Received: 1 March 2022 | Accepted: 15 June 2022 | Published online: 12 October 2022

DOI: 10.1002/csc2.20807

Crop Science

ORIGINAL RESEARCH ARTICLE

Plant Genetic Resources

An inventory of crop wild relatives and wild-utilized plants in Canada

Jens C. Ulrich[1] | **Tara L. Moreau**[2] | **Erika Luna-Perez**[3] | **Kephra I. S. Beckett**[4] | **Lili K. Simon**[4] | **Zoë Migicovsky**[5,9] | **Axel Diederichsen**[6] | **Colin K. Khoury**[7,8]

[1]Dep. of Applied Biology, Faculty of Land and Food Systems, Univ. of British Columbia, Vancouver, BC, Canada

[2]Univ. of British Columbia Botanical Garden, 6804 SW Marine Drive, Vancouver, BC V6T 1Z4, Canada

[3]Institute for Resources, Environment and Sustainability, Faculty of Science, Univ. of British Columbia, Vancouver, BC, Canada

[4]Dep. of Forest and Conservation Sciences, Faculty of Forestry, Univ. of British Columbia, Vancouver, BC, Canada

[5]Dep. of Plant, Food and Environmental Sciences, Faculty of Agriculture, Dalhousie Univ., Truro, NS, Canada

[6]Plant Gene Resources of Canada, Agriculture and Agri-Food Canada, 107 Science Place, Saskatoon, SK S7N 0X2, Canada

[7]San Diego Botanic Garden, 300 Quail Gardens Dr., Encinitas, CA 92024, USA

[8]International Center for Tropical Agriculture (CIAT), Km 17, Recta Cali-Palmira, Apartado Aéreo 6713, Cali 763537, Colombia

[9]Current address: Dep. of Biology, Acadia Univ., Wolfville, NS B4P 2R6, Canada

Correspondence

Jens C. Ulrich, Dep. of Applied Biology, Faculty of Land and Food Systems, Univ. of British Columbia, Vancouver, BC, Canada.
Email: jensj27@mail.ubc.ca

Assigned to Associate Editor Ali Missaoui.

Funding information

National Science Foundation, Grant/Award Number: Plant Genome Research Program 1546869; Natural Sciences and Engineering Research Council of Canada, Grant/Award Numbers: RGPIN-2017-04648, RGPIN-2018-04893; University of British Columbia, Sustainable Communities Field School; National Institute of Food and Agriculture, Grant/Award Numbers: 2019-67012-29733, project accession no. 1019405

Abstract

In the face of global pressures of change and biodiversity loss, crop wild relatives (CWR) and wild-utilized species (WUS) urgently require conservation attention. To advance conservation, we assembled a national inventory of CWR and WUS in Canada. To assess current ex situ conservation of these plant species, we gathered a virtual metacollection of accession data from botanical gardens and national genebanks. The inventory includes 779 CWR and WUS taxa (658 distinct species), with 263 (222 distinct species) that are related to food crops of national and global importance such as blueberry (*Vaccinium corymbosum* L.), apple (*Malus domestica* (Suckow) Borkh.), sunflower (*Helianthus annuus* L.), and saskatoon (*Amelanchier* spp.). Sixty-one food crop relatives are prioritized for breeding potential, and sixteen due to conservation threats. Although most food crop CWR are represented in ex situ collections (91% of species), representation of within-species diversity is low (median = 5% of Canadian ecogeographic types represented per species). Poor representation of within-species diversity demands an integrative conservation

Abbreviations: COSEWIC, Committee on the Status of Endangered Wildlife in Canada; CWR, crop wild relatives; *exGCS*, within-species ex situ genetic diversity conservation score, calculated using geographic diversity of populations in ex situ conservation systems as a proxy for genetic diversity; GBIF, Global Biodiversity Information Facility; GRIN, Germplasm Resources Information Network Global Database; NPGS, National Plant Germplasm System, USDA-ARS; PGRC, Plant Gene Resources of Canada, Agriculture and Agri-Food Canada; VASCAN, Database of Vascular Plants of Canada; WUS, wild-utilized species.

strategy that emphasizes in situ protection, especially focusing on wild populations in Canada's southern ecoregions where diversity is concentrated. While genebank collections represent higher accession counts per species, botanical gardens include living collections of fruit crop relatives and other woody perennials that are well situated to raise broader awareness of CWR and WUS. To promote further conservation action, we present a web application that enables conservation planners and practitioners to identify local CWR and WUS and to identify within-species ecogeographic types that are underrepresented in ex situ conservation systems.

1 | INTRODUCTION

To ensure food security, crop production must adapt to global pressures of change including a growing global population (Khoury et al., 2014; Tilman et al., 2011), pests and diseases (Bebber et al., 2014; Cannon, 1998; Helfer, 2014), and intensifying frequency and magnitude of extreme weather (Qian et al., 2018; Schmidhuber & Tubiello, 2007; Smith et al., 2013; Tito et al., 2018).

Plants that are close relatives of crops (i.e., crop wild relatives or CWR) have the potential to adapt crop production to these challenges (Vavilov, 1926). Through processes including domestication, natural hybridization, and targeted plant breeding, CWR have been part of the evolution of crops from prehistoric to modern times (Bremer, 1961; Hajjar & Hodgkin, 2007; Harlan, 1993; Hufford et al., 2012; Vavilov, 1926). Through traditional and new techniques, plant breeders have used CWR to introduce traits linked to crop productivity and nutrition, as well as resistance to pests, disease, heat, cold, waterlogging, drought, salinity, and soil pH conditions (Dempewolf et al., 2017; Hajjar & Hodgkin, 2007; Khoury et al., 2013; Plucknett et al., 1987; USDA-ARS, 2021; Vincent et al., 2013). Introduction of beneficial traits is well documented for many crop plants, including several of major global importance such as maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), sunflower (*Helianthus annuus* L.), and tomato (*Lycopersicon esculentum* Mill.) (Hake & Richardson, 2019; McCallum et al., 2007; Prescott-Allen & Prescott-Allen, 1986; Rick & Chetelat, 1995; Seiler et al., 2017). The CWR are also utilized directly as rootstock for grafting, thereby providing perennial, cultivated plants with potential resistance or tolerance to pests, pathogens, and novel environments (Ollat et al., 2014; Warschefsky et al., 2016).

To ensure the availability of these important genetic resources for crop breeding, CWR require urgent conservation attention. Globally, ~40% of wild plant species including many CWR are threatened by extinction (Goettsch et al., 2021; IPBES, 2019; Jarvis et al., 2008; Kew, 2016; Khoury et al., 2020). Thirty-three studies have examined genetic diversity of CWR wild populations, and of these, more than 90% have documented and/or predict future loss of within-species genetic diversity (Khoury et al., 2022). Extinction of CWR will encompass the loss of genetic variation that may be invaluable for future crop improvements.

Although previous efforts have identified Canadian CWR (Davidson, 1995) and have reviewed the economic importance of rare Canadian plants (Catling & Porebski, 1998), Canada currently lacks a comprehensive national CWR inventory. An updated Canadian CWR inventory will advance CWR conservation by filling gaps in our knowledge of CWR taxonomy, geographic distribution, and conservation status (Diederichsen & Schellenberg, 2018; Mace, 2004; Maxted et al., 2007). This work complements CWR inventories developed in the United States and Mexico (Contreras-Toldeo et al., 2018; Khoury et al., 2013; Khoury et al., 2020) and will facilitate efforts to advance the Road Map for Conservation, Use, and Public Engagement around North America's Crop Wild Relatives and Wild Utilized Plants which aims to align and accelerate the development of continental-wide policy, plans, and conservation actions (Khoury et al., 2019). Further, the development of a national CWR inventory aligns with global policy goals shared by the Convention on Biological Diversity, the International Treaty on Plant Genetic Resources for Food and Agriculture, and the U.N. Sustainable Development Goals Target 2.5 (AAFC, 2020; CBD, 2020; UN, 2022).

In addition to CWR, wild-utilized species (WUS) – plants that are harvested and utilized or consumed directly by humans – are vital components of livelihoods and diets (Heywood, 1999; Kuhnlein & Turner, 2020; Vavilov, 1926). Including WUS in a national inventory of plant genetic resources recognizes that many plants not directly used in agricultural production systems provide critical food security, income sources, and cultural value, especially in Indigenous food systems and/or in rural communities (Heywood, 1999; Kuhnlein & Turner, 2020). Many WUS are especially important as sources of medicine, both in Indigenous communities (Arnason et al., 1981; Kuhnlein & Turner, 2020) and more widely for potential use in pharmacology (e.g., taxol production from yew [*Taxus* spp.], Fett-Neto et al., 1992). The

CWR and WUS definitions are not mutually exclusive; many CWR are wild-harvested and used directly, including many berry fruits native to Canada (Davidson, 1995; Kuhnlein & Turner, 2020; Small, 2013; Weber, 2021). Conservation of WUS genetic resources provides the basis to safeguard their diversity and the opportunity to adapt to pressures such as climate change (Heywood, 1999; Khoury et al., 2019).

Effective conservation of CWR and WUS requires an integrated strategy including both ex situ and in situ actions (Fu, 2017; Diederichsen & Schellenberg, 2018; Khoury et al., 2019; Maxted & Kell, 2009; Maxted et al., 2012). Ex situ conservation includes protection of genetic diversity in germplasm collections (CBD, 2005). In situ conservation includes the maintenance and recovery of viable populations of species and the genetic diversity contained within these populations in their natural surroundings (CBD, 2005).

Currently, the key centers for ex situ conservation of plant genetic resources are national genebanks. In Canada, this includes the Canadian National Plant Germplasm System (CNPGS) with three genebanks: Plant Gene Resources of Canada (PGRC), Canadian Clonal Genebank (CCGB), and Canadian Potato Gene Resources (CPGR) (AAFC, 2022). In the United States, the genebanks of the USDA-ARS National Plant Germplasm System (NPGS) maintain plant genetic resources (Bretting, 2018; Engelmann & Engels, 2002; Fu, 2017). The main objective of these genebanks is to maintain plant genetic resources for food and agriculture as part of national and global strategies to ensure food security (AAFC, 2020; Byrne et al., 2018). Globally, more than 1,750 genebanks preserve about 7.4 million accessions of plant genetic resources for food and agriculture (FAO, 2010). Genebanks strive to conserve not only overall species diversity but also within-species genetic variation (Engelmann & Engels, 2002), and to share this diversity both domestically and internationally, thereby acting as the key link between plant genetic resources and plant breeding practitioners (Byrne et al., 2018).

The international network of botanical gardens includes >3,000 institutions that maintain collections of living plants (BGCI, 2021; Engelmann & Engels, 2002). These collections complement the conservation work of genebanks through scientific research and training, display and public outreach, and through preservation of germplasm or living specimens (Heywood, 2017; Maxted & Kell, 2013). Botanical gardens are increasingly showing support for plant genetic resource conservation and research through the collection of genetically diverse native plants, and so these institutions have a supportive role to play in acquiring, maintaining, and distributing CWR and WUS (Heywood, 2017; Khoury et al., 2019; Maxted & Kell, 2013; Meyer & Barton, 2019; Mounce et al., 2017). However, resources in botanical gardens remain to be sufficiently integrated with conservation efforts in genebanks (Khoury et al., 2019).

Core Ideas

- Canada contains a rich diversity of crop wild relatives and wild-utilized species, including many relatives of fruit crops.
- The 61 Canadian food crop wild relatives have high potential utility in crop breeding, and 17 are nationally imperiled.
- Living collections of woody-perennial crop wild relatives and wild-utilized species in botanical gardens complement ex situ conservation in genebanks.
- Conservation requires integrative strategy, with coordinated in situ action prioritizing Canada's southern regions.
- Display collections in gardens and new, online tools are situated to advance conservation by raising engagement.

Because ex situ conservation is costly and resources are limited (Clark et al., 1997; Fu, 2017), and because it does not allow continuous adaptation to environmental changes or other external pressures (Bellon et al., 2017), ex situ strategies alone cannot conserve the full breadth of within-species genetic diversity distributed among wild-populations of CWR and WUS (Maxted, 2013). Developing strategies that advance and support in situ conservation is therefore imperative for long-term conservation (Diederichsen & Schellenberg, 2018; Khoury et al., 2019; Maxted, 2013).

Inspired by the framework of the collaboratively created road map for conserving North America's CWR (Khoury et al., 2019), and in order to work towards a strategic and integrative approach for conservation and sustainable use for CWR and WUS in Canada as suggested by Diederichsen and Schellenberg (2018) we aimed to: (a) develop a comprehensive national inventory of Canadian CWR and WUS, containing prioritized species for monitoring and conservation; (b) identify strengths and gaps in conservation of genetic diversity of Canada's CWR and WUS in ex situ collections; (c) explore the potential for botanical gardens to support national genebank efforts as part of a national strategy for conserving Canada's CWR and WUS; and (d) create a web application tool to assist prioritization and planning of both ex situ and in situ conservation efforts and to promote public awareness of CWR and WUS importance and threats in Canada.

2 | MATERIALS AND METHODS

2.1 | Constructing a national inventory of Canada's crop wild relatives and wild-utilized species

We developed a current national inventory of Canadian CWR and WUS (Supplemental Table S1) by extracting and combining information from existing inventories of plant genetic resources. The construction of the inventory proceeded in six steps: (1) we obtained a list of all Canadian plant taxa included in the globally focused USDA-ARS NPGS – Germplasm Resources Information Network (GRIN) Global Database – Crop Wild Relative Data (hereafter, *GRIN*; USDA-ARS, 2021); (2) we added taxa listed by nationally focused treatments of economically important and WUS; (3) we identified Canadian WUS; (4) we used a national eFlora to identify and add any taxa from the genepools identified in steps 1 and 2 that were not included in the lists provided by sources used for steps 1 and 2; and (5) we prioritized species based on breeding utility and conservation threat status.

GRIN, the resource used to compile the initial list of Canadian CWR in step 1, contains a global inventory of CWR in the immediate genepools of globally important agricultural crops. Following the classification system of Harlan and de Wet (1971), the immediate genepool circumscribes all taxa in the same genus as a crop species. Taxa within this immediate genepool have potential utility in traditional plant breeding programs (Harlan & de Wet, 1971). Most or all CWR from the genepools of *GRIN*'s list of globally important agricultural crops are represented in the *GRIN* database, while taxon inclusion may not be fully representative for agricultural crop groups of lesser global importance (USDA-ARS, 2021). We filtered the database to obtain a list of all CWR taxa that occur in Canada as recognized by *GRIN*. *GRIN* considers phylogenetic and breeding trial data to designate within genepool genetic proximity distances between CWR and crop species. Thus, within genepools, taxa are assigned a categorical rank from closest to farthest genetic proximity, following the classification system of Harlan and de Wet (1971): progenitors/primary genepool, secondary genepool, and tertiary genepool (USDA-ARS, 2021; Wiersema, 2019; Wiersema et al., 2012). *GRIN* also provides information on grafstock utility. We retained genetic proximity and graftstock utility information for subsequent prioritization and analyses. This query of the *GRIN* database provided an initial list of 212 CWR taxa related to 61 different crop species.

In step 2, we aimed to increase the inclusion of CWR and WUS in our inventory, particularly of CWR from crop genepools that are not considered in the *GRIN* system, which emphasizes genepools of food crops of global importance (USDA-ARS, 2021). We added 372 plant taxa included in Davidson's (1995) list of Canadian wild-germplasm that were not returned from the *GRIN* query, including many forage and feed crops and their relatives, forest genetic resources, and agricultural food crops and their relatives from three crop genepools that are not recognized in *GRIN* but are of national importance in Canada: sugar maple (*Acer* spp.), saskatoon (*Amelanchier* spp.), and oil-seed flax (*Linum* spp.) (Gouvernement du Québec, 2002; Marchenkov & Rozhmina, 2003; St. Pierre, 1992). We included all additional forest genetic resources (19 taxa) that were not included by *GRIN* or Davidson (1995) that are listed in Canada's national forestry seed bank, the National Tree Seed Centre of Canada (Fredericton, NB), indicating economic importance of these taxa as forest genetic resources in Canada (NTSC, 2021).

To include WUS in this inventory (step 3), we consulted a recent treatment of food, medicinal, material, and spiritual plants that are wild-harvested in Canada (Kuhnlein & Turner, 2020). The 361 of the CWR taxa obtained from steps 1 and 2 are recognized as WUS. Kuhnlein and Turner (2020) do not include all 85 Canadian *Crataegus* taxa that are recognized in the Database of Vascular Plants of Canada eFlora (*VASCAN*; Brouillet et al., 2010) in their list of WUS. However, we scored all taxa in this genus as WUS because lack of consideration may be due to inconsistent taxonomical concepts (Dickinson et al., 2007). We also added all 168 native WUS in Kuhlein and Turner's (2020) list that are not in the immediate genepool of a crop species. Thus, 68% of WUS taxa in the inventory are simultaneously recognized as CWR, while the remaining 32% are not congeneric with crops.

Because CWR can be recognized as those plants within the same genus as a crop species (Harlan & de Wet, 1971; Maxted et al., 2006), comprehensive national CWR inventories include all taxa within all genera of crops of interest (Contreras-Toledo et al., 2018; Khoury et al., 2013). As step 4 of the inventory construction, we used the *VASCAN* eFlora (Brouillet et al., 2010) to confirm that the inventory includes all taxa from all genera identified through steps 1 and 2 that occur in Canada. Through this process we added 26 additional Canadian taxa, including taxa from the genera *Ribes*, *Lupinus*, and *Physalis* that are either not included in the *GRIN* CWR database or are not recognized by *GRIN* as occurring in Canada. Taxon names from all sources were validated using the *GRIN* taxonomy search tool (Wiersema, 2019). In cases where taxon names used by the *GRIN* taxonomy search differed from recently updated National Scientific Names used by NatureServe Canada and for the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) assessments (NatureServe, 2022), we use the National Scientific Names databases for our inventory and conservation assessment.

To prioritize CWR for conservation (step 5), we first grouped CWR into one or more of six different functional categories: (a) food crops, (b) forage and feed, (c) material, (c)

TABLE 1 Categorization scheme for describing crop wild relatives (CWR) diversity and for prioritizing taxa for conservation

Tier	Category	Subcategories	Breeding utility prioritization	Conservation prioritization
1	Food	Cereals and pseudocereals, fruits, herbs and spices, nuts, oils, pulses, sugars, vegetables	1A – progenitor/is the crop itself, or in the primary genepool, or used as graftstock	Nationally imperiled – N1 or N2 [a] rank assigned by NatureServe Canada and/or
			1B – secondary genepool	COSEWIC threat assessment of Special Concern, Threatened, or Endangered
			1C – tertiary genepool or unknown genetic relationship	
2	Forage and feed	na	na	Nationally imperiled – N1 or N2[a] rank assigned by NatureServe Canada and/or COSEWIC threat assessment of Special Concern, Threatened, or Endangered
	Material	na	na	
	Medicinal	na	na	
	Ornamental	na	na	
	Forest resources	na	na	

Note. WUS definitions are not mutually exclusive with CWR definitions, and wild-utilized plants (WUS) in the inventory overlap with Tier 1 and Tier 2 CWR groupings. WUS were not prioritized in their own right.
[a]N1 and N2 NatureServe rankings indicate taxa that are considered critically imperiled or imperiled in Canada.

medicinal, (d) ornamental, and (e) forest resources. Because food crops that are directly consumed by humans are directly relevant for food security, we nested all food crop CWR in a Tier 1 grouping (Table 1). All other CWR were nested in Tier 2 to distinguish these CWR from those of direct relevance for food security (Table 1). To explore patterns of CWR diversity and conservation at a finer scale we grouped food crops and their CWR (Tier 1 CWR) into eight subcategories: Cereals and Pseudocereals, Fruits, Herbs and Spices, Nuts, Oils, Pulses, Sugars, and Vegetables (Table 1).

Using taxon information obtained via *GRIN* in step 1, conservation prioritization scores were then assigned to Tier 1 CWR based on potential utility in breeding programs: 1A = progenitor/crop species itself, primary genepool, or utilized as graftstock; 1B = secondary genepool; 1C = tertiary genepool or relative of unknown genetic distance. Higher priority is given to closer relatives because these taxa are easier to utilize in traditional breeding programs (Maxted et al., 2006) (Table 1). Because we do not know the genetic proximity between CWR and their associated crops for taxa added from sources other than *GRIN*, we assume high genetic distance for these taxa and they were assigned to priority 1C. We did not distinguish taxon priorities based on economic values of associated crops because: (a) global demands for food crops may change unexpectedly over time and (b) we consider diversity of available food crops to be of value. We did not assign breeding utility prioritizations to Tier 2 CWR, because we were unable to obtain genetic proximities for most Tier 2 CWR, and because crop use in Tier 2 is more diffuse. For example, forestry programs utilize species groups, harvesting multiple species from the same genus rather than distinguishing between individual species (Government of Canada, 2006).

The value of different WUS varies through time and between different communities, being of primary food or cultural importance in one community but not utilized at all in another (Kuhnlein & Turner, 2020). As such, we did not rank WUS taxon priorities due to importance for direct use or for breeding utility.

Separate to breeding utility prioritization, we prioritized CWR and WUS taxa facing current conservation threats (Table 1). Through NatureServe Canada (NatureServe, 2022), we obtained NatureServe national conservation scores as well as COSEWIC listings. The COSEWIC assessments are a precursor to legal protection and more comprehensive than NatureServe assessments, however they have only been conducted for a subset of plant taxa (COSEWIC, 2021). Taxa that have not received COSEWIC assessments are not necessarily unthreatened, rather, they may not have been reviewed by a COSEWIC panel (Amie Enns and Anne Francis, personal communication, 2022). We prioritize CWR and WUS if they have received an N1 ("critically imperiled") or N2 ("imperiled") national NatureServe rank and/or have received a COSEWIC threat assessment of "Special Concern", "Threatened" or "Endangered" (Table 1).

2.2 | Data collection for conservation assessments

2.2.1 | Assembling an ex situ virtual metacollection

To assess the current ex situ conservation status of CWR and WUS in our national inventory, we created a virtual metacollection dataset (Griffith et al., 2020) of CWR and WUS accessions, drawing from national genebank institutions and key genebank partners in the neighboring U.S. genebank system, as well as from the national network of botanical gardens.

We retrieved data of all active plant accessions for all CWR and WUS in our inventory from Canada's National Plant Genetic Resources Network as listed on the centralized genebank information system GRIN-Global-CA hosted by PGRC (AAFC, 2021), Canada's national forestry seed bank - the National Tree Seed Centre of Canada (Fredericton, NB) (NTSC, 2021), and the University of Saskatchewan Prairie Fruit Genebank (Saskatoon, SK) (University of Saskatchewan, 2021) (Hereafter, these genebanks collectively will be referred to as "Canada's national ex situ PGR system"). Due to the overlap of plant species diversity between Canada and the United States, we also included accessions currently held in the USDA-ARS National Plant Germplasm System (Hereafter, "NPGS") (USDA-ARS, 2021) for our assessment of current ex situ conservation status of Canada's CWR and WUS. Accessions collected in Canada but conserved in other countries are not considered here. Reported statistics of accessions held in genebanks include accessions from Canada's national ex situ PGR system and the NPGS unless indicated otherwise.

To collect information from botanical gardens we directly requested provenance data from 32 Canadian botanical gardens for which contact information was available via Botanical Gardens Conservation International GardensSearch database (BGCI, 2021). We received collections data from 7 of the 32 gardens contacted: Montreal Botanic Garden (Montreal, QC), the University of Guelph Arboretum (Guelph, ON), the Royal Botanical Gardens (Burlington, ON), Mount Pleasant Cemetery Gardens (Toronto, ON), University of British Columbia Botanical Garden (Vancouver, BC), VanDusen Botanical Garden (Vancouver, BC), and Reader Rock Garden (Calgary, AB).

When latitude and longitude of origin for wild-collected accessions was not available, but locality was included with accession's provenance data (i.e., a township, park, or roadway intersection), we estimated the provenance geolocation. Latitude and longitude of origin was not available for most accessions in Canada's national ex situ PGR system (except for accessions from the National Tree Seed Centre of Canada) and so for these we estimated latitude and longitude using a normal distribution (standard deviation = 1 decimal degree) around the largest population center within the province of origin listed. When a single garden or repository had multiple accessions of the same taxon with the same provenance we considered these accessions as a single entity, because we expect that all plants under the listed accession reflect a narrow diversity of potential genetic resources.

2.2.2 | Identifying CWR and WUS geographic distributions

Geographic distributions of CWR and WUS were determined using occurrence data from the Global Biodiversity Information Facility (*GBIF*; GBIF.org, 2021). Using the "rgbif" package in R (Chamberlain & Boettiger, 2017), we requested occurrence data from within Canada including both herbarium records and human observations, which are validated by data providers prior to *GBIF* download (GBIF.org, 2021). Although many taxa occur more broadly in North America and/or globally (Khoury et al., 2013; Khoury et al., 2020), we focused on defining the range and the current ex situ conservation status at the national scale, within Canada, where the environmental conditions in Canada differ and may be associated with unique genetic adaptations. We created within-Canada, ecoregion-scale taxon distribution maps by conducting a spatial join between the occurrence data and North America's Level III Terrestrial Ecoregion map (USEPA, 2021) (using the "sf" package in R (Pebesma, 2018)). Ecoregions represent geographic areas delineated by climate, geology, physiography, and characteristic biodiversity patterns (Wright et al., 1998). We generated a second set of provincial taxon distribution maps by similarly joining the occurrence data to a provincial boundary shape file (Statistics Canada, 2011).

We trimmed the taxon distribution maps generated with GBIF data to reduce overestimation of geographic ranges, including removal of valid occurrence points in the *GBIF* dataset that do not represent established populations (e.g., cultivated specimens grown in controlled settings outside of their native range). We removed provinces from an occurrence range if the taxon was considered neither “native” nor “introduced but established” in the respective province according to the Flora of North America eFlora (FNA, 2021) or *VASCAN* (Brouillet et al., 2010) (Supplemental Table S2). We removed ecoregions from an occurrence range if the ecoregion was completely nested within removed provinces (Supplemental Table S3).

2.3 | Ex situ conservation assessment

We aimed to identify baseline ex situ conservation by exploring the representation of Canadian CWR in the virtual ex situ metacollection database that we constructed. First, we assessed the number of accessions in ex situ collections at the species taxonomic level. A species level focus was used for this assessment given inconsistent availability of infraspecific taxon designations in ex situ collections, and due to complex taxonomy even at the species level for some groups, such as those in *Rubus* and *Crataegus* (Dickinson et al., 2007).

To identify strengths and gaps in ex situ conservation for food crops and their relatives, we grouped and examined ex situ CWR conservation by genus (n = 32 genera with Canadian food crop CWR). Using the classification system of Harlan and de Wet (1971), crop species in the same genus share CWR taxa in their genepools. For example, CWR of highbush-blueberry (*Vaccinium corymbosum* L.) are also CWR of cranberry (*V. macrocarpon* Aiton). As such, we refer to and report conservation patterns for food crop genepools – genera that contain one or more crops with a shared pool of CWR. We determined the number of CWR species with or without one or more accessions held in ex situ collections as well as the median number of accessions per CWR species in the genus. In this first analysis, we included all accessions of Canadian CWR, regardless of whether or not they were wild collected from within Canada, to identify whether these taxa are conserved broadly, at the species level.

Because conservation status is assessed at the infraspecific taxonomic level (NatureServe, 2022), we also assigned infraspecific counts of Canadian wild-origin accessions where possible (that is, when infraspecific taxon identifications had been made by ex situ collections managers or when we could confidently assign them ourselves due to geographic isolation in Canada of all infraspecific taxa within species). We were able to assign infraspecific wild-origin accessions for all nationally imperiled CWR and for many other CWR and WUS with infraspecific taxonomic units in Canada, and indicate species for which we were unable to do so in the full inventory (Supplemental Table S1) and accessions summary table (Supplemental Table S4).

2.4 | Ecogeographic gap analyses

To identify ex situ conservation gaps in within-species genetic diversity, we used data on germplasm accessions collected from wild populations of plants in Canada. Using provenance data from accessions we calculated an ex situ genetic diversity conservation score for each CWR and WUS (hereafter, "*exGCS*"), again calculated at the species taxonomic level and again with median scores reported for food crop genepools with Canadian CWR (n = 32). Using geographic diversity as a proxy for genetic diversity (Hanson et al., 2017), scores for each species were calculated as (Equation 1):

$$\text{exGCS} = \frac{\text{number of ecoregions from which wild origin accessions collected (within Canada)}}{\text{number of ecoregions where a species occurs (within Canada)}} \quad (1)$$

Thus, exGCS represents the proportion of ecogeographic types conserved in ex situ conservation systems for each species.

To identify geographic regions where CWR and WUS diversity is concentrated and where conservation of plant genetic resources is underrepresented in ex situ systems, we explored the disparity between wild-collected origins of CWR and WUS in the assembled virtual metacollection vs. regional CWR and WUS species richness. First, we used the species distribution data collected above to calculate the CWR and WUS taxon richness in each ecogeographic region by summing the number of species that are native or naturalized in each region. To then determine representation of CWR and WUS in each ecogeographic region we (a) grouped accessions by ecoregion, and (b) divided the number of species with accessions from each ecoregion by the tally of species that occur in each ecoregion.

2.5 | Comparison of ex situ conservation in botanical gardens and genebanks

To explore differences between the CWR accessions currently held in botanical gardens vs. national genebanks, we compared the number of accessions for each CWR in botanical gardens vs. the genebanks within each of the eight food crop subcategories defined for our inventory (Table 1). Given the non-normal distribution of the number of accessions per CWR, we evaluated differences in the median (rather than mean) numbers of accessions per CWR within crop use category, using pairwise Wilcoxon Rank Sum tests (Mann & Whitney, 1947). We also compared pairwise-differences in the proportion of CWR with one or more accessions held in botanical gardens vs. genebanks (again within each of the eight food crop subcategories), using pairwise two-proportion z tests to evaluate the magnitude of differences.

2.6 | Developing a web application for crop wild relative conservation

Broad patterns in CWR and WUS distribution and conservation emerge from species and infraspecific level processes. To make this information accessible for any CWR or WUS of interest, we used the inventory and data provided by genebanks and gardens to develop a web application using R Shiny (Chang et al., 2021) that will enable users to visualize the ex situ conservation status of ecogeographic species types and/or to identify CWR and WUS requiring urgent conservation attention within a local region of interest.

All statistical analyses were performed in R version 4.1.1 (R Core Team, 2021), and code and data needed to reproduce all results are available at: https://github.com/jensculrich/Canadian_CWR_inventory_and_conservation

3 | RESULTS AND DISCUSSION

3.1 | National crop wild relative and wild-utilized species inventory

The national inventory of CWR and WUS contains 779 unique plant taxa (658 distinct species) of potential economic importance. The inventory includes 263 Tier 1 CWR taxa (222 species) (Figure 1a), 285 Tier 2 CWR taxa (246 species), and 529 non-mutually exclusive WUS taxa (444 species) (Supplemental Table S1).

Tier 1 CWR diversity is primarily associated with fruit crops (109 CWR taxa including infraspecific cultivars and subspecies, 88 distinct species) and cereal and pseudocereal crops (68 taxa, 55 species) (Figure 1a). The inventory includes CWR of globally important food crops such as strawberry (*Fragaria* spp.), stone fruits (*Prunus* spp.), apple (*Malus* spp.), grape (*Vitis* spp.), currant and gooseberry (*Ribes* spp.), sunflower, hazelnut (*Corylus* spp.), walnut (*Juglans* spp.), and wheat (Vincent et al., 2013; USDA-ARS, 2021); as well as CWR of nationally important food crops such as cranberry (Alston et al., 2014), blueberry (AAFC, 2012), sugar maple (Gouvernement du Québec, 2002), saskatoon (St. Pierre, 1992), and flax (Marchenkov & Rozhmina, 2003) (Figure 1b).

Sixty-one Tier 1 CWR taxa are of particular value for crop breeding based on high genetic proximity to crop species or potential use as graftstock (Priority 1A taxa), with 51 of these native to Canada (Table 2). More than 70% of these taxa (43 out of the 61) are relatives of fruit crops, including: blueberry and cranberry, currant and gooseberry, grape, apple, stone fruits, blackberry and raspberry (*Rubus* spp.), saskatoon, and strawberry (Table 2). All of these fruit-crop CWR are simultaneously recognized as WUS, directly harvested and consumed as food and/or medicine (Supplemental Table S1).

The 61 Priority 1A CWR taxa include 21 that are cultivated crop plants themselves, for example, highbush blueberry (Table 2). Genetic resources offered by Canadian ecogeographic types of crop species of emerging importance provide a resource for ongoing crop domestication and cultivar development. These emerging crop species include: Saskatoon [*A. alnifolia* (Nutt.)]; four infraspecific cultivars) (St. Pierre, 1992; Lachowicz et al., 2020), rosinweed (*Silphium integrifolium* var. *leave* Torr & A. Gray) (Reinert et al., 2019), cup-plant (*S. perfoliatum* L. var. *perfoliatum*) (Gansberger et al., 2015), and wild rice (*Zizania palustris* L.; two infraspecific cultivars) (Hayes et al., 1989) (Table 2). Both saskatoon and wild-rice are also important components of Indigenous food systems as staple fruit and grain, respectively (Turner & Aderkas, 2012).

Forest products are an important sector of the Canadian resource economy, with a 2020 annual national value of USD$33 billion in exports, the fourth largest in the world (Government of Canada, 2018). The inventory includes 103 CWR that are potential genetic resources for forest products, with spruce (*Picea* spp.), pine (*Pinus* spp.) fir (*Abies* spp.) (softwoods), poplar (*Populus* spp.), birch (*Betula* spp.), and maple (hardwoods) among the most economically important at the national scale (Government of Canada, 2006). Further, 171 Tier 2 CWR are potential genetic resources for 17 different forage and feed crop genera, including relatives of forage and feed crops of global importance such as trefoil (*Lotus* spp., *Acmispon* spp., and *Hosackia* spp.), timothy (*Phleum* spp.), bluegrass (*Poa* spp.), clover (*Trifolium* spp.), and vetch (*Vicia* spp.). The inventory includes 104 taxa of ornamental value including rose (*Rosa* spp.), spiderwort (*Tradescantia* spp.), highbush-cranberry/viburnum (*Viburnum* spp.), and bleeding heart (*Dicentra* spp.) (Supplemental Table S1).

The WUS in the inventory that are not also CWR of food crop plants are largely utilized for medicinal purposes, but many are also key food resources. Edible WUS may be targets for future de novo domestication and several have seen efforts to expand cultivation to a commercial scale, including: elderberry (*Sambucus* spp.) (Mratinić & Fotirić, 2007; Karapatzak et al., 2022), talet-bean [*Amphicarpaea bracteata* (L.) Fernald] (Peña et al., 1999), ground-nut (*Apios americana* Medik.) (Li et al., 2021), and pawpaw [*Asimina triloba* (L.) Dunal] (Layne, 1996) (Supplemental Table S1).

Seventy-two CWR and WUS taxa in the inventory are imperiled in Canada and are of immediate conservation concern, including 16 Tier 1 CWR (three assessed as

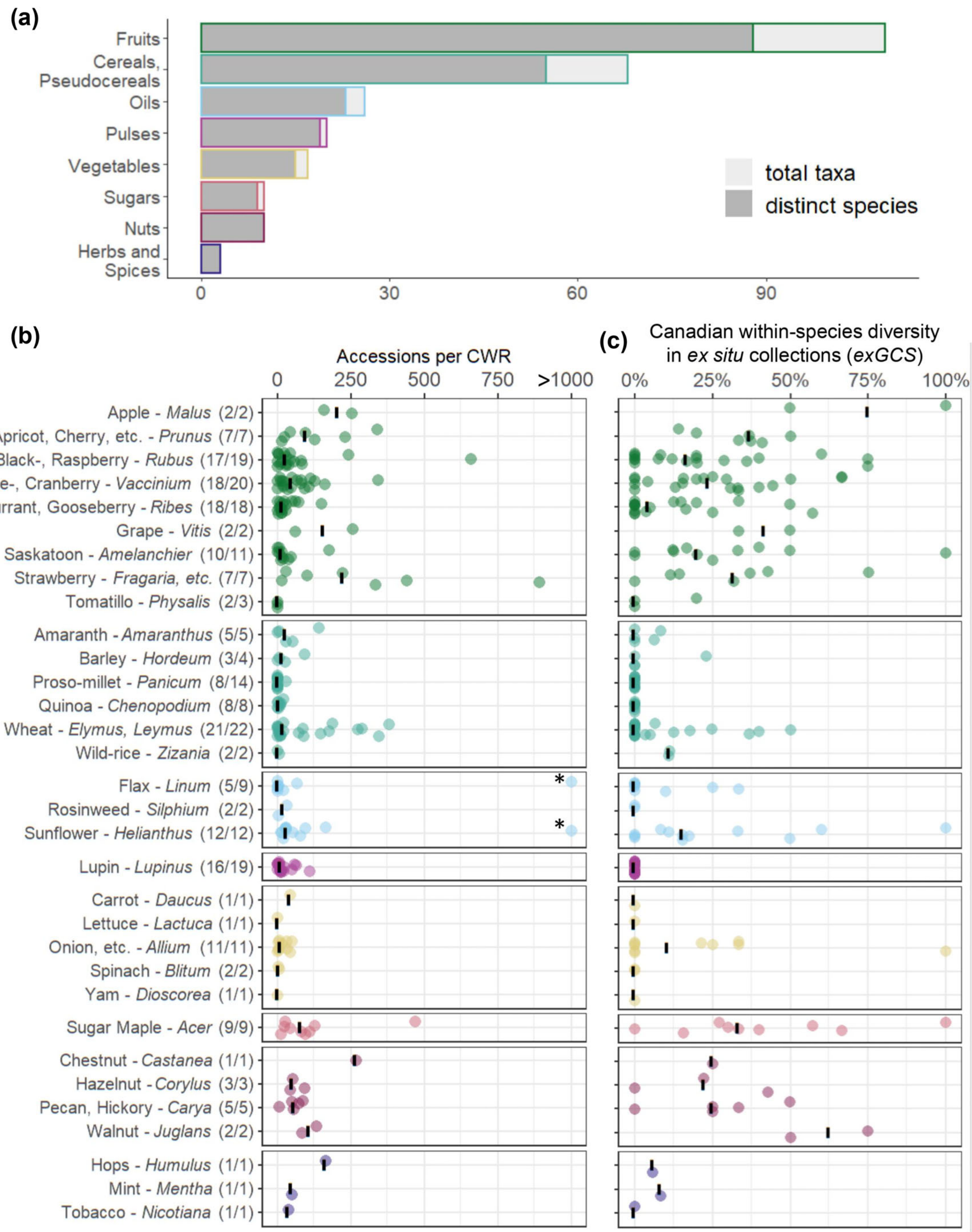

FIGURE 1 (a) Number of total taxa (including all infraspecific subspecies and cultivars) and distinct species in each of the Tier 1 food crop subcategories. (b) Number of accessions held in ex situ collections indicated for all 222 Tier 1 crop wild relatives (CWR) species by jittered points, colored and grouped by food crop subcategory. The median number of accessions per CWR of each food crop genepool is indicated by a vertical black dash ("|". Row labels "(*X*/*X*)" indicate the number of CWR in each genepool out of the total CWR in each genepool represented by one or more accession in ex situ collections. Within crop use categories, crop genepools are arranged alphabetically. Data include CWR accessions of wild-origin (collected from Canada or abroad), cultivated origin, or unknown provenance. **Linum usitatissimum* (flax) and *Helianthus annuus* (sunflower) are both represented by >1,000 accessions (6,337 and 4,295, respectively) (c) Estimated Canadian within-taxon genetic variation conserved in ex situ collections (*exGCS*), calculated using geographic diversity of populations conserved as a proxy for genetic diversity conserved. Scores range from 0% (no wild-origin accessions from Canada with provenance data) to 100% (wild-origin accessions in ex situ collections representative of all Canadian ecoregions where a species occurs). Median *exGCS* for each genepool is indicated by a vertical black dash ("|")

TABLE 2 Crop wild relatives (CWR) with high genetic proximity to cultivated food crops (are progenitors or in the primary genepool of cultivated crops) or have potential use as graftstock

Plant Family	Associated crop	CWR	Native[a]	Is crop [b]	Low rep. in ex situ collections[c]
Amaranthaceae	Amaranth	*Amaranthus hybridus* L.			
Asteraceae	Rosinweed	*Silphium integrifolium* var. *laeve* Torr. & A. Gray		X	X
	Sunflower	*Helianthus annuus* L.		X	
	Jerusalem-Artichoke	*Helianthus hirsutus* Raf.			X
	Jerusalem-Artichoke	*Helianthus tuberosus* L.	X	X	
Cannabaceae	Hops	*Humulus lupulus* var. *lupuloides* E. Small	X		
Ericaceae	Cranberry	*Vaccinium macrocarpon* Aiton	X	X	
		Vaccinium microcarpum Schmalh. ex Busch	X		X
	Blueberry	*Vaccinium angustifolium* Aiton	X	X	
		Vaccinium cespitosum Michx.	X		X
		Vaccinium corymbosum L.	X	X	
		Vaccinium myrtilloides Michx.	X		X
		Vaccinium myrtillus L.	X		
		Vaccinium vitis-idaea L.	X		
Fabaceae	Lupin	*Lupinus polyphyllus* var. *burkei* (S.Watson) *C.L.Hitchc.*	X		
		Lupinus polyphyllus Lindl. var. *polyphyllus*	X		
Fagaceae	Chestnut	*Castanea dentata* (Marshall) Borkh.	X	X	
Grossulariaceae	Currant, Gooseberry	*Ribes aureum* Pursh var. *aureum*	X		
		Ribes aureum var. *villosum* DC.			
		Ribes divaricatum Douglas var. *divaricatum*	X		X
		Ribes hirtellum Michx.	X		X
		Ribes oxyacanthoides L. subsp. *oxyacanthoides*	X		X
		Ribes uva-crispa L.		X	
Juglandaceae	Pecan, Hickory	*Carya cordiformis* (Wangenh.) C.Koch	X		
		Carya laciniosa (F.Michx.) Loudon	X		
		Carya ovata (Mill.) K. Koch	X		
	Walnut	*Juglans nigra L.*	X		
Linaceae	Flax	*Linum usitatissimum* L.		X	
Poaceae	Proso-millet	*Panicum capillare* L.	X		X
	Wild-rice	*Zizania palustris* var. *interior* (Fassett) Dore	X	X	X
		Zizania palustris L. var. *palustris*	X	X	X
Rosaceae	Apple	*Malus fusca* (Raf.) C.K. Schneid.	X		
	Apricot, cherry, peach, plum	*Prunus americana* Marshall	X		
		Prunus emarginata (Douglas ex Hook.) Walp.	X		X
		Prunus pensylvanica L.	X		
		Prunus pumila var. *Besseyi* (L.H. Bailey) Gleason	X		
		Prunus pumila var. *depressa* (Pursh) Gleason	X		
		Prunus pumila L. var. *pumila*	X		
		Prunus pumila var. *susquehanae* (Willd.) H. Jaeger	X		
	Blackberry, raspberry	*Rubus allegheniensis* Porter	X		

(Continues)

TABLE 2 (Continued)

Plant Family	Associated crop	CWR	Native[a]	Is crop[b]	Low rep. in ex situ collections[c]
		Rubus canadensis L.	X		X
		Rubus idaeus L. subsp. *idaeus*		X	
		Rubus idaeus subsp. *strigosus* (Michx.) Focke	X	X	
		Rubus leucodermis Douglas ex Hook.	X		
		Rubus occidentalis L.	X	X	
		Rubus spectabilis Pursh	X		
		Rubus ursinus Cham. & Schltdl.	X		
	Saskatoon	*Amelanchier alnifolia* (Nutt.) Nutt. var. *alnifolia*	X	X	
		Amelanchier alnifolia var. *cusickii* (Fernald) C.L. Hitchcock	X	X	
		Amelanchier alnifolia var. *humptulipensis* (G.N. Jones) C.L. Hitchc.	X	X	
		Amelanchier alnifolia var. *semiintegrifolia* (Hook.) C.L. Hitchc.	X	X	
	Strawberry	*Fragaria* × *ananassa subsp. ananassa* Duchesne ex Rozier		X	
		Fragaria × *ananassa* subsp. *cuneifolia* (Nuttall ex Howell) Staudt		X	
		Fragaria chiloensis subsp. *lucida* (Vilm.) Staudt	X		
		Fragaria chiloensis subsp. *pacifica* Staudt	X		
		Fragaria virginiana subsp. *glauca* (S.Watson) Staudt	X		
		Fragaria virginiana subsp. *platypetala* (Rydb.) A.E. Murray	X		
		Fragaria virginiana Duchesne subsp. *virginiana*	X		
Sapindaceae	Sugar maple	*Acer saccharum* Marshall	X	X	
Vitaceae	Grape	*Vitis aestivalis* Michx.	X		
		Vitis riparia Michx.	X		

[a]Taxa that are native to Canada.
[b]Taxa that are cultivated crop species themselves with native or naturalized populations in Canada.
[c]Taxa with a low number (<30 total accessions at the species level) in ex situ collections.

threatened or endangered by COSEWIC) (Table 3) and 27 Tier 2 CWR (12 assessed as vulnerable by COSEWIC) (Supplemental Table S1). Forty-six WUS are nationally imperiled (12 assessed as vulnerable by COSEWIC) including several WUS that are also CWR, for example, stream currant (*Ribes oxyacanthoides* subsp. *cognatum* (Greene) Q.P. Sinnott) and deerberry (*Vaccinium stamineum* L.) Other nationally imperiled WUS include soapweed (*Yucca glauca* Nutt.), deltoid balsamroot (*Balsamorhiza deltoidea* Nutt.), cherry-birch (*Betula lenta* L.), red-mulberry (*Morus rubra* L.), and 23 hawthorn taxa (*Crataegus* spp.) (Supplemental Table S1).

3.2 | Ex situ conservation assessment

The assembled virtual metacollection from seven contributing gardens and the national genebank systems includes 53,878 individual accessions of Canadian CWR and WUS - 23,923 Tier 1 CWR accessions, 26,401 Tier 2 CWR accessions, and 36,798 WUS accessions. 39,080 of the accessions are held in national genebanks (12,044 from Canada's national ex situ PGR system and 27,036 from the NPGS), and 14,798 accessions in botanical garden collections. 21,337 of the genebank accessions are Tier 1 CWR, while 2,587 garden accessions are Tier 1 CWR.

TABLE 3 Crop wild relatives (CWR) and wild-utilized species (WUS) that are nationally imperiled and/or assessed as at-risk (threatened or endangered) by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC)

Taxon	Associated crop	Status	COSEWIC assessment	Total accessions (BG)	Total accessions (G)	Canadian, wild-origin accessions (BG)	Canadian, wild-origin accessions (G)
Castanea dentata (Marshall) Borkh.	Chestnut	N1	E	258	9	101	5
Chenopodium berlandieri var. *bushianum* (Aellen) Cronquist	Quinoa	N1		0	22	0	0
Linum medium var. *texanum* A. Haines	Flax	N1		0	0	0	0
Linum striatum Walter	Flax	N1		0	0	0	0
Lupinus rivularis Douglas ex Lindl.	Lupin	N1		1	11	0	0
Ribes oxyacanthoides subsp. *cognatum* (Greene) Q.P. Sinnott	Currant, Gooseberry	N1		1	8	0	0
Vaccinium stamineum L.	Blueberry, Cranberry	N1	T	5	20	0	0
Amaranthus californicus (Moq.) S.Watson	Amaranth	N2		0	1	0	0
Dichanthelium wilcoxianum (Vasey) Freckmann	Proso-millet	N2		0	0	0	0
Elymus scribneri (Vasey) M.E. Jones	Wheat	N2		0	2	0	0
Juglans cinerea L.	Walnut	N2	E	47	38	42	0
Linum virginianum L.	Flax	N2		0	0	0	0
Lupinus lepidus Douglas ex Lindl.	Lupin	N2		0	2	0	0
Lupinus perennis L.	Lupin	N2		0	11	0	0
Ribes oxyacanthoides var. *setosum* (Lindl.) Dorn	Currant, Gooseberry	N2		1	8	0	0
Silphium perfoliatum L. var. *perfoliatum*	Rosinweed	N2		8	25	0	0

Note. Total accessions include all accessions in ex situ conservation collections, regardless of provenance of the collection, reported at the species-taxonomic level. Canadian, wild-origin accessions include only those accessions with provenance data that are collected directly from wild-populations in Canada and is reported at the infraspecific-taxonomic level. National Conservation Threat Status: N1 = critically imperiled in Canada, N2 = imperiled in Canada; COSEWIC assessments: (E) = endangered in Canada, (T) = threatened in Canada; BG = in botanical gardens, G = in genebanks, including both Canada's national ex situ Plant Gene Resource (PGR) system and the U.S. National Plant Germplasm System (NPGS).

In total, ex situ accessions represent 202 of 222 (91%) Tier 1 CWR species (Figure 1b, Supplemental Table S4), 201 of 246 (82%) Tier 2 CWR species, and 367 of 440 (83%) WUS species in the inventory (Supplemental Table S4). Many CWR are represented by only a few accessions, with 131 Tier 1 CWR species (59%) represented by 30 or fewer total accessions (Supplemental Table S4). In contrast, a small number of CWR are highly represented in ex situ collections, with 19 Tier 1 CWR species (9%) represented by more than 200 total unique accessions (Supplemental Table S4). In particular this includes species that are native or naturalized cultivated crop plants themselves. This includes crop species that are maintained as seed germplasm – flax (*L. usitatissimum* L.) (6,337 accessions) and sunflower (4,295 accessions) – as well as crop species primarily maintained as clonal germplasm – strawberry (*Fragaria* × *ananassa* Duchesne ex Rozier) (886 accessions), and raspberry (*Rubus idaeus* L.) (621 accessions) (Supplemental Table S4, Figure 1b).

The majority of Tier 1 CWR that are absent from ex situ collections are more distant genetic relatives of crop plants (21 out of 22 species with no accessions are Priority 1C, tertiary genepool, or assumed distant relatives; Supplemental Table S4). However, 11 prioritized, primary genepool or graftstcok CWR (Priority 1A) are relatively poorly represented (<30 total accessions), including several for which a large portion of the native range is restricted to Canada: bitter cherry (*Prunus emarginata* (Douglas ex Hook.) Walp.), dwarf bilberry (*Vaccinium cespitosum* Michx.), velvetleaf huckleberry (*V. myrtilloides* Michx.), smooth blackberry (*Rubus canadensis* L.), spreading gooseberry (*Ribes divaricatum* Douglas), hairystem gooseberry (*Ribes hirtellum* Michx.), Canadian gooseberry (*Ribes oxyacanthoides* L.), and *Zizania palustris* L. (Table 2).

Crop genepools that appear to be particularly well represented in ex situ collections relative to other groups include those of fruit crops (e.g., strawberry – 7/7 CWR species represented in collections, median = 223 accessions per CWR species; stone fruits – 7/7 CWR, median = 97 accessions; and apple – 2/2 CWR, median = 207 accessions). Fruit crop genepools that are less represented in number of accessions include blueberry and cranberry (18/20 CWR, median = 49 accessions), blackberry and raspberry (17/19 CWR, median = 29 accessions), and gooseberry and currant (18/18 CWR, median = 16 accessions). Other functional categories that are relatively well represented in number of ex situ accessions include nut crop genepools (e.g., walnut - 2/2 CWR, median = 110 accessions) and the sugar maple genepool (9/9 CWR, median = 81 accessions) (Figure 1b, Supplemental Table S4).

Outside of the wheat genepool (21/22 CWR represented, median = 20 accessions per CWR), ex situ conservation of cereal and pseudocereal CWR is limited (Figure 1b, Supplemental Table S4). However, many of these cereals and pseudocereals are distant relatives with difficult breeding utility, and further, are mostly non-native and/or weedy species that are not of high conservation concern. For example, all five CWR of Amaranth (*Amaranthus* spp.) in Canada except California amaranth (*A. californicus* (Moq.) S.Watson) are considered weeds in croplands, rangelands, and disturbed habitats and, furthermore, are either known or suspected to cause poisoning to livestock (Darbyshire, 2003). Similarly, relatives of quinoa (*Chenopodium* spp.), proso-millet (*Panicum*/*Dichanthelium* spp.), and barley (*Hordeum* spp.) include a mix of native and introduced species, but most are weedy in Canadian agricultural systems (Darbyshire, 2003). Nonetheless, adaptation of wild-populations of these taxa along their northern range edge in Canada might represent unique within-taxon genetic variation of potential use for plant breeding (Hoffman & Sgro, 2011). The CWR of other weedy cereals and pseudocereals occur in Canada - including relatives of millet (*Setaria* spp.) and oat (*Avena* spp.) (Brouillet et al., 2010; Darbyshire, 2003), but are not included in the inventory, given the focus of our inventory assembly process on crop genepools with one or more native species. Nationally imperiled cereal and pseudocereal CWR California amaranth, Bush's goosefoot (*Chenopodium berlandieri* var. *bushianum* (Aellen) Cronquist), and the nationally threatened, endemic annual wildrice (*Zizania aquatica* var. *brevis* (Fassett)) Chen are not represented in ex situ conservation systems (Table 2, Supplemental Table S4).

Relative to other food crop CWR groups, oil crop genepools are poorly represented outside of those species that are crops in themselves. Canadian sunflower CWR are represented by a median of only 31 ex situ accessions despite the high representation of cultivated sunflower (Figure 1b, Supplemental Table S4). Despite higher accession counts for non-native flax vs. any other taxon in the inventory, flax CWR are represented by a median of three accessions, with four of nine Canadian flax CWR fully absent from ex situ conservation, including nationally endemic prairie flax (*L. lewisii* var. *lepagei* (Boivin) Rogers) (Figure 1b, Supplemental Table S4). However, none of these underrepresented flax CWR are in the primary genepool of cultivated flax (Table 2), which would infer high breeding potential. Other crop genepools that are poorly represented include most vegetables, for example, onion (*Allium cepa* L.), garlic (*A. sativum* L.), and leek (*A. ampeloprasum* L.) (median of 11 accessions per species) (Figure 1b, Supplemental Table S4).

Tier 2 forest genetic resources are generally well represented in the ex situ conservation systems considered, with more than 1,000 accessions for 10 species (Supplemental Table S4).

Conversely, Tier 2 forage and feed CWR are poorly represented in ex situ conservation systems (3,058 total accessions) including several nationally imperiled taxa with no accessions: winter bentgrass (*Agrostis hyemalis* (Walter)

Britton, Sterns & Poggenb.), pinewoods vetchling (*Lathyrus lanszwertii* var. *bijugatus* (White) Broich.), and Fernald's milkvetch (*Astragalus robbinsii* var. *fernaldii* (Rydb.) Barneby) (Supplemental Table S4).

3.3 | Ecogeographic gap analyses

The 13,490 of the total 53,878 accessions of Canadian taxa were of wild origin from within Canada and were used to calculate estimated within-species genetic diversity conservation scores (*exGCS*) (Figure 1c). The remainder of the accessions were either (a) not collected from wild-populations, (b) collected from wild populations in other countries or (c) lacking provenance data). The 13,490 Canadian, wild-origin accessions included 5,083 (1,192 Tier 1) accessions from botanic gardens and 8,407 (1,621 Tier 1) from genebanks (Supplemental Table S5). Overall, *exGCS* scores (ranging from 0 to 100%) are low for Tier 1 CWR (median = 5% of ecogeographic types represented per species, mean = 17%, standard deviation = 23%). At the scale of genepools, *exGCS* is generally correlated with the number of CWR represented and the median number of accessions per CWR (Figure 1b and 1c). Some noteworthy exceptions include CWR from genepools of sugar maple, wild rice, apple, stone fruit, blackberry and raspberry, blueberry and cranberry, grape, amelanchier, hazelnut, pecan, and walnut – which all show relatively high *exGCS* compared with the number of accessions (Figure 1c). The CWR from genepools that are poorly represented in terms of overall accession counts (Figure 1b) have correspondingly low *exGCS*, including many CWR of cereals and pseudocereals, vegetables, oils, herbs and spices, and pulses (Figure 1c).

The low *exGCS* scores calculated here indicate that there are gaps in the ex situ conservation of within-species diversity of Canadian CWR (Figure 1c). Many CWR (including threatened CWR) are represented by accessions in ex situ collections, being conserved at the species level (Figure 1b). However, these collections represent a limited subset of Canadian ecogeographic types (Figure 1c). The disparity between the results of broad, taxon-level conservation coverage (Figure 1b) vs. narrowed consideration of Canadian ecogeographic diversity emphasizes that unique Canadian ecogeographic types lack ex situ conservation protection. This disparity between broad taxon-level conservation coverage and ecogographic conservation may arise given that only 25% of the accessions representing Canadian CWR originate from wild populations in Canada. Other accessions originate from the United States (30% of accessions), from other countries (3%), or are not associated with provenance data that (42%) (Supplemental Table S6). Collection from a narrow ecogeographic distribution of source populations within Canada would further contribute to this pattern. Targeting unprotected Canadian ecogeographic types through a combination of in situ and further ex situ conservation efforts is needed to advance the roadmap for conservation of North America's CWR (Khoury et al., 2019).

As demonstrated here, ex situ conservation efforts alone are limited in extent and only protect a fraction of within-species genetic diversity (Figure 1c). Further, ex situ collections typically aim to maintain genetic identity of accessions, through reproductive isolation of populations (Walters et al., 2018). While this precludes homogenization of ex situ collections and enables unique genotypes to be identified and incorporated into breeding programs, it also prevents further evolution of these sample lineages in response to new and changing abiotic and biotic environmental conditions (Walters et al., 2018). In contrast, populations in the wild continue to evolve to these pressures (Khoury et al., 2019). Ultimately conservation plans must emphasize in situ conservation of CWR and WUS to protect the full range of the potential genetic resources in CWR and WUS (Diederichsen & Schellenberg, 2018; Fu, 2017; Khoury et al., 2019; Maxted & Kell, 2009), with ex situ conservation in genebanks and botanical gardens serving a complement (Maxted, 2013).

The species distributions of Tier 1 CWR (Figure 2a) and of WUS (Figure 2b) are concentrated in the southern ecoregions of Canada, with Tier 1 species richness highest in the Great Lakes (124 CWR species, more than 50% of all CWR that occur in Canada) and surrounding ecoregions: Boreal Shield (112), northern Appalachian/Acadian (112), and St. Lawrence - Champlain Valley (104) (Figure 2a). Aggregated at the provincial scale, the number of Tier 1 CWR is more evenly geographically distributed, highest in British Columbia (138 CWR), Ontario (137), and Quebec (112) (Supplemental Figure S1A). The species distributions of WUS follow a similar pattern; where ecoregion scale species richness is highest in southeastern regions: Great Lakes (240 WUS), Boreal Shield (230), northern Appalachian/Acadian (219), and St. Lawrence - Champlain Valley (210) (Figure 2b); while aggregated at the province scale, species richness in British Columbia (299 WUS) is comparable to Ontario (269) and Quebec (241) (Supplemental Figure S1B). The high concentration of CWR and WUS in the Great Lakes ecoregion in southern Ontario and in other southern ecoregions matches predictions of CWR species distributions modeled using a subset of 34 species (Diederichsen & Schellenberg, 2018), as well as estimates for total plant biodiversity and biodiversity in other taxonomic groups in Canada (Kraus & Hebb, 2020; Muir et al., 2021).

Collections from across all surveyed gardens and germplasm repositories held 2,804 Tier 1 CWR, 10,050 Tier 2 CWR, and 10,614 WUS accessions that were: (a) of wild-origin provenance, (b) included geolocation data, (c) and were collected in Canada. Wild-origin accessions of Tier

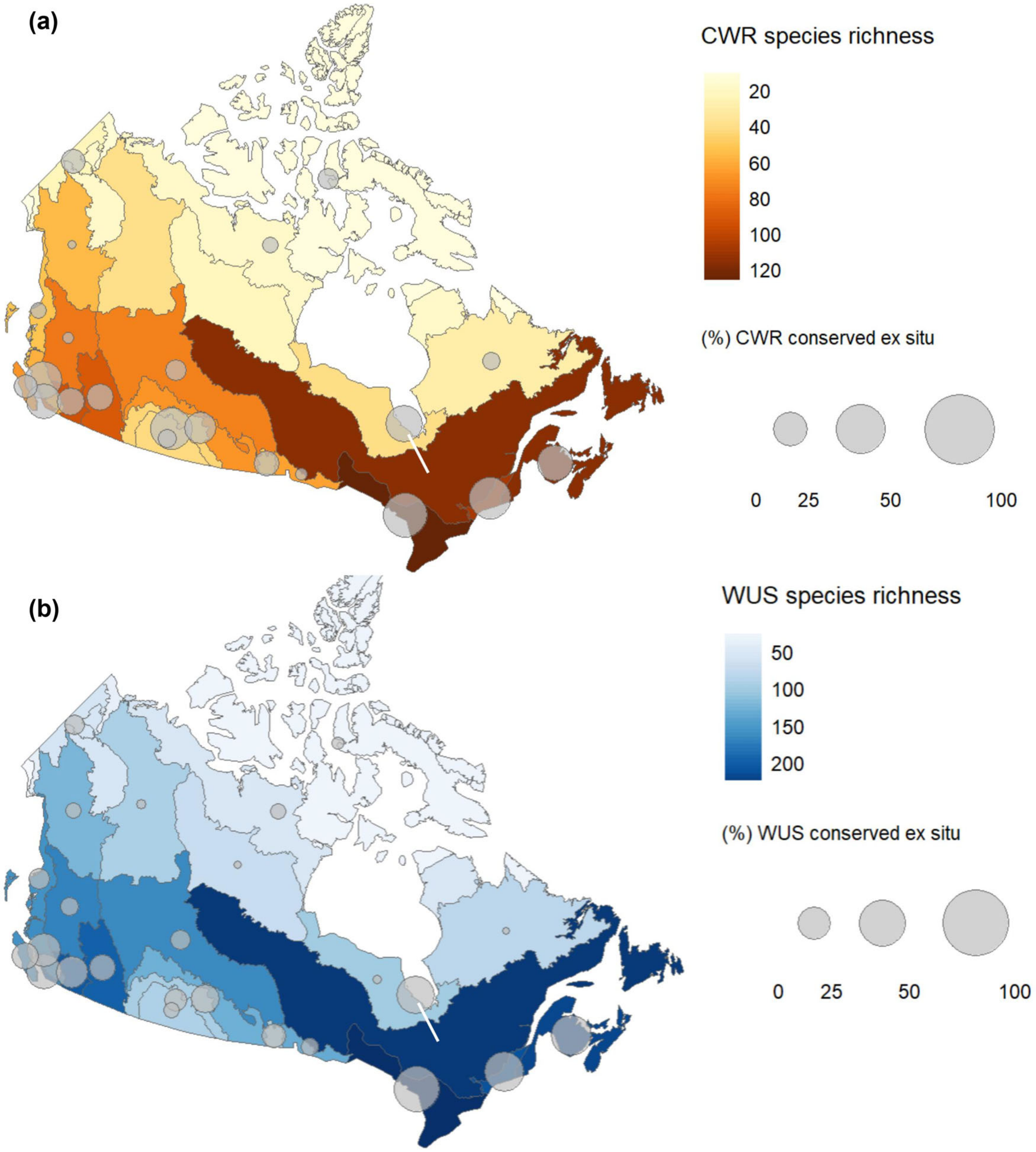

FIGURE 2 Ecogeographic gaps in ex situ conservation of Tier 1 (a) crop wild relatives (CWR) and (b) wild-utilized species (WUS) in Canadian ecoregions. The taxonomic richness (the number of species that occur in each region) is displayed for each of the 30 level III ecoregions in Canada, mapped from light (low richness) to dark (high richness). Radius sizes of overlapping grey circles indicate proportion of species in each region conserved in ex situ collections, ranging from 0% (no species native or naturalized in the region represented by wild-origin accessions from that region; no circle) to 100% (all species native or naturalized in the region represented by wild-origin accessions from that region; large circles)

1 CWR are most frequently collected from southern ecoregions, particularly: Great Lakes (946 wild-origin accessions), northern Appalachian/Acadian (493), and the Willamette Valley - Puget Trough - Georgia Basin: Temperate Conifer Forests (309). There are few geolocated wild-origin CWR accessions from other areas of the country (Figure 2a). Similarly, there are many wild-origin WUS accessions collected from the Great Lakes (3,875 wild-origin accessions), northern Appalachian/Acadian (2,352), and the Boreal Shield (1,646), but few if any accessions from other regions (Figure 2b). There is a correlation between the number of accessions and the CWR species richness of an ecoregion ($R^2 = .50$, p value < .05; Supplemental Figure S2), implying that wild-origin collections are more regularly obtained from Canada's ecogeographic regions with highest CWR diversity. However, even from these species-rich ecoregions, gaps remain in the representation of ecogeographic types. For example, only ~41% of CWR species that occur in the Great Lakes ecoregion are represented by at least one wild-origin accession from that ecoregion (Figure 2a).

In Canada, a top priority for advancing in situ CWR and WUS conservation is establishing genetic reserves in the species-rich Great Lakes region, and other species-rich southern ecoregions. In these ecoregions, rich CWR and WUS species diversity is at odds with concentration of high intensity human land use, where most natural habitat has already been lost or degraded (Coristine & Kerr, 2011; Kerr & Cihlar, 2003), and few protected areas exist (ECCC, 2016). Although funding and policy for in situ conservation in Canada often emerges via provincial administrative avenues (Abbitt et al., 2000; Newediuk et al., 2021), habitat restoration and protection itself largely plays out at local scales, often using more localized ecoregions as the spatial unit for ecological assessment and action planning (Wright et al., 1998). Targeting in situ conservation on prioritized fine-scale ecogeographic areas may follow examples from other countries, where genetic reserves have been established to protect priority taxa, threatened taxa, and/or the highest number of taxa (Maxted & Kell, 2009; Maxted et al., 2012). For example, in the United Kingdom, Jarvis et al. (2015) use vegetation surveys to identify the habitats that are CWR hotspots, where next steps may include increased protection and ongoing monitoring to ensure that genetic diversity is maintained in situ. Monitoring of CWR populations includes assessments of habitat quality, demographic trajectory, and population genetic structure to ensure the efficacy of in situ conservation interventions (Iriondo et al., 2008). In Canada, species-rich CWR and WUS hotspots could be designated as Key Biodiversity Areas or as Indigenous Conserved and Protected Areas and receive prioritized protection and resources (CRP, 2022a).

3.4 | Integrating conservation in botanical gardens and genebank systems

Of the 202 (out of a total of 222) Tier 1 CWR species that were represented by one or more accessions, 196 are held in genebanks (Figure 3a). These include 195 in the NPGS system and 66 in Canada's national ex situ PGR system. All 66 of the species represented in Canada's PGR system are also held in the larger NPGS system of the United States, with the exception of *Prunus nigra* Aiton ('Canadian Plum'). 119 species are found in the seven surveyed botanical gardens (Figure 3a), including six Tier 1 CWR uniquely held in botanical gardens: relatives of saskatoon (*A. bartramiana* (Tausch) M.Roem., *A. humilis* Wiegand, and *A. interior* Nielsen), onion (*Allium stellatum* Nutt. ex Ker Gawl. and *A. crenulatum* Wiegand), and wild rice. Together, Canadian conservation centers (Canada's national ex situ PGR system and the surveyed Canadian botanical gardens) uniquely held Canadian ecogeographic type accessions. Sixty-three Tier 1 CWR that are held in these national centers are also held in the U.S. NPGS but are not represented in that system by any accessions that were collected in Canada (Supplemental Table S5). This demonstrates that the Canadian network of ex situ conservation collections holds unique within-species genetic diversity from CWR populations on the Canadian side of the political border.

Within crop use subcategories, genebanks contained a higher proportion of CWR of cereals and pseudocereals (84 vs. 16% of species; $x_1^2 = 49.8$, $p < .01$), fruits (91 vs. 75% of species; $x_1^2 = 6.8$, $p < .01$), oils (83 vs. 48% of species; $x_1^2 = 4.70$, $p < .05$), pulses (84 vs. 32% of species; $x_1^2 = 8.7$, $p < .01$). There was no difference in the proportion of species in genebanks vs. botanical garden collections for CWR of vegetables (87 vs. 67% of species; $x_1^2 = 0.7$, $p = .39$), sugars (100 and 100% of species), nuts (91 vs. 100% of species; $x_1^2 < 0.01$, $p = 1$), or herbs and spices (100 vs. 67% of species; $x_1^2 < 0.01$, $p = 1$) (Figure 3a).

The median number of accessions per CWR species was significantly higher in genebanks vs. gardens for CWR of vegetables, cereals and pseudocereals (median = 6 accessions per CWR in genebanks vs. 0 in botanical gardens; $p < .01$), fruits (median = 18 vs. 5; $p < .01$), oils (median = 25 vs. 0; $p < .01$), and pulses (median = 11 vs. 0; $p < .01$), vegetables (median = 6 vs. 1; $p < .05$), and marginally significantly higher for herbs and spices (median = 47 vs. 2; $p < .10$). There was no significant difference in the median number of accessions per CWR for sugar (median = 20 accessions per CWR in genebanks vs. 40 in botanical gardens; $p = .50$), and nut crops (median = 31 vs. 29; $p = .80$) (Figure 3b).

The representation of Tier 1 CWR in botanical gardens (Figure 3a and 3b) demonstrates that these institutions are currently contributing alongside genebanks to the ex situ conservation of potential genetic resources for food crops, especially for nut crops and sugar maple. Botanical gardens also contribute to the ex situ conservation of fruit crop CWR; although fruit crop CWR representation is significantly higher in genebanks there is still a large proportion (Figure 3a) and count (Figure 3b) of fruit CWR in botanical gardens. Botanical gardens particularly represent ex situ conservation for the genepools of sugar maple, chestnut (*Castanea* spp.), walnut, stone fruits, saskatoon, hazelnut, pecan, blueberry, raspberry and blackberry; including taxa that are imperiled (Table 3, Supplemental Table S4).

Forest resources are relatively well represented in both botanical gardens and national genebanks. Forest resource taxa of particular conservation concern that are well represented in genebanks but currently not in gardens include white pine (*Pinus albicaulis* Engelm.) (1,139 genebank accessions vs. 1 garden accession), jack pine (*P. banksiana* Lamb.) (1,000 accessions vs. 1), and pitch pine (*P. rigida* Mill.) (38 accessions vs. 9); gardens are playing a key role in ex situ conservation for other threatened forest resources,

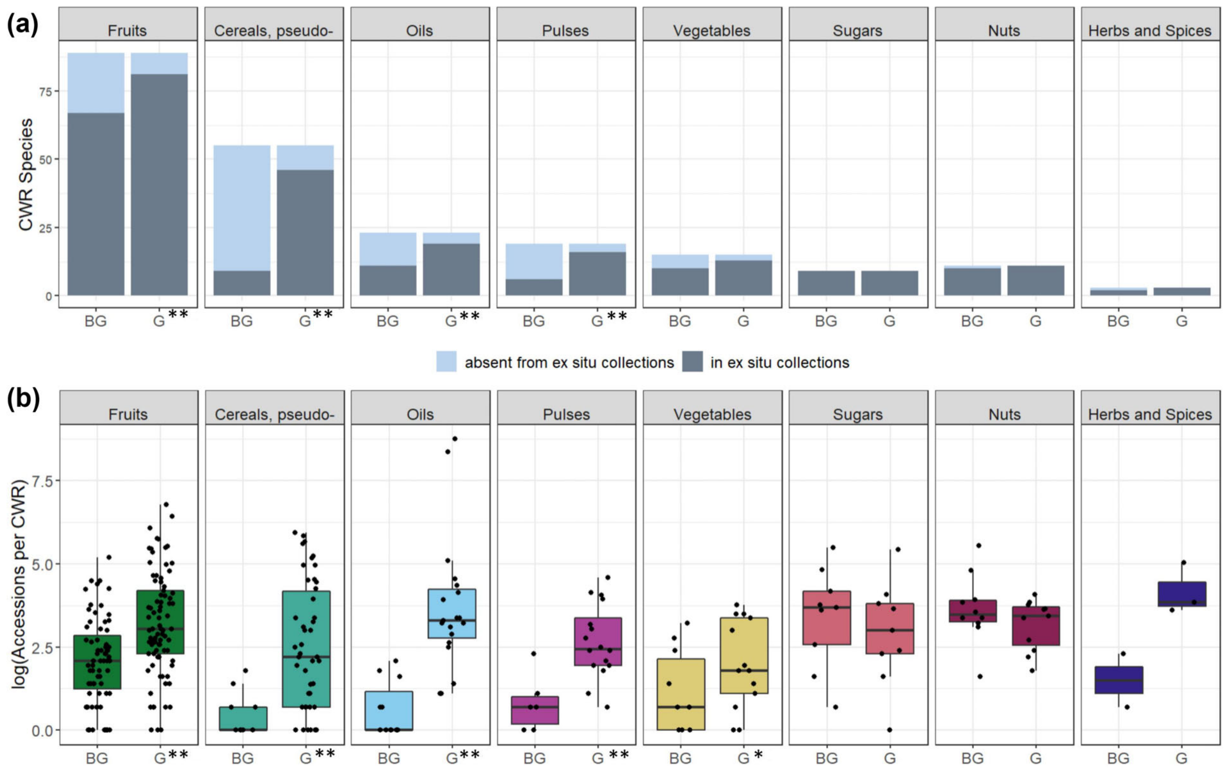

FIGURE 3 Comparison of Tier 1 CWR accessions in botanic garden (BG) vs. genebank (G) ex situ collections. (a) Number of crop wild relatives (CWR) species represented by one or more accessions in BG vs. G, compared within crop use categories. Significant differences between proportions compared within categories are indicated by '*' for p value <.05, and '**' for p value < .01(two-proportion z test). (b) Number of accessions per CWR held in botanic gardens (BG) vs. Canadian and U.S. national plant genebanks (G), compared within crop use categories. Jittered points represent each of the 210 CWR species. Significant differences between *median* number of accessions held in BG vs. G are indicated by '*' for p value <.10, '**' for p value <.05 and '***' for p value <.01 (Wilcoxon Rank Sum test). Accession counts per CWR are displayed on a logarithmic scale given the disproportionately high representation of a small number of CWR species

including: cherry-birch (14 genebank accessions vs. 72 garden accessions), dwarf chinquapin oak (*Quercus prinoides* Willd.) (2 accessions vs. 12), and red-mulberry (3 accessions vs. 14) (Supplemental Table S4).

Forage and feed crops, which are poorly represented in ex situ conservation systems, are particularly poorly represented among garden collections (42 total accessions) vs. genebanks (3,016 accessions, median of 1 accession per forage and feed CWR) (Supplemental Table S4).

Historically, botanical gardens were the first scientifically motivated institutions to assemble large collections of living plant material for research, emerging as early as the 16th century in Europe (Spencer & Cross, 2017; BGCI, 2021), but until recently have focused on maintaining collections of exotic, ornamental, and medicinal plants. The necessity of maintaining genetically diverse plant collections as resources for food and agriculture (maximizing collection from different geographic areas and maternal lineages) was not in the focus of botanical gardens and was initiated by plant breeders and crop researchers who established the first national genebanks in Russia and the United States at the end of the 19th century (Frankel, 1984; Loskutov, 1999). Drawing from seven botanical gardens that are a subset of a larger national and international network of botanical gardens, our results highlight that botanical gardens contribute to ex situ conservation of native germplasm with potential use for food and agriculture, expanding the diversity of populations that have been sampled in the national ex situ metacollection of CWR and WUS. These seven botanical gardens alone contributed nearly half (42%) of the Tier 1 CWR accessions in our assessment that are collected from wild populations in Canada.

The representation of fruit, nut, and sugar crops as well as forest genetic resources demonstrates that botanical gardens especially complement genebanks in the conservation of woody-perennial CWR. Many woody perennials must be maintained in living field collections due to recalcitrant seeds and/or low seed germination rates (Bonner, 1990; FAO, 2022; Migicovsky et al., 2019). These living collections are costly to maintain and/or expand and, correspondingly, are broadly underrepresented in genebanks at the international scale (FAO, 2022; Migicovsky et al., 2019). Maintaining woody perennial collections in botanical gardens through clonal propagation that maintains genetic diversity from wild-population sources is an area where these institutions can contribute to ex situ conservation.

Beyond the act of maintaining ex situ accessions, botanical gardens supplement conservation through their research capabilities and expertise. For example, research on living specimens of red-mulberry at the Royal Botanical Gardens (Hamilton, ON) provides information on the recovery requirements for this imperiled species (RBG, 2022). This type of data, including data on life history and generation time, informs COSEWIC assessments that act as precursors to legal protection in Canada (COSEWIC, 2021). The Rare Woody Plants of Ontario Program at the University of Guelph Arboretum (Guelph, ON) provides information on germination and propagation requirements for many rare, native species (Fox, 2012). The garden continues to contribute to conservation efforts by identifying trait variation in within-species lineages, for example, through disease resistance screens, that could be targeted for ex situ or in situ conservation priority (Fox, 2012; UoG Arboretum, 2022). Within the University of British Columbia Botanical Garden (Vancouver, British Columbia), researchers use living collections to test avenues for remote monitoring of plant health and phenology (UBC BG, 2022). Tracking phenology change could be extended to provide information on phenology traits and climate tolerance of CWR accessions in the collection. These examples demonstrate how data collected on CWR in the living collections of botanical gardens can inform and advance CWR conservation and use.

Raising awareness of the importance and threats to CWR and WUS and plant biodiversity more broadly is expected to mobilize in situ conservation, and botanical gardens are well situated to lead these public engagement efforts (FAO, 2010; Khoury et al., 2019). Some gardens have started to create organized CWR and WUS collections with informational signage to reach the estimated 500 million individuals who visit botanical gardens annually (BGCI, 2021). This provides a critical opportunity for educating visitors on the importance of CWR and WUS. More recently, gardens have reached broader audiences through digital/online engagement tools, for example, the Missouri Botanical Garden's grape graftstock virtual exhibit accompaniment (MBG, 2021). These displays and engagement tools may raise awareness and appreciation of CWR and WUS diversity by focusing on charismatic, flagship species in collections as has been effective in other systems (Bennett et al., 2015). Galvanizing the public around flagship species supports funding and encourages policy decisions that promotes long-term conservation in situ, preserving genetically healthy populations.

In Canada, public outreach efforts through botanical gardens could focus on native Canadian fruit CWR and WUS. These plants are central to the CWR diversity of Canada: fruit CWR make up the largest share of Canadian CWR diversity (Figure 1a) and also include the largest number of high utility CWR (Table 2) and several threatened taxa (Table 3). Many of these are showy, long-lived woody perennials that are already common in botanical garden collections (Supplemental Table S4). These plants may be important for bolstering public support not only because they represent a key contribution of Canadian biodiversity to food security, but also because most of these plants are edible and can be consumed directly (Supplemental Table S1). Further, because fruit CWR and WUS have great significance for Indigenous Peoples in Canada (Kuhnlein & Turner, 2020), these plants may promote deeper appreciation of interactions between plants and humans, including interactions between biodiversity and cultural dimensions such as language and art (Vavilov, 1926). By connecting through these plants, Canada has an opportunity to promote CWR and WUS conservation involving and guided by Indigenous Peoples.

3.5 | Towards a conservation strategy for crop wild relatives and wild-utilized species in Canada

Given potential limitations for expanding or establishing new protected areas in the human dominated landscapes of CWR rich areas, in situ conservation must involve many partners. Although urban land use is intensive in southern Ontario (which contains the Toronto-metropolitan area and several outlying cities), agricultural land use currently occupies the largest share of geographic area (Coristine & Kerr, 2011; Kerr & Cihlar, 2003). Maximizing the conservation value of these extensive agroecosystems includes on-farm (circa situm) conservation of CWR, working alongside farmers and rural landowners to protect genetic diversity in hedgerows, easements, or other open farm spaces (Dawson et al., 2013; Khoury et al., 2019). Ecosystem based protection, such as prescribed fire and hyperabundant deer management as occurs in habitat near Lake Erie (ECCC, 2019) where imperiled CWR such as deerberry occur, offers an efficient strategy for protecting multiple species simultaneously (Kraus et al., 2021). Other CWR face taxon-specific threats that must be managed and addressed uniquely. For example, the imperiled walnut CWR, butternut (*J. cinerea* L.), is primarily threatened by fungal disease (Environment Canada, 2010). Here, current conservation action centers on protection of populations that show disease-resistance potential and propagating new individuals from this stock (Environment Canada, 2010).

Effective in situ conservation also depends on collaboration with Indigenous communities. Wild populations of CWR and WUS are distributed across traditional landscapes of Indigenous Peoples and so enacting conservation efforts on these lands will not be possible, socially justified, nor legal without Indigenous consent and partnership (Artelle et al., 2019). Further, involving Indigenous Peoples whose identity includes

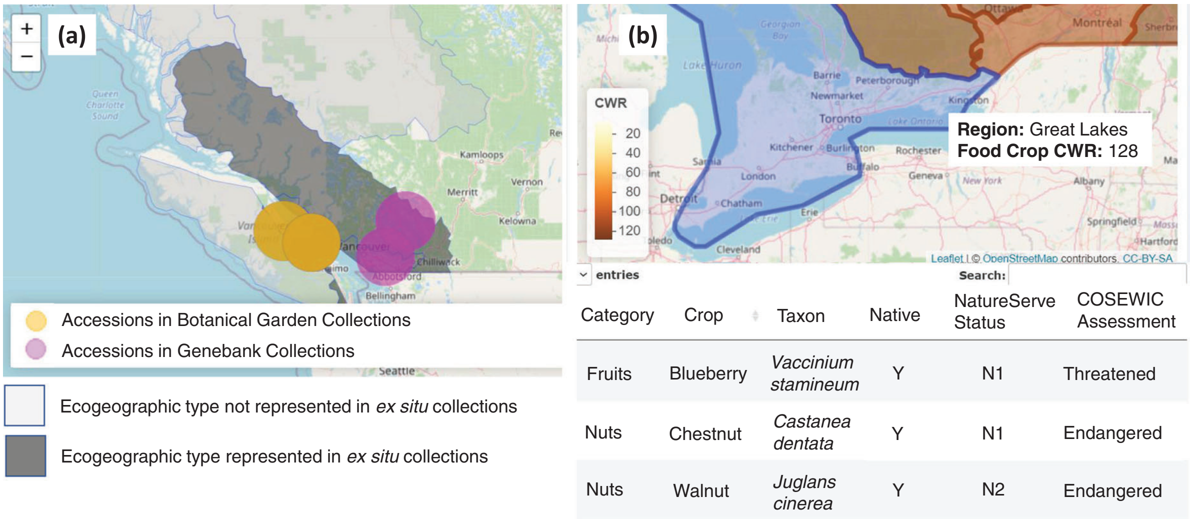

FIGURE 4 Demonstration of web application for crop wild relatives (CWR) conservation. (a) A species distribution map and ecogeographic ex situ conservation assessment is presented for pacific crabapple (*Malus fusca* (Raf.) C.K.Schneid.) (CWR of apple). The geographic origin of accessions held in botanical gardens (yellow) and in genebanks (magenta) are mapped over the ecoregions where the CWR occurs. *Pacific crabapple* ecogeographic types lacking representation in ex situ conservation systems are mapped in light gray, while *Pacific crabapple* ecogeographic types that are represented by one or more accessions in ex situ conservation systems are mapped in dark grey. (b) Illustrates the generation of a local taxon list for the Great Lakes ecoregion, sorted by highest conservation concern (Imperiled NatureServe Status and/or assessed as at-risk by COSEWIC)

centuries of knowledge and practice of interacting with this plant diversity is an invaluable resource for guiding actions towards maintaining healthy, diverse populations of CWR and WUS in these landscapes (Artelle et al., 2019). Specific projects, for example, those led by First Nations communities in British Columbia seek to revitalize Indigenous food sovereignty by restoring access to berry fruit CWR while also building community knowledge that identifies and mitigates abiotic and biotic threats to these CWR populations (Sharifi, 2018). Further involving Indigenous Peoples in CWR conservation includes funding relationship building, enabling Indigenous communities to set conservation goals, funding research based on those goals, and listening to Indigenous ideas of how to restore natural habitats and monitor plant diversity in those habitats (Sidik, 2022). A Parks Canada Indigenous Stewardship Strategy represents a framework for advancing conservation through reconciliation and recognition of Indigenous rights and responsibilities within Canada's protected areas (CRP, 2022b).

The web application tool (https://julrich.shinyapps.io/CWR_app/) that we developed generates ecogeographic conservation assessments for each individual CWR and WUS in the inventory (Figure 4a). With this tool, conservation planners and practitioners, research scientists, garden collection managers, and national genebanks may be able to understand and reduce gaps in conservation. Users may implement the tool to target ex situ conservation efforts for CWR and WUS ecogeographic types that are currently underrepresented in ex situ conservation systems. Setting concrete goals is key for advancing CWR conservation (Walters et al., 2018), and the ecogeographic assessments provided by the web application tool could be used to this end, that is, by providing a target of all ecogeographic types that should be protected in conservation strategies to ensure a minimal range of within-species genetic diversity is maintained. For example, a user of the web application may search for all CWR of apple that occur in Canada and select an individual species from the filtered list of CWR (Figure 4a). In this case, apple CWR, Pacific crabapple (*M. fusca* (Raf.) C.K.Schneid.), which has potential use as graftstock as well as in breeding programs is selected (Figure 4a). The web application then visualizes the ecogeographic range, lists subordinate infraspecific taxa (if any), and visualizes ecogeographic types that are/are not currently represented by accessions in ex situ conservation collections (Figure 4a). Botanical garden or genebank collection managers could then prioritize future collection of *Pacific crabapple* ecogeographic types from the unrepresented ecoregions where it occurs (Figure 4a). The ecogeographic range map could also be used to identify regions within Canada where in situ management is warranted.

We also demonstrate how a user may generate a list of locally occurring CWR from a region of interest. In this example, the user has generated a list of food crop CWR from the Great Lakes region in southern Ontario, sorted to highlight species that have been identified as at-risk by a COSEWIC threat assessments (Figure 4b). Land managers in this region may then seek to implement in situ protection, restoration, and management focusing on food crop CWR of highest conservation concern such as deerberry (*V. stamineum* L.), American chestnut (*C. dentata* (Marshall) Borkh.), and butternut

(*J. cinerea* L.) (Figure 4b) or of highest potential breeding utility.

Additionally, the web application may be used for sharing the importance and threats to CWR and WUS more widely among the public, gathering further support for action. By increasing the accessibility of the information contained in the national inventory, we anticipate that this tool promotes collaborative conservation, building on both ex situ and in situ conservation approaches to secure Canada's plant genetic resources. The web application is dynamic in nature, with potential for future additions such as linking taxon names to iNaturalist.ca pages so that users can view plant images and occurrence records (iNaturalist, 2022). This addition may encourage further iNaturalist citizen science data collection, which can be used to feed back towards informing future conservation assessments, such as those conducted by NatureServe Canada (NatureServe, 2022). Pending data holder permissions, future additions could also include delineation of accessions by the specific conservation centers in which they are held. This would allow a user to project the ecogeographic spread of accessions held under their management or alternatively to contact specific institutions with breeding material of potential interest based on the identified ecogeographic origin. Given the flexibility and room for growth with this web application, we welcome feedback and suggestions from conservation and crop breeding communities. We intend that these discussions will extend the utility of the tool, enhance accessibility to users, and advance an integrative strategy for CWR and WUS in Canada.

AUTHOR CONTRIBUTIONS

Jens C. Ulrich: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Software; Visualization; Writing – original draft; Writing – review & editing. Tara L. Moreau: Conceptualization; Funding acquisition; Methodology; Project administration; Supervision; Writing – review & editing. Erika Luna-Perez: Conceptualization; Methodology; Writing – review & editing. Kephra I. S. Beckett: Conceptualization; Methodology; Writing – review & editing. Lili K. Simon: Conceptualization; Methodology; Writing – review & editing. Zoë Migicovsky: Conceptualization; Methodology; Supervision; Writing – review & editing. Axel Diederichsen: Conceptualization; Methodology; Supervision; Writing – review & editing. Colin K. Khoury: Conceptualization; Methodology; Supervision; Writing – review & editing.

ACKNOWLEDGMENTS

We acknowledge that this work has been conducted on the ancestral and unceded lands of all the Indigenous Peoples (Inuit, Métis, and First Nations) who steward Canada's biodiversity, including CWR and WUS.

We thank two anonymous reviewers for their valuable suggestions for improving the manuscript; Claire Kremen, Angela Brennan and Abby Meyer for assistance with initiating the project and for review of early versions of the manuscript; Amie Enns (and NatureServe Canada) for retrieving conservation status information and Anne Francis for further assistance on interpreting conservation status; Nancy Turner for review of the WUS list; the "Berry Bunch" for providing feedback and helpful ideas; and all 7 surveyed botanical gardens for sharing collections data.

Publication fees were supported by the UBC Botanical Garden's Sustainable Communities Field School; Jens C. Ulrich was supported by a 4YF award from UBC; ELP by NSERC Discovery Grant RGPIN-2017-04648 and RGPIN-2018-04893; Kephra I. S. Beckett by an NSERC CGSD award and the Catalyst Paper Corporation Fellowship; Lili K. Simon by the WHH Fellowship in Ornithology and the UBC Faculty of Forestry; Zoë Migicovsky by National Science Foundation Plant Genome Research Program 1546869; and Colin K. Khoury by grant no. 2019-67012-29733/project accession no. 1019405 from the USDA National Institute of Food and Agriculture.

DATA AVAILABILITY STATEMENT

Data are deposited and shared through the DRYAD long-term data repository, DOI https://doi.org/10.5061/dryad.73n5tb30j. Data, metadata and code to reproduce the results are also available at https://github.com/jensculrich/Canadian_CWR_inventory_and_conservation.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Jens C. Ulrich https://orcid.org/0000-0003-0800-1393
Tara L. Moreau https://orcid.org/0000-0001-7340-2586
Lili K. Simon https://orcid.org/0000-0002-1580-6221
Zoë Migicovsky https://orcid.org/0000-0002-3931-1258
Colin K. Khoury https://orcid.org/0000-0001-7893-5744

REFERENCES

Abbitt, R. J., Scott, J. M., & Wilcove, D. S. (2000). The geography of vulnerability: Incorporating species geography and human development patterns into conservation planning. *Biological Conservation*, *96*(2), 169–175.

Agriculture and Agri-Food Canada (AAFC). (2012). *Statistical overview of the Canadian blueberry industry, 2010*. AAFC. https://publications.gc.ca/collections/collection_2012/agr/A118-44-2012-eng.pdf

Agriculture and Agri-Food Canada (AAFC). (2022). *Canada's country report for the third report on the state of the world's plant genetic resources for food and agriculture*. AAFC.

Agriculture and Agri-Food Canada (AAFC). (2020). *Plant genetic resources for food and agriculture: International treaty - Canada.ca*. AAFC. https://www.canada.ca/en/environment-climate-change/corporate/international-affairs/partnerships-organizations/plant-genetic-resources-food-agriculture.html

Agriculture and Agri-Food Canada (AAFC). (2021). *GRIN-Global-CA: Canadian national genebank information system*. AAFC. https://pgrc-rpc.agr.gc.ca/gringlobal/landing

Alston, J. M., Medellín-Azuara, J., & Saitone, T. L. (2014). *Economic impact of the North American cranberry industry*. University of California.

Arnason, T., Hebda, R., & Johns, T. (1981). Use of plants for food and medicine by Native Peoples of eastern Canada. *Canadian Journal of Botany*, *59*(11), 2189–2325.

Artelle, K. A., Zurba, M., Bhattacharyya, J., Chan, D. E., Brown, K., Housty, J., & Moola, F. (2019). Supporting resurgent Indigenous-led governance: A nascent mechanism for just and effective conservation. *Biological Conservation*, *240*, 108284.

Bebber, D. P., Holmes, T., & Gurr, S. J. (2014). The global spread of crop pests and pathogens. *Global Ecology and Biogeography*, *23*(12), 1398–1407. https://doi.org/10.1111/GEB.12214

Bellon, M. R., Dulloo, E., Sardos, J., Thormann, I., & Burdon, J. J. (2017). In situ conservation-harnessing natural and human-derived evolutionary forces to ensure future crop adaptation. *Evolutionary Applications*, *10*(10), 965–977.

Bennett, J. R., Maloney, R., & Possingham, H. P. (2015). Biodiversity gains from efficient use of private sponsorship for flagship species conservation. *Proceedings of the Royal Society B: Biological Sciences*, *282*(1805), 1–7. https://doi.org/10.1098/rspb.2014.2693

Bonner, F. T. (1990). Storage of seeds: Potential and limitations for germplasm conservation. *Forest Ecology and Management*, *35*(1–2), 35–43.

Botanic Gardens Conservation International (BGCI). (2021). *About botanic gardens*. BGCI. https://www.bgci.org/about/about-botanic-garden/

Bremer, G. (1961). Problems in breeding and cytology of sugar cane - II. The sugar cane breeding from a cytological view-point. *Euphytica*, *10*(2), 121–133. https://doi.org/10.1007/BF00022203

Bretting, P. (2018). 2017 Frank Meyer medal for plant genetic resources lecture: Stewards of our agricultural future. *Crop Science*, *58*, 1–8.

Brouillet, L., Coursol, F., Meades, S. J., Favreau, M., Anions, M., Bélisle, P., & Desmet, P. (2010). *VASCAN, the database of vascular plants of Canada*. http://data.canadensys.net/vascan/

Byrne, P. F., Volk, G. M., Gardner, C., Gore, M. A., Simon, P. W., & Smith, S. (2018). Sustaining the future of plant breeding: The critical role of the USDA-ARS national plant germplasm system. *Crop Science*, *58*(2), 451–468. https://doi.org/10.2135/cropsci2017.05.0303

Cannon, R. J. C. (1998). The implications of predicted climate change for insect pests in the UK, with emphasis on non-indigenous species. *Global Change Biology*, *4*(7), 785–796. https://doi.org/10.1046/J.1365-2486.1998.00190.X

Catling, P. M., & Porebski, S. (1998). Rare wild plants of potential or current economic importance in Canada — A list of priorities. *Journal of Plant Science*, *78*, 653–658.

Chamberlain, S. A., & Boettiger, C. (2017). R, Python, and Ruby clients for GBIF species occurrence data. https://doi.org/10.7287/PEERJ.PREPRINTS.3304V1

Chang, W., Cheng, J., Allaire, J. J., Sievert, C., Schloerke, B., Xie, Y., Allen, J., McPherson, J., Dipert, A., & Borges, B. (2021). *Shiny: Web application framework for R* [R package version, 1(5)]. https://CRAN.R-project.org/package=shiny

Clark, R. L., Shands, H. L., Bretting, P. K., & Eberhart, S. A. (1997). Germplasm regeneration: Developments in population genetics and their implications for managing large diverse germplasm collections. *Crop Science*, *37*, 1–6. https://doi.org/10.2135/cropsci1997.0011183x0

Committee on the Status of Endangered Wildlife in Canada (COSEWIC). (2021). *COSEWIC assessment process, categories, and guidelines*. COSEWIC. https://www.cosewic.ca/index.php/en-ca/assessment-process/wildlife-species-assessment-process-categories-guidelines

Conservation through Reconciliation Partnership (CRP). (2022a). *Indigenous Protected and Conserved Areas (IPCA). (2022)*. CRP. https://conservation-reconciliation.ca/about-ipcas

Conservation through Reconciliation Partnership (CRP). (2022b). *Parks Canada Indigenous stewardship strategy. (2022)*. CRP. https://conservation-reconciliation.ca/knowledge-systems-projects/parks-canada-indigenous-stewardship-strategy

Contreras-Toledo, A. R., Cortés-Cruz, M. A., Costich, D., Rico-Arce, M. d. L., Magos Brehm, J., & Maxted, N. (2018). A crop wild relative inventory for Mexico. *Crop Science*, *58*(3), 1292–1305. https://doi.org/10.2135/CROPSCI2017.07.0452

Convention on Biological Diversity (CBD) (2020). *Aichi biodiversity targets*. CBD. https://www.cbd.int/sp/targets/

Coristine, L. E., & Kerr, J. T. (2011). Habitat loss, climate change, and emerging conservation challenges in Canada. *Canadian Journal of Zoology*, *89*(5), 435–451. https://doi.org/10.1139/Z11-023

Darbyshire, S. J. (2003). *Inventory of Canadian agricultural weeds*. Agriculture and Agri-Food Canada, Research Branch.

Davidson, C. G. (1995). Canadian wild plant germplasm of economic significance. *Canadian Journal of Plant Science*, *75*(1), 23–32. https://doi.org/10.4141/cjps95-006

Dawson, I. K., Guariguata, M. R., Loo, J., Weber, J. C., Lengkeek, A., Bush, D., Cornelius, J., Guarino, L., Kindt, R., Orwa, C., Russell, J., Jamnadass, R., Dawson, I. K., Kindt, Á. R., Orwa, Á. C., Jamnadass, Á. R., Guariguata, M. R., Loo, J., Weber, J. C., …, & Russell, J. (2013). What is the relevance of smallholders' agroforestry systems for conserving tropical tree species and genetic diversity in circa situm, in situ and ex situ settings? A review. *Biodiversity and Conservation*, *22*, 301–324. https://doi.org/10.1007/s10531-012-0429-5

Dempewolf, H., Baute, G., Anderson, J., Kilian, B., Smith, C., & Guarino, L. (2017). Past and future use of wild relatives in crop breeding. *Crop Science*, *57*, 1070–1082. https://doi.org/10.2135/cropsci2016.10.0885

Dickinson, T. A., Lo, E., & Talent, N. (2007). Polyploidy, reproductive biology, and Rosaceae: Understanding evolution and making classifications. *Plant Systematics and Evolution*, *266*(1), 59–78.

Diederichsen, A., & Schellenberg, M. P. (2018). Genetic resources of crop wild relatives: A Canadian perspective. *North American Crop Wild Relatives: Conservation Strategies*, *1*, 33–62. https://doi.org/10.1007/978-3-319-95101-0_2

Engelmann, F., & Engels, J. M. M. (2002). Technologies and strategies for ex situ conservation. In J. Engels, V.R. Rao, A. Brown, & M. Jackson (Eds.), *Managing plant genetic diversity* (pp. 89–104). CABI.

Environment and Climate Change Canada (ECCC). (2016). *Canadian environmental sustainability indicators: Protected areas, by ecological region*. Environment and Climate Change Canada. www.ec.gc.ca/indicateurs-indicators

Environment and Climate Change Canada (ECCC). (2019). *Recovery strategy for the Blue Racer (Coluber constrictor foxii) in Canada*. Environment and Climate Change Canada.

Environment Canada. (2010). *Recovery strategy for the butternut (Juglans cinerea) in Canada. Species at risk act recovery strategy series*. Environment Canada.

Fett-Neto, A. G., DiCosmo, F., Reynolds, W. F., & Sakata, K. (1992). Cell culture of Taxus as a source of the antineoplastic drug taxol and related taxanes. *Bio/Technology*, *10*(12), 1572–1575.

Flora of North America (FNA). (2021). *Flora of North America*. FNA. http://www.efloras.org/flora_page.aspx?flora_id=1

Food and Agriculture Organization of the United Nations (FAO). (2010). *The second report on the State of the world's plant genetic resources for Food and Agriculture*. FAO. https://www.fao.org/3/i1500e/i1500e00.htm

Food and Agriculture Organization of the United Nations (FAO). (2022). *WIEWS - World information and early warning system on plant genetic resources for Food and Agriculture | Food and Agriculture Organization of the United Nations*. FAO. https://www.fao.org/wiews/data/ex-situ-sdg-251/overview/en/

Fox, S. (2012). Picking up the pawpaws: The rare woody plants of Ontario Program at the University of Guelph Arboretum. *Arnoldia*, *69*(3), 2–13.

Frankel, O. H. (1984). Genetic perspectives of germplasm conservation. In W. Arber, K. Illmensee, W.J. Peacock, & P. Starlinger (Eds.), *Genetic manipulation: Impact on man and society* (pp. 161–170). Cambridge University Press.

Fu, Y. B. (2017). The vulnerability of plant genetic resources conserved ex situ. *Crop Science*, *57*(5), 2314–2328. https://doi.org/10.2135/CROPSCI2017.01.0014

Gansberger, M., Montgomery, L. F. R., & Liebhard, P. (2015). Botanical characteristics, crop management and potential of *Silphium perfoliatum* L. as a renewable resource for biogas production: A review. *Industrial Crops and Products*, *63*, 362–372. https://doi.org/10.1016/j.indcrop.2014.09.047

GBIF.org. (2021). *GBIF occurrence download*. Global Biodiversity Information Facility. https://doi.org/10.15468/dl.n9hrqq

Goettsch, B., Urquiza-Haas, T., Koleff, P., Acevedo Gasman, F., Aguilar-Meléndez, A., Alavez, V., Alejandre-Iturbide, G., Aragón Cuevas, F., Azurdia Pérez, C., Carr, J. A., Castellanos-Morales, G., Cerén, G., Contreras-Toledo, A. R., Correa-Cano, M. E., De la Cruz Larios, L., Debouck, D. G., Delgado-Salinas, A., Gómez-Ruiz, E. P., González-Ledesma, M., … R, K. B. (2021). Extinction risk of Mesoamerican crop wild relatives. *Plants People Planet*, *3*(6), 775–795. https://doi.org/10.1002/PPP3.10225

Government of Canada. (2006). *Table 2.2 Standing timber volume by species group and ecozone, 2006*. Government of Canada. https://www150.statcan.gc.ca/n1/pub/16-201-x/2018001/sec-2/tbl/tbl-2.2-eng.htm

Government of Canada. (2018). *How does the forest sector contribute to Canada's economy?* Government of Canada. https://www.nrcan.gc.ca/our-natural-resources/forests-forestry/state-canadas-forests-report/forest-industry-contribute/16517

Gouvernement du Québec. (2002). *Profil sectorial de l.'industrie bioalimentaire au Québec*. Edition 2002. Ministère des Ressources Naturelles.

Griffith, M. P., Clase, T., Toribio, P., Piñeyro, Y. E., Jimenez, F., Gratacos, X., Sanchez, V., Meerow, A., Meyer, A., Kramer, A., Fant, J., Havens, K., Magellan, T. M., Dosmann, M., & Hoban, S. (2020). Can a botanic garden metacollection better conserve wild plant diversity? A case study comparing pooled collections with an ideal sampling model. *International Journal of Plant Sciences*, *181*(5), 485–496. https://doi.org/10.1086/707729

Hajjar, R., & Hodgkin, T. (2007). The use of wild relatives in crop improvement: A survey of developments over the last 20 years. *Euphytica*, *156*(1–2), 1–13. https://doi.org/10.1007/s10681-007-9363-0

Hake, S., & Richardson, A. (2019). Using wild relatives to improve maize. *Science*, *365*(6454), 640–641.

Hanson, J. O., Rhodes, J. R., Riginos, C., & Fuller, R. A. (2017). Environmental and geographic variables are effective surrogates for genetic variation in conservation planning. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(48), 12755–12760. https://doi.org/10.1073/PNAS.1711009114

Harlan, J. R. (1993). *Crops and man*. ASA and CSSSA.

Harlan, J. R., & de Wet, J. M. (1971). Toward a rational classification of cultivated plants. *Taxon*, *20*(4), 509–517.

Hayes, P. M., Stucker, R. E., & Wandrey, G. G. (1989). The domestication of American wildrice. *Economic Botany*, *43*(2), 203–214.

Helfer, S. (2014). Rust fungi and global change. *New Phytologist*, *201*(3), 770–780. https://doi.org/10.1111/NPH.12570

Heywood, V. H. (1999). Use and potential of wild plants in farm households *(No. 15)*. Food & Agriculture Organization.

Heywood, V. H. (2017). The future of plant conservation and the role of botanic gardens. *Plant Diversity*, *39*(6), 309–313. https://doi.org/10.1016/j.pld.2017.12.002

Hoffmann, A. A., & Sgrò, C. M. (2011). Climate change and evolutionary adaptation. *Nature*, *470*(7335), 479–485.

Hufford, M. B., Xu, X., Van Heerwaarden, J., Pyhäjärvi, T., Chia, J. M., Cartwright, R. A., Elshire, R. J., Glaubitz, J. C., Guill, K. E., Kaeppler, S. M., Lai, J., Morrell, P. L., Shannon, L. M., Song, C., Springer, N. M., Swanson-Wagner, R. A., Tiffin, P., Wang, J., Zhang, G., …, & Ross-Ibarra, J. (2012). Comparative population genomics of maize domestication and improvement. *Nature Genetics*, *44*(7), 808–811. https://doi.org/10.1038/ng.2309

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). (2019). *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. IPBES Secretariat.

iNaturalist. (2022). https://www.inaturalist.ca

Iriondo, J. M., Maxted, N., & Dulloo, M. E., & Eds. (2008). *Conserving plant genetic diversity in protected areas: Population management of crop wild relatives*. CABI.

Jarvis, S., Fielder, H., Hopkins, J., Maxted, N., & Smart, S. (2015). Distribution of crop wild relatives of conservation priority in the UK landscape. *Biological Conservation*, *191*, 444–451. https://doi.org/10.1016/j.biocon.2015.07.039

Jarvis, A., Lane, A., & Hijmans, R. J. (2008). The effect of climate change on crop wild relatives. *Agriculture, Ecosystems & Environment*, *126*(1–2), 13–23. https://doi.org/10.1016/J.AGEE.2008.01.013

Karapatzak, E., Dichala, O., Ganopoulos, I., Karydas, A., Papanastasi, K., Kyrkas, D., Yfanti, P., Nikisianis, N., Fotakis, D., Patakioutas, G., & Maloupa, E. (2022). Molecular authentication, propagation trials and field establishment of Greek native genotypes of *Sambucus nigra* L. (Caprifoliaceae): Setting the basis for domestication and sustainable utilization. *Agronomy*, *12*(1), 114.

Kerr, J. T., & Cihlar, J. (2003). Land use and cover with intensity of agriculture for Canada from satellite and census data. *Global Ecology and Biogeography*, *12*(2), 161–172. https://doi.org/10.1046/j.1466-822X.2003.00017.x

Kew, Royal Botanic Gardens. (2016). *The state of the world's plants, 2016*. Royal Botanic Gardens.

Khoury, C. K., Bjorkman, A. D., Dempewolf, H., Ramirez-Villegas, J., Guarino, L., Jarvis, A., Rieseberg, L. H., & Struik, P. C. (2014). Increasing homogeneity in global food supplies and the implications for food security. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(11), 4001–4006. https://doi.org/10.1073/pnas.1313490111

Khoury, C. K., Brush, S., Costich, D. E., Curry, H. A., de Haan, S., Engels, J. M. M., Guarino, L., Hoban, S., Mercer, K. L., Miller, A. J., Nabhan, G. P., Perales, H. R., Richards, C., Riggins, C., & Thormann, I. (2022). Crop genetic erosion: Understanding and responding to loss of crop diversity. *New Phytologist*, *233*(1), 84–118. https://doi.org/10.1111/NPH.17733

Khoury, C. K., Carver, D., Greene, S. L., Williams, K. A., Achicanoy, H. A., Schori, M., León, B., Wiersema, J. H., & Frances, A. (2020). Crop wild relatives of the United States require urgent conservation action. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(52), 33351–33357. https://doi.org/10.1073/PNAS.2007029117

Khoury, C. K., Greene, S. L., Krishnan, S., Miller, A. J., & Moreau, T. (2019). A road map for conservation, use, and public engagement around North America's crop wild relatives and wild utilized plants. *Crop Science*, *59*(6), 2302–2307. https://doi.org/10.2135/cropsci2019.05.0309

Khoury, C. K., Greene, S., Wiersema, J., Maxted, N., Jarvis, A., & Struik, P. C. (2013). An inventory of crop wild relatives of the United States. *Crop Science*, *53*(4), 1496–1508. https://doi.org/10.2135/cropsci2012.10.0585

Kraus, D., & Hebb, A. (2020). Southern Canada's crisis ecoregions: Identifying the most significant and threatened places for biodiversity conservation. *Biodiversity and Conservation*, *29*(13), 3573–3590. https://doi.org/10.1007/s10531-020-02038-x

Kraus, D., Murphy, S., & Armitage, D. (2021). Ten bridges on the road to recovering Canada's endangered species. *FACETS*, *6*(1), 1088–1127.

Kuhnlein, H. V., & Turner, N. J. (2020). *Traditional plant foods of Canadian indigenous peoples: Nutrition, botany and use*. Routledge. https://doi.org/10.4324/9781003054689

Lachowicz, S., Seliga, Ł., & Pluta, S. (2020). Distribution of phytochemicals and antioxidative potency in fruit peel, flesh, and seeds of Saskatoon berry. *Food Chemistry*, *305*, 125430. https://doi.org/10.1016/j.foodchem.2019.125430

Layne, D. R. (1996). The pawpaw [*Asimina triloba* (L.) Dunal]: A new fruit crop for Kentucky and the United States. *Hortscience*, *31*(5), 777–784.

Li, Y., Zhou, S., Zheng, X., & Chu, Q. (2021). Apios americana Medicus: A potential staple food candidate with versatile bioactivities. *Trends in Food Science & Technology*, *112*, 735–752.

Loskutov, I. G. (1999). *Vavilov and his institute. A history of the world collection of plant genetic resources in Russia*. International Plant Genetic Resources Institute. https://doi.org/10.13140/2.1.2632.0644

Mace, G. M. (2004). The role of taxonomy in species conservation. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *359*(1444), 711–719. https://doi.org/10.1098/RSTB.2003.1454

Mann, H. B., & Whitney, D. R. (1947). On a test of whether one of two random variables is stochastically larger than the other. *The Annals of Mathematical Statistics*, *8*(1), 50–60.

Marchenkov, A., & Rozhmina, T. (2003). Cultivation of flax. In A. Muir & N. Westcott (Eds.), *Flax* (pp. 86–103). CRC Press.

Maxted, N. (2013). In situ, ex situ conservation. In S. A. Levin (Ed.), *Encyclopedia of biodiversity* (2nd ed., pp. 313–323). Academic Press. https://doi.org/10.1016/B978-0-12-384719-5.00049-6

Maxted, N., Ford-Lloyd, B. V., Jury, S., Kell, S., & Scholten, M. (2006). Towards a definition of a crop wild relative. *Biodiversity & Conservation*, *15*(8), 2673–2685.

Maxted, N., & Kell, S. P. (2009). Establishment of a global network for the situ conservation of crop wild relatives: Status and needs. In *FAO Commission on Genetic Resources for Food and Agriculture*. FAO.

Maxted, N., & Kell, S. (2013). A role for botanic gardens in CWR conservation for food security. *BG Journal*, *10*(2), 32–35.

Maxted, N., Kell, S., Ford-Lloyd, B., Dulloo, E., & Toledo, Á. (2012). Toward the systematic conservation of global crop wild relative diversity. *Crop Science*, *52*(2), 774–785. https://doi.org/10.2135/cropsci2011.08.0415

Maxted, N., Scholten, M., Codd, R., & Ford-Lloyd, B. (2007). Creation and use of a national inventory of crop wild relatives. *Biological Conservation*, *140*(1-2), 142–159. https://doi.org/10.1016/j.biocon.2007.08.006

McCallum, B. D., Fetch, T., & Chong, J. (2007). Cereal rust control in Canada. *Australian Journal of Agricultural Research*, *58*(6), 639–647.

Meyer, A., & Barton, N. (2019). Botanic gardens are important contributors to crop wild relative preservation. *Crop Science*, *59*(6), 2404–2412.

Migicovsky, Z., Warschefsky, E., Klein, L. L., & Miller, A. J. (2019). Using living germplasm collections to characterize, improve, and conserve woody perennials. *Crop Science*, *59*(6), 2365–2380. https://doi.org/10.2135/cropsci2019.05.0353

Missouri Botanical Garden (MBG). (2021). *Discover and share - Grafting the grape: American grapevine rootstock in Missouri and the world*.https://discoverandshare.org/2021/08/31/grafting-the-grape-american-grapevine-rootstock-in-missouri-and-the-world/

Mounce, R., Smith, P., & Brockington, S. (2017). Ex situ conservation of plant diversity in the world's botanic gardens. *Nature Plants*, *3*(10), 795–802. https://doi.org/10.1038/s41477-017-0019-3

Mratinić, E., & Fotirić, M. (2007). Selection of black elderberry (*Sambucus nigra* L.) and evaluation of its fruits usability as biologically valuable food. *Genetika*, *39*(3), 305–314.

Muir, G., Lawrence, E. R., Grant, J. W. A., & Fraser, D. J. (2021). Assessing biodiversity hotspots below the species-level in Canada using designatable units. *Global Ecology and Conservation*, *26*, e01506. https://doi.org/10.1016/j.gecco.2021.e01506

National Tree Seed Centre (NTSC). (2021). *NTSC – Seed collection and conservation*. https://www.nrcan.gc.ca/science-and-data/research-centres-and-labs/forestry-research-centres/atlantic-forestry-centre/national-tree-seed-centre/ntsc-seed-collection-and-conservation/23984

NatureServe. (2022). *NatureServe Canada*. NatureServe. https://www.natureserve.org/canada

Newediuk, L., Ethier, J. P., Boyle, S. P., Aubin, J. A., Balluffi-Fry, J., Dedeban, E., Laforge, M. P., Prokopenko, C. M., Turner, J. W., Webber, Q. M. R., & Wal, E. V. (2021). Sociopolitical factors drive conservation planning timelines: A Canadian case study with global implications. *Biological Conservation*, *257*, 109091. https://doi.org/10.1016/J.BIOCON.2021.109091

Ollat, N., Bordenave, L., Tandonnet, J. P., Boursiquot, J. M., & Marguerit, E. (2014). Grapevine rootstocks: Origins and perspectives. *I International Symposium on Grapevine Roots*, *1136*, 11–22.

Pebesma, E. (2018). Simple features for R: Standardized support for spatial vector data. *R Journal*, *10*(1), 439–446. https://doi.org/10.32614/RJ-2018-009

Peña, F. B., Villalobos, G., Martínez, M. A., Sotelo, A., Gil, L., & Delgado-Salinas, A. (1999). Use and nutritive value of talet beans, *Amphicarpaea bracteata* (Fabaceae: Phaseoleae) as human food in Puebla, Mexico. *Economic Botany*, *53*(4), 427–434.

Plucknett, D. L., Smith, N. J. H., Williams, J. T., & Murthi, A. N. (1987). *Gene banks and the world's food*. Princeton University Press.

Prescott-Allen, C., & Prescott-Allen, R. (1986). *The first resource: Wild species in the North American economy*. Yale University Press.

Qian, B., Jing, Q., Bélanger, G., Shang, J., Huffman, T., Liu, J., & Hoogenboom, G. (2018). Simulated canola yield responses to climate change and adaptation in Canada. *Agronomy Journal*, *110*(1), 133–146. https://doi.org/10.2134/AGRONJ2017.02.0076

R Core Team. (2021). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Reinert, S., Van Tassel, D. L., Schlautman, B., Kane, N. C., & Hulke, B. S. (2019). Assessment of the biogeographical variation of seed size and seed oil traits in wild *Silphium integrifolium* Michx. genotypes. *Plant Genetic Resources*, *17*(5), 427–436.

Rick, C. M., & Chetelat, R. T. (1995). Utilization of related wild species for tomato improvement. *I International Symposium on Solanacea for Fresh Market*, *412*, 21–38.

Royal Botanical Gardens (RBG). (2022). *Plants & conservation: Science*. RBG. https://www.rbg.ca/plants-conservation/science/

Schimdhuber, J., & Tubiello, F. N. (2007). Food security under climate change. *PNAS*, *104*(50), 19703–19708.

Secretariat of the Convention on Biological Diversity (CBD) (2005). *Handbook of the Convention on Biological Diversity Including its Cartagena Protocol on Biosafety*, 3rd edition. Secretariat of the Convention on Biological Diversity.

Seiler, G. J., Qi, L. L., & Marek, L. F. (2017). Utilization of sunflower crop wild relatives for cultivated sunflower improvement. *Crop Science*, *57*(3), 1083–1101. https://doi.org/10.2135/cropsci2016.10.0856

Sharifi, M. (2018). *Revitalizing indigenous cultivation and seeding agricultural resilience*. CGU-CSSS-CIG-ESSSA-CSAFM.

Sidik, S. M. (2022). Weaving Indigenous knowledge into the scientific method. *Nature*, *601*(7892), 285–287. https://doi.org/10.1038/D41586-022-00029-2

Small, E. (2013). *North American cornucopia: Top 100 indigenous food plants*. CRC Press.

Smith, W. N., Grant, B. B., Desjardins, R. L., Kroebel, R., Li, C., Qian, B., Worth, D. E., McConkey, B. G., & Drury, C. F. (2013). Assessing the effects of climate change on crop production and GHG emissions in Canada. *Agriculture, Ecosystems & Environment*, *179*, 139–150. https://doi.org/10.1016/J.AGEE.2013.08.015

Spencer, R., & Cross, R. (2017). The origins of botanic gardens and their relation to plant science, with special reference to horticultural botany and cultivated plant taxonomy. *Muelleria*, *35*, 43–93.

Statistics Canada. (2011). *2011 Census boundary files*. Statistics Canada. https://www12.statcan.gc.ca/census-recensement/2011/geo/bound-limit/bound-limit-2011-eng.cfm

St. Pierre, R. G. (1992). The development of native fruit species as horticultural crops in Saskatchewan. *Hortscience*, *27*(8), 866–947. https://doi.org/10.21273/HORTSCI.27.8.866

Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(50), 20260–20264. https://doi.org/10.1073/pnas.1116437108

Tito, R., Vasconcelos, H. L., & Feeley, K. J. (2018). Global climate change increases risk of crop yield losses and food insecurity in the tropical Andes. *Global Change Biology*, *24*(2), e592–e602. https://doi.org/10.1111/GCB.13959

Turner, N. J., & Aderkas, P. V. (2012). Sustained by First Nations: European newcomers use of Indigenous plant foods in temperate North America. *Acta Societatis Botanicorum Poloniae*, *81*(4), 295–315.

United Nations. (2022). *SDG Indicators - Metadata repository; Target 2.5*. United Nations. https://unstats.un.org/sdgs/metadata?Text=&Goal=2&Target=2.5

United States Environmental Protection Agency (USEPA). (2021). *Ecoregions of North America*. USEPA. https://www.epa.gov/eco-research/ecoregions-north-america

University of British Columbia Botanical Garden (UBC BG). (2022). *Research & collections: Research in the garden*. https://botanicalgarden.ubc.ca/research-collections/research/research-in-the-garden/

University of Guelph Arboretum (UoG Arboretum). (2022). *Research & conservation: Elm Recovery Project*. University of Guelph Arboretum. https://arboretum.uoguelph.ca/researchandstewardship/elmrecovery

University of Saskatchewan. (2021). *University of Saskatchewan prairie Fruit gene bank*. University of Saskatchewan. https://research-groups.usask.ca/fruit/extension-events-/gene-Bank/

USDA-ARS. (2021). *GRIN-Global*. USDA-ARS. https://npgsweb.ars-grin.gov/gringlobal/

Vavilov, N. I. (1926). Studies on the origin of cultivated plants. *Bulletin of Applied Botany*, *16*, 3–248.

Vincent, H., Wiersema, J., Kell, S., Fielder, H., Dobbie, S., Castañeda-Álvarez, N. P., Guarino, L., Eastwood, R., León, B., & Maxted, N. (2013). A prioritized crop wild relative inventory to help underpin global food security. *Biological Conservation*, *167*, 265–275.

Walters, C., Richards, C. M., & Volk, G. M. (2018). Genebank conservation of germplasm collected from wild species. *North American Crop Wild Relatives: Conservation Strategies*, *1*, 245–280. https://doi.org/10.1007/978-3-319-95101-0_10/TABLES/4

Warschefsky, E. J., Klein, L. L., Frank, M. H., Chitwood, D. H., Londo, J. P., von Wettberg, E. J. B., & Miller, A. J. (2016). Rootstocks: Diversity, domestication, and impacts on shoot phenotypes. *Trends in Plant Science*, *21*(5), 418–437. https://doi.org/10.1016/J.TPLANTS.2015.11.008

Weber, J. (2021). Traditional uses and beneficial effects of various species of berry-producing plants in eastern Canada. *Botany*, *99*(999), 1–8.

Wiersema, J. H. (2019). *GRIN Taxonomy. U.S. National Plant Germplasm System: Checklist dataset*. https://doi.org/10.15468/AO14PP

Wiersema, J. H., León, B., & Garvey, E. J. (2012). Identifying wild relatives of subtropical and temperate fruit and nut crops. *Acta Horticulturae*, *948*, 285–288.

Wright, R. G., Murray, M. P., & Merrill, T. (1998). Ecoregions as a level of ecological analysis. *Biological Conservation*, *86*(2), 207–213. https://doi.org/10.1016/S0006-3207(98)00002-0

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Ulrich, J. C., Moreau, T. L., Luna-Perez, E., Beckett, K. I. S., Simon, L. K., Migicovsky, Z., Diederichsen, A., & Khoury, C. K. (2022). An inventory of crop wild relatives and wild-utilized plants in Canada. *Crop Science*, *62,* 2294–2318. https://doi.org/10.1002/csc2.20807