR taxa that may be threatened. However, caution should be exercised in applying this subcriterion because assigning significant weight to it can result in more widespread CWR taxa being ignored in conservation planning.
Degree of genetic erosion	No	This can be considered a subcriterion of Criterion 3, relative threat status, because "genetic erosion" is a term commonly used in relation to taxa and populations under threat of extinction.	As a subcriterion of Criterion 3, this measure can be important for prioritizing CWR taxa that may be threatened but have not been Red Listed. However, caution should be exercised in applying this subcriterion because assigning significant weight to it can result in more widespread CWR taxa being ignored in conservation planning.
Species listed in the annexes of the EU Habitats Directive	No	This can be considered a subcriterion of Criterion 3, relative threat status, because the species listed in the annexes of this EU legislative instrument are those considered to be endangered, vulnerable, rare, or endemic and requiring particular attention (due to known threats impacting the species) (EU, 1998–2016).	This subcriterion should not be afforded significant weight in planning CWR conservation because the Directive does not take into account the particular value of CWR and the species are already subject to conservation measures. Nonetheless, it can be valuable to include this subcriterion as justification for CWR conservation due to the obligations of EU Member States to implement the provisions of the Directive.
National protection status	No	This can be considered a subcriterion of Criterion 3, relative threat status, because the species listed in national legislative instruments are generally those considered to be rare, threatened, or of particular national importance due to their endemic status.	This subcriterion should not be afforded significant weight in planning CWR conservation because it does not take into account the particular value of CWR and the species are already subject to conservation measures. Nonetheless, it can be valuable to include this subcriterion as justification for CWR conservation due to the obligations of national biodiversity conservation agencies to implement the provisions of national legislation.
Expected effects of climate change on distribution	No	This can be considered a subcriterion of Criterion 3, relative threat status, because it implies that results of climate change modeling indicate that taxa may be under greater or lesser threat of genetic erosion under projected climate change scenarios.	As a subcriterion of Criterion 3, this measure is important for prioritizing CWR taxa that may be threatened in the future based on results of climate change modeling. However, it is more likely to apply to the later stage of CWR conservation planning in which specific populations are targeted for conservation action after conducting diversity and gap analyses.
Occurrence status	Yes	Not applicable	The criterion should not be afforded the same weight as the three main CWR prioritization criteria because it is applicable to any wild species.
The center of diversity of the crop gene pool	Yes	Not applicable	The criterion should not be afforded the same weight as the three main CWR prioritization criteria because CWR populations in the margins of the range of crop gene pool taxa may contain unique and important genetic diversity.
State of knowledge and availability of information	Yes	Not applicable	This criterion should not influence the selection of priority CWR taxa. If there is a paucity of information on priority taxa, the need to collect more information should be highlighted in the conservation plan.

Table 1. Continued.

Criteria	Supplemental to the three main prioritization criteria?	Placement within the framework of the three main prioritization criteria	Value for prioritizing CWR taxa
Ex situ and in situ conservation status	Not applicable. This does not apply to prioritization at taxon level.	Not applicable	Assessing conservation status is undertaken after the selection of priority taxa. Regardless of a CWR taxon's conservation status, it should remain in the priority list based on its value as a gene donor for crop improvement. This is also taking into account that its conservation status may change in the future.
Traditional use	Not applicable. This criterion does not apply to prioritization of CWR taxa.	Not applicable	Traditional use (including use by local people as a food source) refers to the direct use of wild plants (i.e., by harvesting plant parts or whole plants from the wild), such as for food, medicine, materials, and ceremonial uses. The criterion may be used as a supplement to CWR prioritization to add weight to the need for CWR taxon conservation or to highlight traditional uses as a threat to populations. However, it is not in itself a criterion for prioritizing CWR taxa.
Use by local people as a food source	Not applicable. This criterion does not apply to prioritization of CWR taxa.	Not applicable	Traditional use (including use by local people as a food source) refers to the direct use of wild plants (i.e., by harvesting plant parts or whole plants from the wild), such as for food, medicine, materials, and ceremonial uses. The criterion may be used as a supplement to CWR prioritization to add weight to the need for CWR taxon conservation or to highlight traditional uses as a threat to populations. However, it is not in itself a criterion for prioritizing CWR taxa.

of socioeconomically valuable crops. Having made this point, practitioners must make a pragmatic decision on the best approach, which may be influenced by a number of factors including: (i) the particular nature of the conservation action (e.g., different national authorities may require or prefer a specific approach or may specify a maximum number of taxa that can be considered for conservation action), (ii) the number of taxa in the base list (e.g., if starting from a complete checklist of thousands of taxa related to crops in all the main use categories, the task of scoring all taxa may prohibit taking the parallel approach), and (iii) the availability of data (there may be significant gaps in the information required to score all taxa in a checklist across all criteria, and in such cases, the parallel approach would not be appropriate).

Whichever approach is chosen, the number of priority taxa resulting from the exercise should not unduly influence the process. Although it is important to acknowledge that conservation agencies are forced to direct limited resources for conservation action where they are most needed and thus may be alarmed if presented a list of 200 priority taxa as opposed to only 20, the rationale for maintaining a priority list, regardless of the number of taxa included, is twofold. First, systematic conservation planning methods using advanced geographic information system (GIS) techniques aim to maximize CWR diversity conservation through action targeted at the minimum number of populations and sites. Second, if necessary, a priority taxon list can itself be prioritized to identify the highest priority taxa in most urgent need of conservation attention, while the remaining taxa may be considered for active conservation intervention at a later date.

In addition to the sources cited in this paper, there are a number of published case studies detailing the national CWR conservation strategy planning process, which practitioners can consult to help inform the choice of prioritization approach. A compilation is published by Bioversity International at www.cropwildrelatives.org/inventories-and-strategies/. Importantly, to ensure the uptake of conservation recommendations arising from the national CWR conservation strategy planning process, the relevant national stakeholders, including the national authorities that are responsible for wild plant species conservation and conservation of PGRFA, should be involved in the prioritization process. One option is through the organization of workshops in which the practitioner undertaking the prioritization can explain the options to national stakeholders and seek their agreement on the approach to be taken, after which the procedure and resulting list of priority taxa can be validated, either through a subsequent workshop (a process which was undergone in Jordan; Magos Brehm et al., 2016) or through correspondence.

CWR Prioritization at Regional Level

The rationale for a regional approach to CWR conservation (and thus a regional approach to CWR prioritization) lies first in the recognition of the importance of a region's PGR and their common value to the region as a whole, with each region tending to be characterized by having CWR related to different crops [e.g., sunflower, *Helianthus annuus* L. in North America, maize in Central America, potato in South America, sugarbeet in Europe, cowpea, *Vigna unguiculata* (L.) Walp. in East Africa, grape, *Vitis vinifera* L. in West Asia, and rice in East Asia). Second, because such resources are not restricted to national borders, their conservation is the shared responsibility of the countries in which the populations occur. Third, only taking a national approach to CWR conservation does not systematically address the conservation of CWR diversity throughout a region due to differing national priorities and the pace at which nations are able to develop national CWR conservation strategies, with some countries already being advanced in the process and others having not yet started. In addition, the identification of regionally important populations or sites of CWR diversity may lend weight to the urgency of those countries in which they occur to enact conservation, recognizing the regional (and potentially global) importance of the resources. Further, the existence of regional administrative bodies adds to the justification for taking a regional approach to PGR conservation because, in some cases, associated legislative instruments such as regional biodiversity conservation action plans are already in place and may act as frameworks and provide the impetus for CWR conservation action in the region.

An approach involving the integration of national and regional CWR conservation strategies is encapsulated by Maxted et al. (2015) and, as mentioned above, is being taken forward in Europe under the auspices of the regional network for PGR conservation, the ECPGR. Taking a lead from the European integrated initiative, a similar approach is currently in the planning phase in the South African Development Community (SADC) region in the context of the SADC Crop Wild Relatives Project (www.cropwildrelatives.org/sadc-cwr-project). In both regions, a similar approach to the prioritization of the region's CWR diversity has been undertaken following the method illustrated in Fig. 1, but with some variation in the process due to the comparative availability of data to apply the prioritization criteria and sensitivity related to the mandate of the bodies responsible for PGRFA conservation in the region.

In Europe, Kell et al. (2014) selected a preliminary list of high priority CWR species for regional conservation planning by: (i) identifying priority human food crops (or crop groups, such as brassicas, alliums, and stonefruits; Kell et al., 2015b) based on their production value and contribution to dietary energy in the region (Criterion 1); (ii) extracting taxa from the regional CWR checklist (Kell et al., 2005) in the genera of the priority crop genepools; and (iii) selecting taxa from the list created under step ii that either have the greatest use potential for crop improvement based on Vincent et al. (2013) (Criterion 2) or are threatened or Near Threatened (Criterion 3). In this case, the application of Criterion 3, "relative threat status," was possible because most species related to the highest priority crops or crop groups identified for the region had already been Red Listed at the regional level (Bilz et al., 2011; www.iucnredlist.org/initiatives/europe).

A similar approach was taken to prioritize CWR taxa in the SADC region (Kell et al., 2015a), although the process differed because there is no regional floristic checklist available to create a regional CWR checklist and no regional Red List. Further, in addition to using FAOSTAT crop production value and contribution to dietary energy statistics (www.fao.org/faostat/) to identify priority crops or crop groups in the region, there was strong justification to include taxa related to additional crops included in the base collection of the regional genebank managed by the SADC Plant Genetic Resources Centre (SPGRC) due to their clear importance for nutrition and food security in the region. Thus, the application of Criterion 1 involved the compilation of priority crops or crop groups from two sources: FAOSTAT and the SPGRC base collection database. A partial CWR checklist for the region was created by identifying CWR in the genepools of the priority crops or crop groups using taxon and geographic (countries of occurrence) data from GRIN Taxonomy for Plants and Vincent et al. (2013). From this list, a subset of high priority CWR taxa were selected on the basis of their use potential (Criterion 2) using the same sources. For the additional priority crops included from the SPGRC base collection for which GP classifications were not available, online and literature searches were conducted to ascertain which taxa related to those crops can be considered of greatest use potential, in some cases including wild populations of the crop species themselves. Criterion 3 was not applied because, as already noted, there is no regional Red List available for the SADC region. The application of a proxy for relative threat status based on relative distribution was not considered to be of value because, as previously noted, the aim of CWR conservation is to maximize conservation of infraspecific diversity—thus, populations of taxa that are known to occur both inside and outside the region should be actively conserved across their range. Thus, in the SADC region, the list of high priority CWR taxa is based only on the application of Criteria 1 and 2.

An important consideration when prioritizing CWR taxa at either the national or regional level is to not only consider the value of CWR diversity to a country or region, but also its value to other countries and regions.

For example, in Europe, there is significant native wild relative diversity of crops of particular global importance in terms of their direct contribution to food security in other regions. These include mustard seed [*Brassica nigra* (L.) K. Koch and *Sinapis alba* L.], rapeseed (*B. napus* L.), wheat, sugarbeet, some roots and tubers, and other vegetable crops. In the SADC region, crops of particular global importance that have CWR in the region include millets, rice, and sorghum, *Sorghum bicolor* (L.) Moench. Likewise, both regions depend on PGR from other regions, including potato, sunflower seed, soybean, maize, and rice in Europe, and beans (*Phaseolus* L. spp.), cassava, maize, soybean, and wheat in the SADC region. Taking a national example, in an analysis of priority CWR taxa in China, Kell et al. (2015b) identified 20 crops (or crop groups) of global importance due to their contribution to food security, based on their value as major sources of plant-derived dietary energy supply in one or more subregions of the world. The authors highlighted that, out of 11 of these crops or crop groups that have native wild relatives in China, eight are important to the nation due to their production and/or dietary energy value, while the remaining three are important for their dietary energy value in other regions (olive, *Olea europaea* L. in Europe and sorghum and yam, *Dioscorea alata* L. in Africa). These examples illustrate the interdependence of countries and regions on PGR and serve to highlight the potential regional and/or global value of CWR diversity, providing strong justification for prioritizing the conservation of CWR taxa that may not be valuable as potential gene sources for the improvement of socioeconomically important crops in the country or region developing the CWR conservation strategy, but which may be of value in other parts of the world.

Prioritizing CWR Taxa at Global Level

The rationale for a global approach to CWR prioritization is clear. Crop wild relative populations contain valuable traits for adapting crops to meet the needs of the increasing human population under the pressure of a rapidly changing climate. They are a reservoir of genetic diversity adapted to a wide range of environmental conditions that plant breeders are increasingly likely to need to create new varieties able to cope under the duress of exceptional and uncertain abiotic conditions, as well as for adaptation to future biotic stresses (Zamir, 2001; Vollbrecht and Sigmon, 2005; FAO, 2008, 2010, 2012; Ford-Lloyd et al., 2011; Guarino and Lobell, 2011; Kell et al., 2012b; Maxted et al., 2012). The production of new crop varieties has been highlighted by the Intergovernmental Panel on Climate Change (IPCC) as a critical intervention to mitigate the impacts of climate change (e.g., see Easterling et al., 2007; Tao and Zhang, 2010; Challinor et al., 2014; Noble et al., 2014)—therefore, to underpin global food security, CWR require systematic conservation action (Maxted et al., 2008, 2012, 2015, 2016; Maxted and Kell, 2009; McCouch et al., 2013; Vincent et al., 2013; Dempewolf et al., 2014).

In a study commissioned by the FAO Commission on Genetic Resources for Food and Agriculture (CGRFA), Maxted and Kell (2009) initiated research on CWR of 14 globally important food crops reported by FAO (1997) to supply >5% of the plant-derived energy intake in one or more subregions of the world, as a starting point for the establishment of a global network of CWR genetic reserves. For each crop, the global, regional, and local importance was elaborated, genepool classifications defined, distribution and center of diversity outlined, known or potential uses of their CWR reviewed, and recommendations put forward for the conservation of the highest priority species based on their utilization potential and relative threat status.

Following the work of Maxted and Kell (2009), Vincent et al. (2013) produced the Harlan and de Wet CWR Inventory (www.cwrdiversity.org/checklist), which contains information on the GP, TG, or Provisional GP concepts and known actual or potential use of species related to 173 food crops. Global priority crops for inclusion in the Inventory were identified as those listed in Annex I of the International Treaty on PGRFA, combined with the major and minor food crops listed by Groombridge and Jenkins (2002). In addition, after identifying the genera encompassing the genepools of these crops, because many of the genera contain multiple crop species, Vincent et al. (2013) consulted Manfeld's World Database of Agricultural and Horticultural Crops (Hanelt and IPK, 2001) to ensure that all crop species within these genera were included. Following the methodology of Maxted and Kell (2009), the priority wild relatives of the 173 food crops were identified as those in GPs (or Provisional GPs) 1b and 2 or TGs 1b, 2, and 3 (CWR within the same subgenus as the crop) and more distantly related taxa that are documented to have been previously used for crop improvement or that have shown promise for crop improvement, resulting in a global priority list of CWR comprising 1392 species (Vincent et al., 2013).

The prioritization methodology of Vincent et al. (2013) served to identify priority CWR of a wide range of crops that are undoubtedly important for nutrition and food security in many parts of the world. However, in identifying native CWR diversity in China of global importance, Kell et al. (2015b) argued that the inclusion of wild relatives of crops listed in Annex I of the International Treaty on PGRFA would not only inflate the number of taxa in the list of priority CWR of China beyond a reasonable number to attract sufficient resources for their conservation, but that, because China is not signatory to the International Treaty on PGRFA, basing the selection of priority CWR on this legal instrument was not appropriate and would be difficult to justify to the relevant national authorities. Taking the lead from FAO

(1997), the authors proposed a shortlist of 20 crops (or crop groups, such as millets) "of particular global importance in terms of their direct contribution to food security on the premise that they provide 3% or more of plant-derived dietary energy supply in one or more subregions" (Kell et al., 2015b, p. 147). A counter argument to prioritizing this subset of food crops is that it is limited only to those crops that contribute the most calories to human diets and does not take account of the nutritional needs of the human population, particularly bearing in mind that six are oil crops (cottonseed, *Gossypium hirsutum* L., mustard, palm, *Elaeis guineensis* Jacq., olive, rape, *Brassica napus* L., and sunflower), which have limited nutritional value. However, global statistics on the nutritional value of food crops are not currently available to prioritize them objectively for their nutritional qualities, and as the authors note, "regardless of their place in our diet and of their contribution to health and nutrition, they are clearly crops of modern global socioeconomic importance" (Kell et al., 2015b, p. 147). In addition, taking a global holistic approach to CWR conservation by integrating national and regional strategies with a global strategy, CWR prioritization at the national and regional levels will most likely capture wild relatives of a broad range of crops, including minor crops of particular nutritional value at the national and subregional levels. In conclusion, while the Harlan and de Wet CWR Inventory is a highly valuable and comprehensive source of information on global food CWR diversity, its universal use in establishing conservation priorities for CWR taxa should not be taken for granted. Rather, practitioners should use it selectively as a resource for CWR prioritization based on clearly defined objective criteria.

CONCLUSIONS

To effectively conserve CWR diversity for its actual and potential use, there is an urgent need for comprehensive and systematic CWR conservation strategies to be implemented worldwide, integrating national, regional, and global approaches to maximize conservation of the full range of important CWR genetic resources. Taxon prioritization is a fundamental step in conservation planning, and with the vast number of CWR taxa that exist, a harmonized, logical, and pragmatic means of assigning priority status is needed that can be applied nationally, regionally, and globally as part of a holistic global CWR conservation strategy. In this paper, we have presented an approach based on three main criteria and reviewed their practical application at the national, regional, and global scales to highlight the strengths and commonalities of this approach, as well as to untangle some common misconceptions when applying CWR prioritization criteria. Based on experience in and knowledge of CWR prioritization practice over recent years, and particularly on the results of the analysis presented in Table 1, we reiterate the three criteria here with greater clarity regarding the potential subcriteria that are frequently used in the prioritization process to provide clearer guidance on their application in the future (Table 2). While acknowledging that the precise method chosen depends on several factors and that there is no one definitive way of undertaking CWR prioritization, we recommend that practitioners consider the approach presented in Fig. 1. It is logical and relatively simple to apply, both at the national and regional levels, and reduces the potential for introducing unintentional bias in the selection of priority CWR taxa for conservation action, particularly towards relative threat status over the potential value of taxa for the improvement of socioeconomically valuable crops.

Conflict of Interest

We, the authors, declare that we have no conflicts of interest.

Table 2. The three main crop wild relative prioritization criteria defined and associated subcriteria that have been applied by different countries.

Main criterion	Associated subcriteria
1 The socioeconomic value of crops	1. Stakeholder priorities (e.g., plant breeders and researchers) 2. Crops listed in Annex I of the International Treaty on Plant Genetic Resources for Food and Agriculture 3. Multiple or combined value
2 The potential value of the wild relatives of socioeconomically valuable crops for variety improvement	1. Stakeholder priorities (e.g., plant breeders and researchers) 2. Multiple or combined value
3 The threat status of the wild relatives of socioeconomically valuable crops	1. Relative distribution 2. Endemic status (national and regional) 3. Geographical or regional responsibility for certain taxa with restricted worldwide distribution 4. Rarity of the habitat in which the species grow 5. Relative abundance 6. Status in surrounding countries 7. Degree of genetic erosion 8. Species listed in the annexes of the EU Habitats Directive 9. National protection status 10. Expected effects of climate change on distribution

References

Bilz, M., S.P. Kell, N. Maxted, and R.V. Lansdown. 2011. European red list of vascular plants. Publ. Off. of the EU, Luxembourg. doi:10.2779/8515

Bradshaw, J.E., G.J. Bryan, and G. Ramsay. 2006. Genetic resources (including wild and cultivated *Solanum* species) and progress in their utilization in potato breeding. Potato Res. 49:49–65. doi:10.1007/s11540-006-9002-5

Branca, F., and D. Donnini. 2011. *Medicago pironae*. The IUCN red list of threatened species 2011: E.T176605A7275063. IUCN, Cambridge, UK. doi:10.2305/IUCN.UK.2011-1.RLTS.T176605A7275063.en

Challinor, A.J., J. Watson, D.B. Lobell, S.M. Howden, D.R. Smith, and N. Chhetri. 2014. A meta-analysis of crop yield under climate change and adaptation. Nat. Clim. Change 4:287–291. doi:10.1038/nclimate2153

Dempewolf, H., R.J. Eastwood, L. Guarino, C.K. Khoury, J.V. Müller, and J. Toll. 2014. Adapting agriculture to climate change: A global initiative to collect, conserve, and use crop wild relatives. Agroecol. Sustainable Food Syst. 38:369–377. doi:10.1080/21683565.2013.870629

Easterling, W.E., P.K. Aggarwal, P. Batima, K.M. Brander, L. Erda, S.M. Howden et al. 2007. Food, fibre and forest products. In: M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, editors, Climate change: Impacts, adaptation and vulnerability. Contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, Cambridge, UK. p. 273–313. www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4_wg2_full_report.pdf (accessed 10 Oct. 2016).

EU. 1998–2016. Council directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. EU. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31992L0043 (accessed 10 Oct. 2016).

FAO. 1997. The state of the world's plant genetic resources for food and agriculture. FAO, Rome. www.fao.org/agriculture/crops/thematic-sitemap/theme/seeds-pgr/sow/en/ (accessed 11 Apr. 2017).

FAO. 2001. International treaty on plant genetic resources for food and agriculture. FAO, Rome. www.fao.org/plant-treaty/en/ (accessed 10 Oct. 2016).

FAO. 2008. Climate change and biodiversity for food and agriculture. FAO, Rome. www.fao.org/uploads/media/FAO_2008a_climate_change_and_biodiversity_02.pdf (accessed 10 Oct. 2016).

FAO. 2010. The second report on the state of the world's plant genetic resources for food and agriculture. FAO Commission on Genetic Resources for Food and Agriculture, Rome. www.fao.org/docrep/013/i1500e/i1500e00.htm (accessed 10 Oct. 2016).

FAO. 2012. Second global plan of action on plant genetic resources for food and agriculture. FAO Commission on Genetic Resources for Food and Agriculture, Rome. www.fao.org/docrep/015/i2624e/i2624e00.htm (accessed 10 Oct. 2016).

Fitzgerald, H. 2016. Development of a common Nordic CWR conservation action plan: Goals and progress. In: Proceedings of the Nordic/ECPGR Workshop, Plant genetic resources for food security and ecosystem services: Planning and implementing national and regional conservation strategies—CWR conservation strategies, Vilnius, Lithuania. 19–21 Sept. 2016. NordGen, Alnarp, Sweden.

Ford-Lloyd, B., and N. Maxted. 1993. Preserving diversity. Nature 361:579. doi:10.1038/361579a0

Ford-Lloyd, B.V., J.M.M. Engels, and M. Jackson. 2014. Genetic resources conservation challenges under the threat of climate change. In: M. Jackson, B. Ford-Lloyd, and M. Parry, editors, Plant genetic resources and climate change. CAB Int., Wallingford, UK. p. 16–37.

Ford-Lloyd, B.V., N. Maxted, and S.P. Kell. 2008. Establishing conservation priorities for crop wild relatives. In: N. Maxted, B.V. Ford-Lloyd, S.P. Kell, J. Iriondo, E. Dulloo, and J. Turok, editors, Crop wild relative conservation and use. CAB Int., Wallingford, UK. p. 110–119.

Ford-Lloyd, B.V., N. Maxted, and S. Kell. 2009. Prioritization of wild *Beta* species for conservation: The PGR Forum experience. In: L. Frese and L. Maggioni, editors, Report of a Working Group on *Beta* and World Beta Network, Third Joint Meeting, Puerto de la Cruz, Tenerife, Spain. 8–11 Mar. 2009. European Cooperative Programme for Plant Genetic Resources (ECPGR), Bioversity Int., Rome. p. 27–30.

Ford-Lloyd, B.V., M. Schmidt, S.J. Armstrong, O. Barazani, J. Engels, R. Hadas et al. 2011. Crop wild relatives: Undervalued underutilized, and under threat? Bioscience 61:559–565. doi:10.1525/bio.2011.61.7.10

Groombridge, B., and M.D. Jenkins. 2002. World atlas of biodiversity. Prepared by the UNEP World Conservation Monitoring Centre. Univ. of California Press, Berkeley, CA.

Guarino, L., and D.B. Lobell. 2011. A walk on the wild side. Nat. Clim. Change 1:374–375. doi:10.1038/nclimate1272

Hajjar, R., and T. Hodgkin. 2007. The use of wild relatives in crop improvement: A survey of developments over the last 20 years. Euphytica 156:1–13. doi:10.1007/s10681-007-9363-0

Hanelt, P., and IPK (Institut für Pflanzengenetik und Kulturpflanzenforschung Gatersleben), editors. 2001. Mansfeld's encyclopedia of agricultural and horticultural crops. 1st English ed. Springer, Berlin, Heidelberg, New York.

Harlan, J.R., and J.M.J. de Wet. 1971. Towards a rational classification of cultivated plants. Taxon 20:509–517. doi:10.2307/1218252

Heywood, V.H., and M.E. Dulloo. 2005. In situ conservation of wild plant species: A critical global overview of good practices. Tech. Bull. 11. IPGRI. www.bioversityinternational.org/fileadmin/user_upload/online_library/publications/pdfs/1092.pdf (accessed 10 Oct. 2016).

Hoyt, E. 1988. Conserving the wild relatives of crops. IBPGR, IUCN, WWF, Rome and Gland, Switzerland.

Hunter, D., and V. Heywood, editors. 2011. Crop wild relatives: A manual for in situ conservation. Bioversity Int. www.cropwildrelatives.org/fileadmin/templates/cropwildrelatives.org/upload/In_situ_Manual/Crop-wild-relatives-a-manual-of-In-situ-conservation-full.pdf (accessed 10 Oct. 2016).

Iriondo, J.M., M.E. Dulloo, N. Maxted, E. Laguna, J.M.M. Engels, and L. Maggioni. 2008. Final considerations for the in situ conservation of plant genetic diversity. In: J.M. Iriondo, N. Maxted, and M.E. Dulloo, editors, Conserving plant genetic diversity in protected areas. CAB Int., Wallingford, UK. p. 182–202. doi:10.1079/9781845932824.0182

Iriondo, J.M., S. Kell, H. Fitzgerald, V. Negri, J. Magos Brehm, and N. Maxted. 2016. National strategies for the conservation of crop wild relatives. In: N. Maxted, B.V. Ford-Lloyd, and M.E. Dulloo, editors, Enhancing crop genepool use: Capturing wild relative and landrace diversity for crop improvement. CAB Int., Wallingford, UK. p. 161–171. doi:10.1079/9781780646138.0161

IUCN. 2012a. IUCN red list categories and criteria. Version 3.1. 2nd ed. IUCN, Gland, Switzerland, and Cambridge, UK.

IUCN. 2012b. Guidelines for application of IUCN red list criteria at regional and national levels. Version 4.0. IUCN, Gland, Switzerland, and Cambridge, UK.

Kell, S., E. Allen, M.E. Dulloo, H. Gaisberger, J. Magos Brehm, N. Maxted, and I. Thormann. 2015a. CWR diversity in the SADC region: Development of an integrated conservation strategy. In: Proceedings of the Mid-Term Review Meeting: In situ conservation and use of crop wild relatives of the three ACP countries of the SADC region, Rome, Italy. 30 Sept.–2 Oct. 2015. Bioversity Int., Rome.

Kell, S., H. Qin, B. Chen, B.V. Ford-Lloyd, W. Wei, D. Kang, and N. Maxted. 2015b. China's crop wild relatives: Diversity for agriculture and food security. Agric. Ecosyst. Environ. 209:138–154. doi:10.1016/j.agee.2015.02.012

Kell, S.P., B.V. Ford-Lloyd, and N. Maxted. 2014. Europe's crop wild relative diversity: From conservation planning to conservation action. In: N. Maxted, M.E. Dulloo, and B.V. Ford-Lloyd, editors, Enhanced genepool use: Capturing wild relative and landrace diversity for crop improvement. CAB Int., Wallingford, UK. p. 125–136. doi:10.1079/9781780646138.0125

Kell, S.P., H. Knüpffer, S.L. Jury, N. Maxted, and B.V. Ford-Lloyd. 2005. Catalogue of crop wild relatives for Europe and the Mediterranean. CD-ROM. Univ. of Birmingham, Birmingham, UK.

Kell, S.P., N. Maxted, and M. Bilz. 2012a. European crop wild relative threat assessment: Knowledge gained and lessons learnt. In: N. Maxted, M.E. Dulloo, B.V. Ford-Lloyd, L. Frese, J.M. Iriondo, and M.A.A. Pinheiro de Carvalho, editors, Agrobiodiversity conservation: Securing the diversity of crop wild relatives and landraces. CAB Int., Wallingford, UK. p. 218-242.

Kell, S.P., N. Maxted, L. Frese, and J.M. Iriondo. 2012b. In situ conservation of crop wild relatives: A strategy for identifying priority genetic reserve sites. In: N. Maxted, M.E. Dulloo, B.V. Ford-Lloyd, L. Frese, J.M. Iriondo, and M.A.A. Pinheiro de Carvalho, editors, Agrobiodiversity conservation: Securing the diversity of crop wild relatives and landraces. CAB Int., Wallingford, UK. p. 7-19.

Labokas, J. 2016. Assessment of the current status of CWR conservation strategies based on questionnaire data. In: Proceedings of the Nordic/ECPGR Workshop, Plant genetic resources for food security and ecosystem services: Planning and implementing national and regional conservation strategies—CWR conservation strategies, Vilnius, Lithuania. 19–21 Sept. 2016. NordGen, Alnarp, Sweden.

Magos Brehm, J., N. Maxted, M.A. Martins-Loução, and B.V. Ford-Lloyd. 2010. New approaches for establishing conservation priorities for socio-economically important plant species. Biodiv. Conserv. 19:2715–2740.

Magos Brehm, J., S. Saifan, H. Taifour, K. Abu Laila, A. Al-Assaf, A. Al-Oqlah et al. 2016. Crop wild relatives, a priority in Jordan? Developing a national strategy for the conservation of plant diversity in Jordan using a participatory approach. In: N. Maxted, B.V. Ford-Lloyd, and M.E. Dulloo, editors, Enhancing crop genepool use: Capturing wild relative and landrace diversity for crop improvement, CAB Int., Wallingford, UK. p. 172–188.

Martín, A., and A. Cabrera. 2005. Cytogenetics of *Hordeum chilense*: Current status and considerations with reference to breeding. Cytogenet. Genome Res. 109:378–384. doi:10.1159/000082423

Maxted, N., A. Amri, N.P. Castañeda-Álvarez, S. Dias, M.E. Dulloo, H. Fielder et al. 2016. Joining up the dots: A systematic perspective of crop wild relative conservation and use. In: N. Maxted, B.V. Ford-Lloyd, and M.E. Dulloo, editors, Enhancing crop genepool use: Capturing wild relative and landrace diversity for crop improvement. CAB Int., Wallingford, UK. p. 87–124. doi:10.1079/9781780646138.0087

Maxted, N., A. Avagyan, L. Frese, J.M. Iriondo, J. Magos Brehm, A. Singer, and S.P. Kell. 2015. ECPGR concept for in situ conservation of crop wild relatives in Europe. Wild Species Conservation in Genetic Reserves Working Group, European Cooperative Programme for Plant Genetic Resources. www.ecpgr.cgiar.org/fileadmin/templates/ecpgr.org/upload/WG_UPLOADS_PHASE_IX/WILD_SPECIES/Concept_for_in__situ_conservation_of_CWR_in_Europe.pdf (accessed 10 Oct. 2016).

Maxted, N., B.V. Ford-Lloyd, and J.G. Hawkes, editors. 1997a. Plant genetic conservation: The in situ approach. Chapman and Hall, London. doi:10.1007/978-94-009-1437-7

Maxted, N., B.V. Ford-Lloyd, S.L. Jury, S.P. Kell, and M.A. Scholten. 2006. Towards a definition of a crop wild relative. Biodiv. Conserv. 15:2673–2685.

Maxted, N., B.V. Ford-Lloyd, and S.P. Kell. 2008. Crop wild relatives: Establishing the context. In: N. Maxted, B.V. Ford-Lloyd, S.P. Kell, J. Iriondo, E. Dulloo, and J. Turok, editors, Crop wild relative conservation and use. CAB Int., Wallingford, UK. p. 3–30.

Maxted, N., J.G. Hawkes, L. Guarino, and M. Sawkins. 1997b. The selection of taxa for plant genetic conservation. Genet. Resour. Crop Evol. 44:337–348. doi:10.1023/A:1008643206054

Maxted, N., P. Mabuza-Dlamini, H. Moss, S. Padulosi, A. Jarvis, and L. Guarino. 2004. An ecogeographic survey: African *Vigna*. Systematic and ecogeographic studies of crop genepools 10. IPGRI, Rome, Italy.

Maxted, N., and S.P. Kell. 2009. Establishment of a global network for the in situ conservation of crop wild relatives: Status and needs. FAO Commission on Genetic Resources for Food and Agriculture. www.fao.org/docrep/013/i1500e/i1500e18d.pdf (accessed 10 Oct. 2016).

Maxted, N., S.P. Kell, B.V. Ford-Lloyd, M.E. Dulloo, and A. Toledo. 2012. Toward the systematic conservation of global crop wild relative diversity. Crop Sci. 52(2):774–785. doi:10.2135/cropsci2011.08.0415

Maxted, N., S. Kell, and J. Magos Brehm. 2014. Crop wild relatives and climate change. In: M. Jackson, B. Ford-Lloyd, and M. Parry, editors, Plant genetic resources and climate change. CAB Int., Wallingford, UK. p. 114–136.

Maxted, N., J. Magos Brehm, and S.P. Kell. 2013. Resource book for preparation of national conservation plans for crop wild relatives and landraces. FAO Commission on Genetic Resources for Food and Agriculture. www.fao.org/fileadmin/templates/agphome/documents/PGR/PubPGR/ResourceBook/TEXT_ALL_2511.pdf (accessed 10 Oct. 2016).

McCouch, S., G.J. Baute, J. Bradeen, P. Bramel, P.K. Bretting, E. Buckler et al. 2013. Feeding the future. Nature 499:23–24. doi:10.1038/499023a

Meilleur, B.A., and T. Hodgkin. 2004. In situ conservation of crop wild relatives. Biodiv. Conserv. 13:663–684.

Noble, I., S. Huq, Y. Anokhin, J. Carmin, D. Goudou, F.P. Lansigan, B. Osman-Elasha, and A. Villamizar. 2014. Adaptation needs and options. In: C.B. Field et al., editors, Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, Cambridge, UK, and New York. p. 833–868. www.ipcc.ch/report/ar5/wg2/ (accessed 11 Apr. 2017).

Prescott-Allen, R., and C. Prescott Allen. 1986. The first resource: Wild species in the North American economy. Yale Univ., New Haven, CT.

Santos Guerra, A., D. Draper Munt, J. Magos Brehm, M.C. Duarte, M. Tavares, and M. Carvalho. 2011a. *Allium schmitzii*. The IUCN red List of threatened species 2011: E.T172153A6838008. http://dx.doi.org/10.2305/IUCN.UK.2011-1.RLTS.T172153A6838008.en. (accessed 10 Oct. 2016).

Santos Guerra, A., D. Draper Munt, J. Magos Brehm, M.C. Duarte, M. Tavares, and M. Carvalho. 2011b. *Asparagus nesiotes*. The IUCN Red List of Threatened Species 2011: E.T176453A7245005. IUCN, Cambridge, UK. doi:10.2305/IUCN.UK.2011-1.RLTS.T176453A7245005.en

Strajeru, S. and V. Stevanović. 2011. *Barbarea lepuznica*. The IUCN red list of threatened species 2011: E.T176458A7245936. IUCN, Cambridge, UK. doi:10.2305/IUCN.UK.2011-1.RLTS.T176458A7245936.en

Tao, F., and Z. Zhang. 2010. Impacts of climate change as a function of global mean temperature: Maize productivity and water use in China. Clim. Change 10:409–432.

UN. 1992. Convention on biological diversity. UN. www.cbd.int/doc/legal/cbd-en.pdf (accessed 10 Oct. 2016).

USDA, ARS, GRIN. 2017. Germplasm Resources Information Network [online]. United States Department of Agriculture, Agricultural Research Service, Beltsville, MD. http://www.ars-grin.gov/ (accessed 11 Apr. 2017).

Vincent, H., J. Wiersema, S. Dobbie, S. Kell, H. Fielder, N. Castenada et al. 2013. A prioritized crop wild relative inventory to help underpin global food security. Biol. Conserv. 167:265–275. doi:10.1016/j.biocon.2013.08.011

Vollbrecht, E., and B. Sigmon. 2005. Amazing grass: Developmental genetics of maize domestication. Biochem. Soc. Trans. 33:1502–1506. doi:10.1042/BST0331502

WCMC, editor. 1995. Plant occurrence and status scheme: A standard for recording the relationship between a plant and a place. An international working group on taxonomic databases standard. World Conserv. Monit. Centre. https://github.com/tdwg/prior-standards/tree/master/poss (accessed 8 Oct. 2016).

Wiersema, J.H., and B. León. 2013. World economic plants: a standard reference, second edition. CRC Press, Boca Raton, FL.

Zamir, D. 2001. Improving plant breeding with exotic genetic libraries. Nat. Rev. Genet. 2:983–989. doi:10.1038/35103590