GLOBAL STRATEGY FOR THE CONSERVATION AND USE OF *CAPSICUM* GENETIC RESOURCES

With support from

CROP TRUST

The International Treaty ON PLANT GENETIC RESOURCES FOR FOOD AND AGRICULTURE

Federal Ministry of Food and Agriculture

DISCLAIMER

This document aims to provide a framework for the efficient and effective conservation of genetic resources of *Capsicum* crops. The Crop Trust supported this initiative and commissioned the World Vegetable Center and the San Diego Botanic Garden to coordinate the development of the strategy. The overall objective is to outline shared responsibilities and needs for the long-term conservation of these genetic resources and to facilitate their use for food security and sustainable agriculture. The Crop Trust considers this document to be an important framework for guiding the allocation of its resources. However, the Crop Trust does not take responsibility for the relevance, accuracy or completeness of the information in this document and does not commit to funding any of the priorities identified. This strategy document (26 September 2022) is expected to continue to evolve and be updated as and when circumstances change or new information becomes available. Please direct any specific questions and/or comments to the strategy coordinators Derek Barchenger (derek.barchenger@worldveg.org) and Colin Khoury (ckhoury@sdbgarden.org).

COVER

Photograph by World Vegetable Center

ACKNOWLEDGMENTS

The development of this Global Crop Conservation Strategy was funded by the Government of Germany (BMEL) as part of the three-year project led by the Crop Trust: "Breathing new life into the Global Crop Conservation Strategies: Providing an Evidence Base for the Global System of *Ex situ* Conservation of Crop Diversity."

The Crop Trust also cooperated with the Secretariat of The International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) in the development of this document.

Appendix IV of this document provides a summary of a recent report: "The plants that feed the world: baseline information to underpin strategies for their conservation and use". That study was produced as a collaboration led by the Secretariat of the ITPGRFA, and involving the International Center for Tropical Agriculture (CIAT) and the Crop Trust, funded by the Norwegian Agency for Development Cooperation (NORAD, Government of Norway).

The development of this strategy was a collaborative effort of researchers and *Capsicum* experts donating individual and group contributions. We thank Asta M. Tamang, Axel Diederichsen, Cristina Mallor, Dallas Kessler, Daniel Fernández Rivera, Danise Coon, Dario Danojević, Erika Salazar Suazo, Fanuel Triaswanto, Gustavo Heiden, Helena Stavělíková, Helmi Kurniawan, Hiroshi Matsunaga, Hoang Thi Hue, Huynh Thi Phuong Lien, Indivar Prasad, Isaura Martín, Jose Vicente Valcarcel, Juliano Gomes Pádua, Kunyaporn Pipithsangchan, Leonardo Togno, Maarten van Zonneveld, Manuel Alejandro Guzmán Hernández, Maria Jose Diez, Mohammad Shahid, Nadica Sandeva Atanasova, Najla Mezghani, Nguyen Van Kien, Oscar Alfonso Loaiza Loaiza, Pasquale Tripodi, Philip Kauth, Ponnam Naresh, Rajesh Kumar, Rebecca Stevens, Rinda Kirana, Robert Jarret, RR. Rahmi Sri Sayekti S.P., Sally Norton, Schierscher Beate, Surapong Dumrongkittikule, Tanyarat Tarinta, Thabo Tjikana, Theerapat Luangsuphabool, Tran Kim Cuong, Tran Ngoc Hung, Tso-chi Yang, Ugyen Phuntsho, Velichka Todorova, Veselina Banova Masheva, Willem van Dooijeweert, and William Solano Sanchez and their colleagues for data/survey contributions.

We thank Anas Musallam, Aristide Carlos Houdegbe, Bradbury Browne, Chadeene Beckles, Cristina Mallor, Dallas Kessler, Dennis Nicuh Lozada, Dimitrina Kostova, Enoch G. Achigan-Dako, Erika Salazar, Evaldina Pedro, Fayaz Shah, Gloria Barboza, Gustavo Heiden, Herbaud Zohoungbogbo, Hiroshi Matsunaga, Hoang Minh Chau, Hugo Ramirez, Indivar Prasad, Juan Camilo Henao-Rojas, Khandaker Nafiz Bayazid, Kien Nguyen Van, Kunyaporn Pipithsangchan, Lien Huynh, Lynn Bohs, Ma. Queenie S. Tabur, Maarten van Zonneveld, Manoj Kumar Nalla, María de los Ángeles Mérida Guzmán, María J. Diez, Michael Kantar, Michael Kwabena Osei, Min San Thein, Mirjana Jankulovska, Nadica Sandeva Atanasova, Najla Mezghani, Nakarin Jeeatid, Nurul Hidayatun, Omaira Avila Rostant, Oscar Loaiza, Pasquale Tripodi, Patcharaporn Suwor, Paul Bosland, Raisa Ramdeen, Rinda Kirana, Robert Jarret, Sumitha Thushar, Tanyarat Tarinta, Tiny Mpho Motlhaodi, Tran Ngoc Hung, Velichka Todorova, Véronique Lefebvre, Veselina Masheva, Vicens, Willem van Dooijeweert, William Solano, Yacenia Morillo Coronado, Ziad Tahabsom, and Zvezda Bogoevska for participation in stakeholder meetings. We thank all colleagues who reviewed the draft strategy.

AUTHORS

Derek W. Barchenger, World Vegetable Center, Tainan, Taiwan; Colin K. Khoury, San Diego Botanic Garden, San Diego, USA and International Center for Tropical Agriculture (CIAT), Cali, Colombia

RECOMMENDED CITATION

Barchenger D.W. and Khoury C.K. 2022. *A Global Strategy for the Conservation and Use of* Capsicum *Genetic Resources*. Global Crop Diversity Trust. Bonn, Germany. DOI: 10.5281/zenodo.8367264

The Crop Trust, Bonn, Germany, https://www.croptrust.org | Project coordinator at the Crop Trust: Peter Giovannini

Supplementary data: Supplementary data for Barchenger D.W. and Khoury C.K. 2022. A Global Strategy for the Conservation and Use of *Capsicum* Genetic Resources. Global Crop Diversity Trust. Bonn, Germany. DOI: 10.22001/wvc.74702 (https://worldveg.tind.io/record/74702)

CONTENTS

Capsicum annuum, 1897. Illustration: Franz Eugen Köhler, Köhler's Medizinal-Pflanzen

Capsicum diversity. Photo: World Vegetable Center

EXECUTIVE SUMMARY

Chile peppers are used worldwide as a vegetable, spice, medicine, colorant, and chemical deterrent. They are consumed daily by approximately a quarter of the world's population. There are five domesticated taxa and ca. 37–40 wild taxa in the chile pepper (*Capsicum* L.) genus. Chile peppers are typically a high value crop, providing economic benefits to both smallholders and larger-scale farmers. Over the past 60 years there have been increases in both harvested area and tonnage for both fresh or green and dry red chile pepper globally, with particular increases in Asia, where more than two-thirds of production now occurs. Chile peppers are also a highly traded commodity worldwide.

Substantial *Capsicum* genetic resources are conserved *ex situ* in international, national, and subnational genebanks, universities, botanic gardens, seed conservation organizations, and other institutions worldwide, with over 50,000 accessions in total. It is not currently clear, or straightforward to clarify, what proportion of these represent distinct and unique accessions, although stakeholder surveys conducted during the development of this strategy indicate that many collections are considered to be highly distinct/unique. Several collections stand out in terms of numbers of accessions, species-level diversity, and/or diversity in terms of countries of origin of samples. These include the World Vegetable Center (WorldVeg), the USDA Plant Genetic Resources Conservation Unit (USA), the Centre for Genetic Resources (Netherlands), the Leibniz Institute of Plant Genetics and Crop Plant Research (IPK)/Information and Coordination Centre for Biological Diversity (IBV) (Germany), Embrapa (Brazil), New Mexico State University (USA), the Institute for Agrobotany (RCA)/Centre for Plant Diversity (Hungary), the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), the Departamento Nacional de Recursos Fitogenéticos (Ecuador), the Instituto Nacional de Innovación Agropecuaria y Forestal (Bolivia), the Research Centre for Vegetable and Ornamental Crops (Italy), the Taiwan Agricultural Research Institute (Taiwan), the National Agriculture and Food Research Organization Genebank (Japan), the Universitat Politècnica de València (Spain), the Corporación Colombiana de investigación Agropecuaria (AGROSAVIA) (Colombia), and the Centre de Ressources Biologiques Légumes, Institut national de recherche pour l'agriculture, l'alimentation et l'environnement (INRAE) (France). This list should not be considered comprehensive of all collections with notable or important *Capsicum* diversity. It is evident that *Capsicum* collections worldwide are not fully reported in global databases; likewise, the information contained within these databases may not be fully updated or accurate. Moreover, the stakeholder surveys returned during this strategy process were not comprehensive of all *Capsicum* collections worldwide, with particularly notable gaps for collections in Mexico and other parts of Mesoamerica, the Caribbean, as well as South America, and important secondary regions of diversity in Asia such as China, Korea, and India.

Regarding taxonomic representation of *Capsicum* in *ex situ* conservation, the cultivated taxa are clearly much better represented than the wild species, as with most crop genepools, and likely comprise around 97–99% of all *Capsicum* accessions worldwide. Representation of cultivated taxa generally reflects their global importance and geographic spread. Conversely, the wild species are generally extremely poorly represented *ex situ*, with only a few exceptions. Further collecting of the wild species is clearly needed to improve their representation in *ex situ* conservation and their availability and accessibility for research. Further collecting within taxonomic hotspots, namely Brazil, Andean countries, and parts of Mesoamerica, is of particular importance and may provide a focus for efficient conservation of multiple taxa and ecotypes.

Existing gaps in collections have been identified at species/taxa, genetic, ecogeographic, varietal, trait, and other levels. The *Capsicum* community engaged in this strategy identified a series of ways in which further acquisition may proceed, toward the larger goal of greater representation of *Capsicum* diversity within *ex situ* collections globally. Collaboration to this end is key, including by international and regional institutions partnering with national genebanks to jointly conduct field collection. Recognizing current policy challenges to bilateral exchange of *Capsicum* genetic resources, international facilitation by organizations such as the Crop Trust may be extremely helpful in negotiating such partnerships and in organizing funding.

Long-term storage infrastructure exists for the great majority of collections and their accessions, while medium- and short-term conditions supplement the long-term infrastructure. Further efforts should be made to enhance long-term conservation for all distinct accessions, either at their current sites or through duplication at institutions already having long-term storage infrastructure. Likewise, further efforts to improve storage materials (e.g. aluminum packets) and processes (i.e. temperature and humidity standards) should be made for collections not currently following optimum practices. For many collections, pests and diseases present challenges to storage and maintenance, and further efforts to limit their negative impacts are important.

Almost 40% of *Capsicum* accessions on average worldwide presently require urgent regeneration, according to stakeholder survey respondents, with some institutions reporting up to 100% of accessions requiring urgent regeneration. Further efforts – and therefore resources – are clearly needed to reduce the proportion of accessions urgently needing regeneration.

A substantial proportion of *Capsicum* accessions globally have been characterized for phenotypic characters. This is good news for their potential value for crop breeding, and further efforts should be made to complete characterization of collections. There may be a disconnect, though, between basic characters recorded and those of most importance to crop breeders, thus more interaction may be in order, including potentially an update to characterization guidelines for *Capsicum* genetic resources. Much less data currently exists on evaluation for biotic and abiotic stresses, and on genetic characterization. Funding for evaluation and genotyping is less easily found than for phenotypic or basic characterization. Relatively few *Capsicum* collections currently can and will be able to continue to afford continuous screening for disease and other biotic pressures, which appear to be increasing.

As *Capsicum diversity* can be conserved as seed, existing facilities appear to be capable of providing safety duplication of chile pepper collections globally, including at the Svalbard Global Seed Vault (SGSV) and at WorldVeg and the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), as well as at several national genebanks. Global genetic resources databases indicate that around 18% to 37% of *Capsicum* accessions globally are currently safety duplicated. The SGSV currently holds over 6000 *Capsicum* accessions; this may represent around 13% of the total worldwide. The stakeholder surveys indicate that around 41% of accessions on average are already safety duplicated, although considerable variation exists across institutions, with more than one quarter of institutions having no safety duplication of their *Capsicum* collection and an additional 5% being unaware of the status of safety duplication.

As with acquisition, regeneration, characterization, and safety duplication, collaboration on documentation and information management may help to resolve current limitations, although national and international policies on genetic resources and associated information may constrain such collaboration in some cases. A variety of free tools and programs, for example the GRIN-Global software for collections management, are available, including with ongoing development and support, and these are increasingly linkable/communicable with global databases such as Genesys. Further capacity building on the value and operation of these tools may aid in further adoption.

The substantial collections of *Capsicum* in international and regional centers such as WorldVeg and CATIE, as well as in public national genebanks, particularly in North America and in Europe, enable a global system of facilitated and widespread access to *Capsicum* genetic resources, including online information/ordering systems and free or low-cost distributions. Due to the mandates of these institutions, these *Capsicum* genetic resources are largely accessible under the SMTA of the International Treaty on Plant Genetic Resources for Food and Agriculture, foregoing the need for bilateral negotiations under the Nagoya Protocol in most cases, even though *Capsicum* is not listed in Annex 1 of the ITPGRFA. These are likely among the reasons why *Capsicum* genetic resources are distributed at a relatively high rate, compared to many other fruit and vegetable crops. For other *ex situ* repositories, facilitated international access to *Capsicum* genetic resources is currently much more limited, with corollary reductions in annual distributions. This said, substantial within-country distributions are occurring in some countries and regions, supporting national and sub-national research efforts. Several types of users are working with *Capsicum* genetic resources, including academics, public breeding programs, research institutions, government departments, farmer organizations, private industry, non-governmental organizations, and other genebanks.

Improving access to *Capsicum* genetic resources is not simple or straightforward, as it is often linked to national and institutional policy, which is largely outside the responsibilities and power of *Capsicum* genetic resources practitioners. All efforts to motivate more open sharing of these resources are important, including by advocating for the inclusion of *Capsicum* within Annex 1 of the ITPGRFA, based on its clear international importance. Steps to reduce constraints caused by pests and diseases, in particular viruses, are also important to increase the availability of *Capsicum* genetic resources.

In addition to the challenges to the conservation and use of *Capsicum* genetic resources mentioned above, stakeholders identified lack of funding, lack of staff capacity, and inadequate facilities as major factors limiting the abilities of many collections to perform optimally. None of these are simple to resolve in a global context of limited and often declining funding for biodiversity conservation and agricultural research.

Collaboration offers some potential to mitigate these enormous and fundamental challenges, particularly through capacity building. Further efforts should be made to share information, tools, and methods for the conservation of chile pepper resources, while reductions in unnecessary duplication of efforts could also be explored. For these steps to be taken, members of the global *Capsicum* genetic resources community need more opportunities to get to know one another and to build an atmosphere of trust and collaboration. Global-level projects focused on creating and strengthening networks within the *Capsicum* community, as well as building capacities and addressing constraints related to the management and acquisition, regeneration, characterization and evaluation, safety duplication, documentation and information systems, and access will likely be very useful, if not essential, to further progress.

Capsicum frutescens. Photo: World Vegetable Center

1 INTRODUCTION

1.1 Rationale

As part of an initiative led by the Global Crop Diversity Trust (Crop Trust) and funded by the Federal Ministry of Food and Agriculture of Germany, a conservation and use strategy has been developed for the genetic resources of crops in the *Capsicum* L. genus. This strategy provides information on the current status of *Capsicum* genetic resources and outlines a framework for enhancements to their conservation and accessibility for use. While this strategy has been published (dated 21 October 2022), the process is intended to be ongoing, with updates as circumstances change or when important new information becomes available.

The strategy begins by providing summary background information on *Capsicum* crops. It then documents the current status of conservation and use of *Capsicum* genetic resources, based on published literature and online databases as well as community surveys and stakeholder meetings. The strategy concludes by outlining the further steps needed to strengthen the conservation and accessibility for use of these resources, with focus on collaborative efforts.

1.2 Methods and data sources

The development of this strategy took place between April 2021 and April 2022, facilitated by Derek W. Barchenger of WorldVeg and Colin K. Khoury of the San Diego Botanic Garden and the International Center for Tropical Agriculture (CIAT) and coordinated by Peter Giovannini of the Crop Trust.

Summary information was synthesized from published literature, online databases, and direct communications with taxonomists and crop breeders on: the origins and history of *Capsicum* crops; their current economic, nutritional, and cultural importance; and the diversity and genetic resources within the genus. Data on the current status of conservation and accessibility for use of *Capsicum* genetic resources were compiled from pertinent online genetic resource databases, a *Capsicum* genetic resource community survey, and *Capsicum* genetic resource stakeholder meetings.

Regarding online genetic resource databases, information on *Capsicum* was retrieved from the Genesys plant genetic resources portal (Global Crop Diversity Trust 2022), the World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture (WIEWS) of the United Nations Food and Agriculture Organization (FAO 2022b), the Botanic Gardens Conservation International PlantSearch database (BGCI 2018), the Global Biodiversity Information Facility (GBIF) (GBIF 2022), and the Seed Portal of the Svalbard Global Seed Vault (Nordgen 2022).

A *Capsicum* genetic resources survey (Annex 1) was developed for this strategy by the facilitating authors and distributed to genetic resource institutions/practitioners, who were identified based on reported holdings in existing databases, relevant literature, and the authors' knowledge of collections worldwide. The survey was made available both through an online survey platform (Survey Monkey) and through an emailed Microsoft Word document, and contained 65 questions relevant to the current status of collections, as well as perceived future trends. A total of 40 surveys were returned and the data was processed by the facilitating authors for inclusion in this strategy.

Capsicum genetic resource stakeholder meetings were conducted on January 11–13, 2022 to report the synthesized results of the genetic resource surveys and provide a forum for discussion on the status of *Capsicum* genetic resources worldwide, as well as future goals, challenges, and needs. All respondents to the surveys were directly invited to participate, while an open invitation was also made to all known *Capsicum* genetic resource institutions, as well as to relevant taxonomists, plant breeders, and other experts. These meetings were repeated twice (at different hours) within this timeframe to enable as many stakeholders as possible worldwide to participate. The meetings were attended by a total of 64 participants from 36 countries. The meetings occurred virtually (on Zoom) in light of the ongoing SARS-CoV-2 pandemic.

Following the stakeholder meetings, the facilitating authors drafted the strategy based on information drawn from all project activities and data sources. The draft strategy was distributed to stakeholders and inputs were received and incorporated prior to finalization. The Crop Trust conducted final technical and copy edits.

2 OVERVIEW OF *CAPSICUM* CROPS AND THEIR WILD RELATIVES

2.1 Origins and history

The chile pepper genus, *Capsicum* L, originated in South America in an arid regionincluding areas of southern Brazil, Bolivia, Paraguay, and northern Argentina (Pickersgill 1984). This region continues to hold the highest *in situ* concentration of wild chile pepper taxa, as well as cultivated areas of all major domesticated species (Pickersgill 1984; Walsh and Hoot 2001). The genus dispersed from this region, initially likely by birds and later also by people, throughout the neo-tropics and -subtropics (Bosland and Votava 2012; Carrizo Garcia et al. 2016; Noss and Levey 2014). Documented uses of wild chile peppers by people date as early as 8,000 to 10,000 years ago (Davenport 1970; Heiser 1969; Pickersgill 1966). Domesticated forms and human dispersal within the Americas, including to parts of the Caribbean, have been documented from at least 6,000 years ago, making chile pepper one of the earliest domesticated crops of the Americas (Aguilar-Melendez et al. 2009; Eshbaugh 2012; Jarret et al. 2019; Perry and Flannery 2017; Perry et al. 2007; Pickersgill 1969, 1977; Walsh and Hoot 2001).

Originally used primarily for medicinal and ceremonial purposes, chile peppers became an important spice and vegetable for diverse Indigenous peoples across the tropics and subtropics of the Americas (Bosland and Votava 2012; Luna-Ruiz et al. 2018; Smith 1967). Perry et al. (2007) identified *Capsicum*-specific starch grains at seven separate sites ranging from Southern Peru to the Bahamas, dating to more than 6,000 years ago. Knowledge of the culinary uses of chile pepper is derived from such archeological artifacts, reports from early European explorers, botanical observations, and even uses among modern populations living in the region where chile peppers were first cultivated (DeWitt 2020). Such work has demonstrated that maize (*Zea mays* L.) and chile pepper occurred together within an ancient food complex that predates pottery in some regions (Perry et al. 2007).

Chile pepper plays a role in the creation myth of the Inca peoples in Peru (de la Vega 1609) and the Cora peoples in Mexico (Nabhan 1985), among others. In addition to being used for medicine and for ceremonial purposes, the fruits were also reported to serve as a currency. Chile peppers were used as taxation or tribute by the Aztecs and the Incas, a practice which was later adopted by the Spanish colonizers (Durán 1588). Into the 20th century, the fruits were used to barter for goods in Central America, for example with twelve chile peppers being worth around ten grams of salt or four onions (McBryde 1933, 1944).

Chile pepper was largely, or more likely wholly, unknown outside of the Americas prior to the 15th century. Peter Martyr wrote in 1493 that Columbus had brought home "pepper more pungent than that of the Caucasus" (Andrews 1984). The novel spice was rapidly incorporated in local cuisines not only in Europe but across Africa and Asia (Bosland and Votava 2012). In some places in India and China, for example, chile pepper became the principal or dominant spice. This adoption was so extensive in East Asia that early taxonomists erroneously identified China as a region of origin for the crop and included the country in the scientific name of one of the domesticated species (i.e. *Capsicum chinense* Jacq., named in 1777).

Recent genotype-by-sequencing (GBS)-derived single nucleotide polymorphism (SNP) analysis of more than 10,000 *Capsicum* accessions held in genebanks around the world has shed further light on the dissemination patterns of *Capsicum* crops (Tripodi et al. 2021). The authors found chile pepper was clearly a desirable and widely tradable cultural commodity, spreading rapidly throughout the globe along major maritime and terrestrial trade routes, particularly those of the Spanish and the Portuguese in the 16th century. Marker associations and possible selective sweeps affecting traits such as heat (capsaicinoid production) were observed, and these traits were non-uniformly distributed around the world, suggesting that human preferences exerted a major influence on the genetic structure of domesticated chile pepper. These findings strongly support previous hypotheses regarding the dissemination of *Capsicum* from the Americas to the rest of the world (Bosland and Votava 2012), including via the Portuguese empire trade routes connecting coastal colonies in Brazil, Africa, India, and China (Russell-Wood 1998) and the "silver route," connecting Spanish colonies of Peru and Mexico to China (Flynn and Giraldez 1994).

2.2 Current economic, nutritional, and cultural importance

Today, chile peppers are used worldwide as a vegetable, spice, colorant, pharmaceutical, and chemical deterrent (Wall and Bosland 1998). They are consumed daily by approximately a quarter of the world's population (Halikowksi Smith 2015). Some chile pepper varieties have exceptionally high levels of provitamin A (Guzman et al. 2011; Kantar et al. 2016), and thus can make a significant contribution to fulfilling that nutritional requirement. Chile peppers are typically a high value crop (DeWitt and Bosland 1993), providing economic benefits to both smallholders and larger-scale farmers (Kahane et al. 2013).

A number of wild *Capsicum* taxa continue to be harvested from nearby populations and sold in local and regional markets. For example, fruits of *Capsicum eximium* Hunz. and the wild progenitor *Capsicum baccatum* L. var. *baccatum* are in demand in Bolivia due to their unique taste profiles, thus providing market opportunities for local communities (van Zonneveld et al. 2015). In Mexico, flavors produced by the wild progenitor taxon *Capsicum annuum* L. var. *glabriusculum* (Dunal) Heiser & Pickersgill makes them highly sought after, with consumers paying premiums for more flavorful fruit (Villalon-Mendoza et al. 2014).

According to the Food and Agricultural Organization (FAO) of the United Nations, in 2020, total global production of chile pepper was 40,294,201 tonnes on an area of 3,685,130 ha, of which 36,136,996 tonnes produced on 2,069,990 ha was green or fresh pepper or sweet pepper, and 4,157,205 tonnes produced on 1,615,140 ha was chile pepper for the dry/powder market (FAO 2020a). Over the past 60 years there have been increases in both harvested area (**Figure 2.1**) and tonnage (**Figure 2.2**) for both fresh or green and dry red chile pepper globally. There was a substantial increase in production, particularly for fresh green chile pepper, in the mid-1990s, and in the early 2000s the total hectarage of production of fresh green chile pepper surpassed that of dry red chile pepper. This growth was mostly located in China, which has seen a major increase in production of fresh green chile pepper in the last 20 years, whereas most other countries have seen an overall decrease in production (**Figure 2.3**). India, Indonesia, Mexico, Spain and Turkey have also had notable increases in production over the past 20 years.

Approximately 68% of the total area and 67% of the total tonnage of chile pepper was produced in Asia in 2020, followed by Africa (21% and 12%, respectively), the Americas (8% and 12%, respectively), Europe (3% and 9%, respectively) and Oceania (0.06% and 0.11%, respectively). The estimated per capita consumption of chile pepper was also highest in Asia (6 kg/person/yr), while it was relatively consistent across Africa (4.2 kg/person/yr), the Americas (4.7 kg/person/yr) and Europe (4.8 kg/person/yr). Oceania currently has the lowest per capita consumption, with an estimated 1.02 kg/person/yr. At the country level, China was the largest producer of fresh market or green chile pepper by far, with 16,650,855 tonnes produced on an area of 734,961 ha, followed by Mexico (2,818,443 tonnes), Indonesia (2,772,594 tonnes), Turkey (2,636,905 tonnes), and Spain (1,472,850 tonnes). The largest producer of chile pepper for the dry or powder market was India, with 1,702,000 tonnes produced on 683,000 ha, followed by Thailand (322,886 tonnes), China (307,593 tonnes), Ethiopia (295,981 tonnes), and Bangladesh (157,607 tonnes).

Worldwide, chile pepper is an important cash crop, with a high farmgate value; being able to access the fresh and processing markets provides farmers multiple profit opportunities (Bosland and Votava 2012). In general, chile peppers are produced by smallholder farmers, with less than 2 ha, particularly in lower and lower middle-income countries, which are often the largest chile pepper producers and consumers. For example, in one of the largest chile pepper producing regions, Bogra (Bangladesh), the average chile pepper

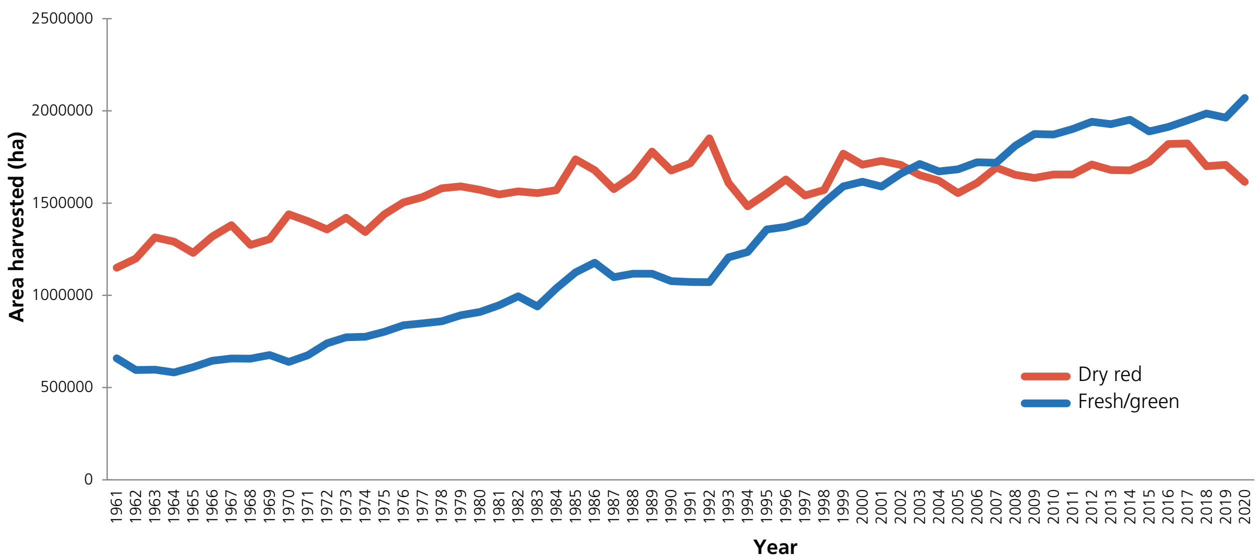

Figure 2.1. Total area harvested of chile pepper, globally, from 1961 to 2020. Data from FAO (2022a).

farm size is 0.06 ha (Islam et al., 2020). For smallholders, chile pepper serves as an important source of revenue and is a significant contributor to socioeconomic mobility. The crop is often produced in a rotation with a grain such as rice or wheat, and can be grown in very small holdings near the home, providing income for women and other vulnerable and marginalized members of society.

Globally, chile pepper is a highly traded commodity, with 118 countries being net importers (**Figure 2.4**) and 34 countries net exporters (**Figure 2.5**). On a cash value basis, the United States is the largest importer of chile pepper, closely followed by China and then Thailand, Spain, and Mexico. India is by far the largest exporter of chile pepper on a cash value basis, predominantly dry chile powder, followed by China, Spain, and Peru (**Figure 2.6**) (BACI, 2021).

Chile peppers continue to have extremely high cultural significance worldwide. They are relished for the burning sensation they cause when consumed, but also because of the unique flavors, aromas and colors they add to cuisine. Aji amarillo (*Capsicum baccatum* L. var. *pendulum* (Willd.) Eshbaugh) and rocoto (*Capsicum pubescens* Ruiz & Pav.) are synonymous with the food of Peru, while paprika (*Capsicum annuum* L. var. *annuum*) has a "second and, at the same time, true home in Hungary" (Halász 1963). Across Asia, chile peppers are a part of the daily cuisines in many cultures from: as far north as Korea, where it is an essential ingredient in kimchi; as far south as Indonesia, where sambal (*Capsicum frutescens* L.) is eaten with nearly every meal; westward, with sivri biber (*C. annuum* var. *annuum*) being a mainstay of Turkish cooking; and practically everywhere in between. Members of the species *Capsicum chinense* Jacq. are widely

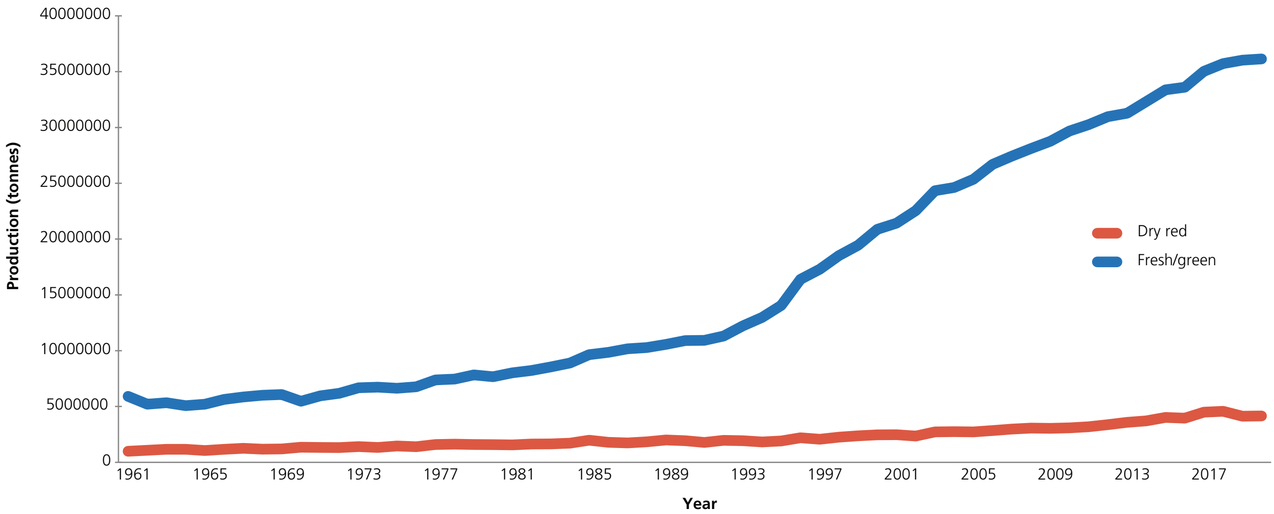

Figure 2.2. Total production (tonnes) of chile pepper, globally, from 1961 to 2020. Data from FAO (2022a).

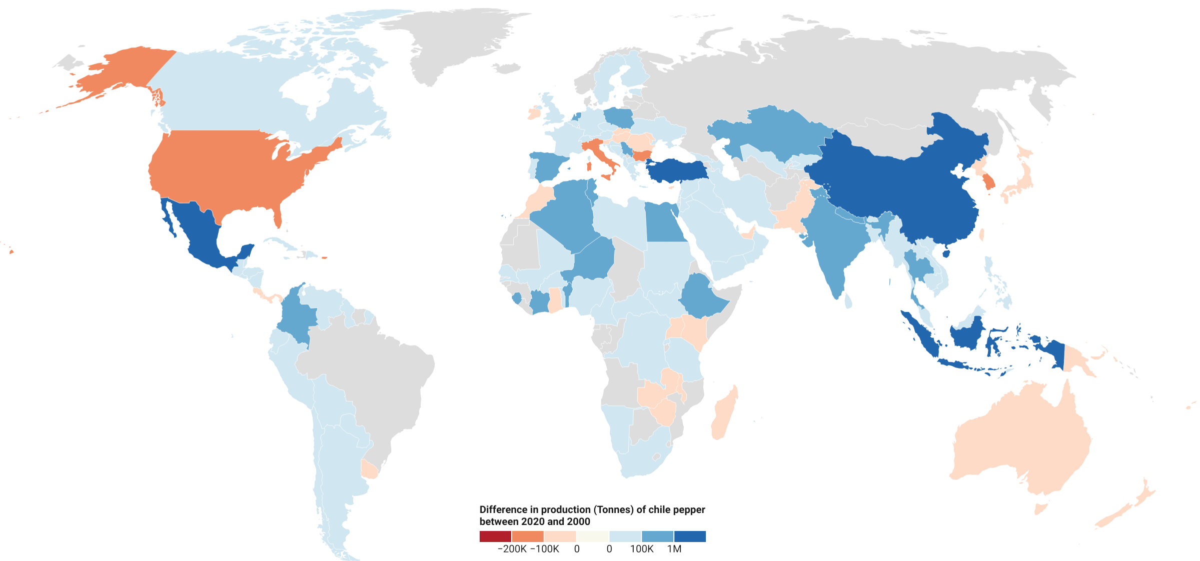

Figure 2.3. Difference in production (tonnes) of chile pepper (summed value of red dry and fresh green) between 2020 and 2000. The darker the blue scale color, the greater the increase in production that has occurred during the last 20 years; the darker the red, the greater the decrease. Data are not available for countries in gray. Data from FAO (2022a). Map made with Datawrapper.de

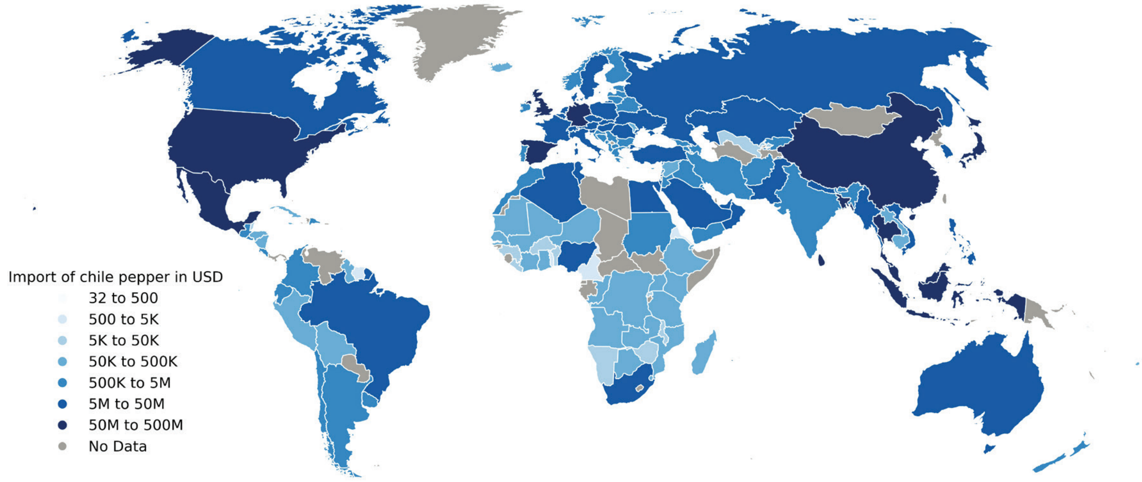

Figure 2.4. Degree of import in USD of chile pepper per country based on the International Trade Database at the Product-Level (BACI) database with data from 1995–2019. Darker colors display higher degrees of import.

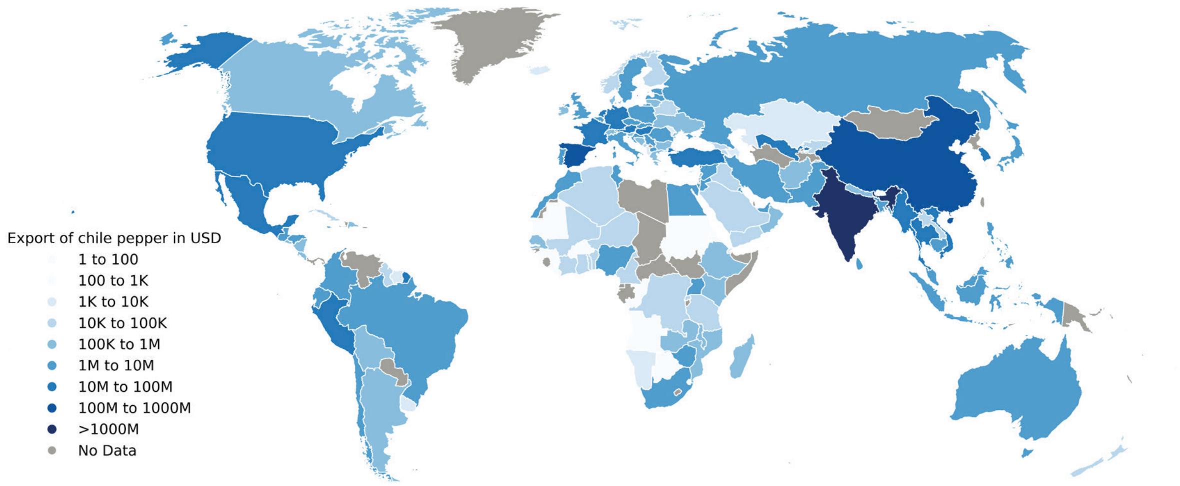

Figure 2.5. Degree of export in USD of chile pepper per country based on the International Trade Database at the Product-Level (BACI) database with data from 1995–2019. Darker colors display higher degrees of export.

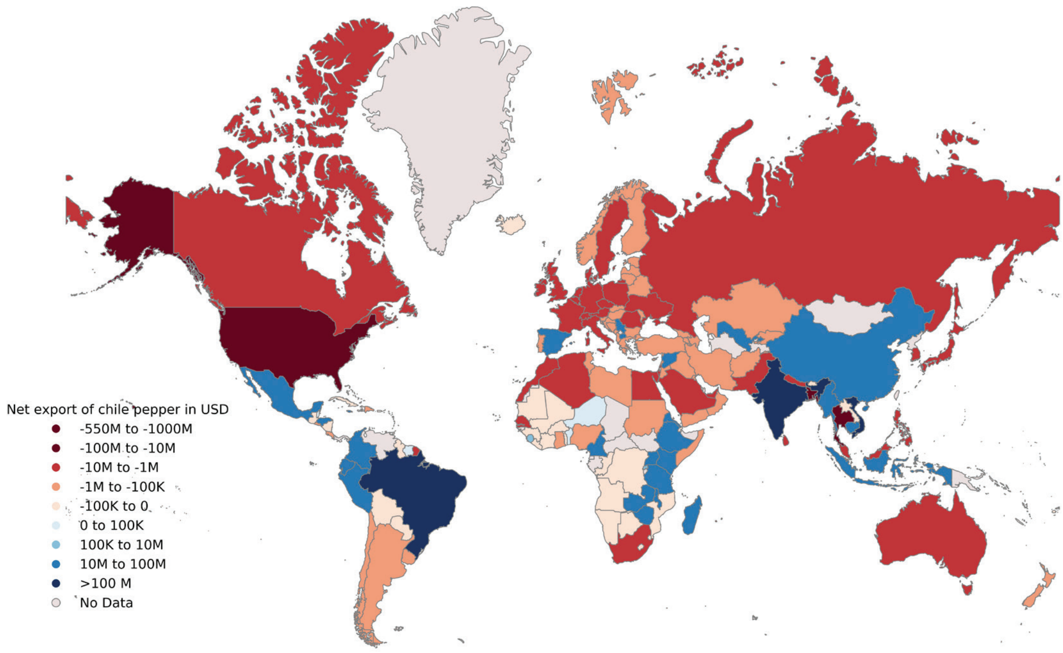

Figure 2.6. Net export of chile pepper in USD per country based on the International Trade Database at the Product-Level (BACI) database with data from 1995–2019

consumed and prized for their very high levels of capsaicinoids (being "super hot") and unique strong flavor on both sides of the Atlantic Ocean, especially in West and Central Africa and in the Caribbean. It has been stated that chile pepper is a defining feature of the New Mexican culture in the United States (Lozada et al. 2022). Chile peppers are celebrated in a multitude of ways in the state: it is one of the official state vegetables, and the official state question is "Red or Green?", referring to the preference for physiologically mature or immature chile peppers. There are also annual festivals and conferences dedicated to the crop in New Mexico, and this culture has spread across the region and increasingly across the country.

2.3 Diversity and genetic resources

Capsicum contains five main domesticated chile pepper taxa (Bosland and Votava 2012; Walsh and Hoot 2001):

1. *Capsicum annuum* L. var. *annuum*
2. *Capsicum baccatum* L. var. *pendulum* (Willd.) Eshbaugh [incl. syn. *Capsicum baccatum* L. var. *umbilicatum* (Vell.) Hunz. & Barboza]
3. *Capsicum chinense* Jacq.
4. *Capsicum frutescens* L.
5. *Capsicum pubescens* Ruiz & Pav.

Among the domesticated species, *C. annuum* var. *annuum* is the most widely grown and studied. The genus also includes ca. 37–40 wild taxa (with a few very recently described), some of which are also occasionally cultivated in home gardens (**Table 2.1**) (Baral and Bosland 2002; van Zonneveld et al. 2018; Khoury et al. 2019; Barboza et al. 2022). Both *C. annuum* var. *annuum* and *C. baccatum* var. *pendulum* have extant putative progenitors (*Capsicum annuum* var. *glabriusculum* (Dunal) Heiser & Pickersgill and *C. baccatum* L. var. *baccatum*, respectively); the progenitors of the remaining domesticates have not been identified.

Three genetic (species) complexes have been recognized within the genus, based on genetic relatedness and reproductive compatibility with the domesticated taxa (Barchenger and Bosland 2019; Emboden 1961; Eshbaugh 1970; Heiser and Smith 1948; Pickersgill 1971, 1980; Scaldaferro 2019; Tong and Bosland 1999). Each of these complexes contain both domesticated and wild taxa.

1. Annuum: Member species of the annuum complex generally have white, greenish, or yellowish (and occasionally purple) flowers, and include the crop species *C. annuum* var. *annuum*, *C. chinense*, and *C. frutescens*.
2. Baccatum: Members of the baccatum complex typically have white flowers with yellow to green corolla spots.
3. Pubescens: Members of the pubescens complex have purple flowers.

While comprehensive crossability studies between all species in the genus have yet to be completed (Barchenger and Bosland 2019), successful hybridizations are known among various species (Scaldaferro 2019), including between those belonging to different complexes (Walsh and Hoot 2001; Parry et al. 2021). Provisional clades of *Capsicum* species, based on their positions in phylogenetic trees derived from sequence-based molecular markers, have also been described (Carrizo Garcıa et al. 2016). Genetic relatedness classifications based on inter-fertility research, supplemented by taxonomic, phylogenetic, and ploidy information, provide partial indications of the genepools of the domesticated species (**Table 2.1**) (USDA ARS NPGS 2019).

Efforts to understand the diversity among *Capsicum* material from different regions around the world began in earnest around the mid-2000s. Studies first on morphological traits and later using basic molecular markers such as simple sequence repeat (SSR) (Nicolaï et al. 2013) and more recently genomic sequencing (Colonna et al. 2019; Pereira-Dias et al. 2019; Tripodi et al. 2021) have revealed quite consistent findings, indicating that some key traits, such as earliness, fruit morphology (shapes, sizes, color), and capsaicinoid production (Lee et al. 2016; Hill et al. 2013; Nicolaï et al. 2013; Colonna et al. 2019; Tripodi et al. 2021), were selected early on within a given region and often define the regional chile pepper market (Nankar et al. 2020b).

In the primary region of diversity in South America, there are several genetic groups among the domesticated types in addition to the wild species. For example, Ibiza et al. (2012) studied *Capsicum* accessions from the Andean region and found that in *C. baccatum* and *C. pubescens*, the Bolivian and Ecuadorian accessions formed generally distinct groups, with the Perurvian accessions landing within both groups. Looking at a more diverse set of samples of *C. baccatum*, Albrecht et al. (2011) found two distinct clusters, one comprising accessions from Bolivia, Chile, Colombia, Ecuador, Peru, and northwest Argentina and a second group from eastern Argentina and Paraguay. Brazil likely comprises at least one additional distinct group of *C. baccatum* (Albrecht et al. 2012). These two species are produced in significant quantities only within South America;having multiple distinct genetic groups demonstrates their strong cultural significance and importance in the Americas.

For *C. chinense*, Peruvian accessions generally form a distinct cluster, while Ecuadorian and Bolivian accessions tend to be more closely related (Ibiza et al., 2012), while Brazil (Baba et al. 2016; Moreira et al., 2018) and the Yucatan (Lopez-Castilla et al., 2019) and the Caribbean likely represent independent clusters. West and Central Africa also represents a significant secondary region of diversity for *C. chinense*; however, studies on the relatedness between these types and those of the Americas is lacking. There are also pockets of production of *C. chinense* across Asia, and the limited research in this area has revealed they likely also represent a unique genetic group (Jha and Bhowmick, 2021; Rai et al., 2013), potentially being natural interspecific hybrids with the closely related *C. frutescens* (Bosland and Baral, 2007; Kehie et al., 2016; Rai et al., 2013).

In Mesoamerica, there are several major genetic groups of wild, semi-wild (e.g. wild species sometimes cultivated in home gardens), and domesticated *C. annuum*, with accessions from the Yucatan forming a unique clade separate from the accessions from the rest of Mexico (Aguilar-Melendez et al., 2009) and northwestern Mexico having particularly high levels of genetic variation (Pacheco-Olvera et al. 2012). In North America, landraces from the southwest United States and northern Mexico form genetically distinct groups, despite being in relatively close proximity (Votava et al., 2005). Similarly, for the wild progenitor *C. annuum* var. *glabriusculum*, the northernmost populations are genetically distinct from those originating in Mexico and Guatemala (Votava et al. 2002).

There are likely two major European secondary regions of diversity for chile pepper (*C. annuum*) (Lee et al. 2016): the Central and Eastern European group, which also includes types from Turkey (Nicolaï et al. 2013), and the Mediterranean European group (Pereira-Dias et al. 2019) which also includes some types from the Netherlands (Nicolaï et al., 2013) and areas of North Africa and the Middle East (Tripodi et al. 2021). In regions where these two groups are grown, landraces (traditional or farmer varieties) are still produced for niche markets (Nankar et al. 2020a). Members of these groups are generally well conserved *ex situ* and on farm (Nanker et al. 2020a) and are among the most well characterized groups of *Capsicum* accessions worldwide.

The Asian groups are generally distinct from the European groups of *C. annuum* (Lee et al. 2016). The

Table 2.1. *Capsicum* L. taxa and their known chromosome numbers, clades, complexes, genetic relative/potential genepool classifications, and domestication/cultivation status. Derived from Khoury et al. 2019 with updates as per Barboza et al. (2020) and (2022).

Taxon	Chromosome (n)	Clade[1]	Complex[2]	Genetic relative/potential genepool classification[3]	Wild or domesticated[4]
Capsicum annuum L. var. *annuum*	12	Annuum	Annuum	B2, P3	Domesticated
Capsicum annuum L. var. *glabriusculum* (Dunal) Heiser & Pickersgill	12	Annuum	Annuum	A1, B2, P3	Wild
Capsicum baccatum L. var. *baccatum*	12	Baccatum	Baccatum	A2, B1, P3	Wild
Capsicum baccatum L. var. pendulum (Willd.) Eshbaugh [incl. syn *Capsicum baccatum* L. var. *umbilicatum* (Vell.) Hunz. & Barboza]	12	Baccatum	Baccatum	A2	Domesticated
Capsicum benoistii Hunz. ex Barboza	Unknown				Wild
Capsicum caatingae Barboza & Agra	12	Caatinga			Wild
Capsicum caballeroi M. Nee	Unknown	Bolivian			Wild
Capsicum campylopodium Sendtn.	13	Atlantic Forest			Wild
Capsicum carassense Barboza & Bianchetti	13	Atlantic Forest			Wild
Capsicum cardenasii Heiser & P. G. Sm.	12	Purple Corolla	Pubescens	A3, B3, P1	Wild, also cultivated in home gardens
Capsicum ceratocalyx M. Nee	Unknown	Bolivian			Wild
Capsicum chacoense Hunz.	12	Baccatum	Annuum	A2, B2	Wild, also cultivated in home gardens
Capsicum chinense Jacq.	12	Annuum	Annuum	A2, B2, P3	Domesticated; wild status uncertain
Capsicum coccineum (Rusby) Hunz.	Unknown	Bolivian			Wild

Taxon	Chromosome (n)	Clade[1]	Complex[2]	Genetic relative/potential genepool classification[3]	Wild or domesticated[4]
Capsicum cornutum (Hiern) Hunz.	13	Atlantic Forest			Wild
Capsicum dimorphum (Miers) Kuntze	NA	Andean			Wild
Capsicum eshbaughii Barboza	12	Purple Corolla		P2	Wild
Capsicum eximium Hunz.	12	Purple Corolla	Pubescens	A3, B3, P1	Wild, also cultivated in home gardens
Capsicum flexuosum Sendtn.	12	Flexuosum			Wild
Capsicum friburgense Bianchetti & Barboza	Unknown	Atlantic Forest			Wild
Capsicum frutescens L.	12	Annuum	Annuum	A2, B2, P3	Domesticated; wild status uncertain
Capsicum galapagoense Hunz.	12	Annuum	Annuum	A2, P3	Wild
Capsicum geminifolium (Dammer) Hunz.	13	Andean			Wild
Capsicum hookerianum (Miers) Kuntze	Unknown	Andean			Wild
Capsicum hunzikerianum Barboza & Bianchetti	Unknown	Atlantic Forest			Wild
Capsicum lanceolatum (Greenm.) C. V. Morton & Standl.	13	Andean			Wild
Capsicum longidentatum Agra & Barboza	12	Longidentatum			Wild
Capsicum longifolium Barboza & S. Leiva	13	Andean			Wild
Capsicum lycianthoides Bitter	13	Andean			Wild
Capsicum minutiflorum (Rusby) Hunz.	Unknown	Bolivian			Wild
Capsicum mirabile Mart. ex Sendtn. (syn. Capsicum *buforum* hunz.)	13	Atlantic Forest			Wild
Capsicum mirum Barboza	Unknown	Atlantic Forest			Wild
Capsicum muticum (Sendtn.) Barboza					Wild
Capsicum neei Barboza & X. Reyes	Unknown	Bolivian			Wild
Capsicum parvifolium Sendtn.	12	Caatinga			Wild
Capsicum pereirae Barboza & Bianchetti	13	Atlantic Forest			Wild
Capsicum piuranum Barboza & S. Leiva	13	Andean			Wild
Capsicum pubescens Ruiz & Pav.	12	Pubescens	Pubescens		Domesticated; wild status uncertain
Capsicum rabenii Sendtn. (syn. *Capsicum praetermissum* Heiser & P. G. Sm.)	12	Baccatum	Baccatum	A2, B1, P3	Wild
Capsicum recurvatum Witas.	13	Atlantic Forest			Wild
Capsicum regale Barboza & Bohs	13	Andean			Wild
Capsicum rhomboideum (Dunal) Kuntze	13	Andean			Wild
Capsicum schottianum Sendtn.	13	Atlantic Forest			Wild
Capsicum tovarii Eshbaugh et al.	12	Tovarii	Baccatum	B3	Wild
Capsicum villosum Sendtn.	13	Atlantic Forest			Wild

[1]Provisional clades of *Capsicum* species based on their positions in strict consensus trees using three molecular markers (Carrizo Garcıa et al. 2016 and Barboza et al. 2022). [2]As outlined in Scaldaferro 2019. [3]A denotes the crop *C. annuum* var. *annuum*; B for *C. baccatum* var. *pendulum*, and P for *C. pubescens*. Taxa are assigned to genetic relative categories for these domesticated species into three groups: 1 for primary (closest relatives), 2 for secondary, and 3 for tertiary (most distant relatives in the genus). Assignments as per USDA ARS NPGS (2019), based on crossability, phylogenetic, and other evidence. [4]Home garden use as noted in van Zonneveld et al. (2018).

number of secondary regions of diversity in Asia is not yet resolved. South and Southeast Asia are sometimes combined into a single secondary region of diversity (Hill et al. 2013; Lee et al. 2016; Tripodi et al. 2021); however, this is likely due to an overall lack of representation in the analyses. Probably, South and Southeast Asia represent at least two major independent secondary regions of diversity, with multiple groupings within each broader region. South Asia has long been recognized as an important secondary region of diversity for chile pepper (IBPGR 1983) and there is evidence that three species of *Capsicum* were being cultivated in India by the mid-16th century (Heiser 1976; Purseglove 1968), which is quite soon after introduction into the Old World. Within South Asia, Northeast India, Bangladesh, and parts of Myanmar represent a major secondary region of diversity of chile pepper (Islam et al., 2016; Rai et al., 2013), as do Northwest India and Pakistan, and South India and Sri Lanka. Southeast Asia has also been recognized as an important secondary region of diversity for chile pepper, and 40 years ago, collections in Thailand and Indonesia were listed as high priority by IBPGR (1983). More well studied and understood is the East Asian group of chile pepper, which comprises an additional Asian secondary region of diversity. While East Asian types are typically grouped together, they are quite diverse and even within China there are region-specific groupings, with at least three major genetic clades (Zhang et al. 2016). In the past decade or so, there has been a shift from traditional landraces to hybrid chile peppers across Asia, which has resulted in the rapid loss of many traditional varieties and landraces grown by farmers in these regions. Some efforts have been made to collect and conserve these landraces (Naresh Ponam, personal communication) and Northeast India is one of the few remaining areas with large scale landrace production.

In addition to *C. annuum*, there are also large swathes of production of *C. frutescens* across Asia (Yamamoto and Nawata 2005; 2009) and Africa (DeWitt 2020). Although not well studied and certainly not resolved, some work in this area has demonstrated that Asian *C. frutescens* are genetically similar to certain accessions from specific areas in the Americas, while African *C. frutescens* form a genetically distinct group (Zhong et al. 2021), indicating a likely important secondary region of diversity for *C. frutescens* in Africa. However, collection efforts and characterization of African accessions of *Capsicum* is lacking. In addition to North Africa, there are broadly two major secondary regions of diversity in Africa: the Eastern and Southern Africa group and the West and Central Africa group. However, similar to other parts of the world, there are sub-regional secondary diversity areas. For example, Ethiopia is an important producer and consumer of chile pepper and has unique market segments that are rare in other places, such as brown or chocolate-colored chile pepper and members of *C. frutescens*, which form genetically distinct groups (Solomon et al. 2019).

Geographic origin alone can be misleading when used to define secondary regions of diversity. High levels of overlap among types of pepper originating from different areas have been reported (Nargele et al. 2016). Apparently, selection for traits like fruit shape can also be important for defining genetic clades, with similar pod-type lines collected or developed in geographically distant regions being more closely related than expected (Hill et al. 2013). Movement of material internationally for use in breeding and a shift from the production of landraces to hybrids, particularly in Asia, has resulted in these traditionally distinct secondary areas of diversity becoming more mixed and therefore more similar.

Pimenta fr. em Agosto.

Freire.

Capsicum annuum L. Illustration: José Joaquim Freire

3 *EX SITU* CONSERVATION AND USE OF *CAPSICUM* GENETIC RESOURCES

3.1 *Capsicum* genetic resource collections

Online genetic resource databases and the results of the stakeholder survey provide complementary insights into current *Capsicum* collections, summarized below.

Genesys plant genetic resources portal

The Genesys plant genetic resources portal currently contains accession-level information for about 4 million genebank accessions, which is around half of the estimated total number in the world, held in ca. 450 institutes (Global Crop Diversity Trust 2022). Many of these collections are reported through genetic resource networks representing multiple institutions. For example, almost 2 million accessions in Genesys are provided by the European Cooperative Programme for Plant Genetic Resources (ECPGR) through their online database (European Plant Genetic Resources Search Catalogue [EURISCO]). In addition, many individual international (including CGIAR genebanks, WorldVeg, and CATIE) and national genebanks, research institutions and smaller networks publish their collection information on the portal. Updates are made periodically, for example at least once a year by the CGIAR genebanks. Accession-level data includes passport information following Multi-crop Passport Descriptors (MCPD) standards (Bioversity International 2015) as well as more limited quantities of characterization and evaluation, subsetting, and other related data.

For *Capsicum*, the Genesys portal reports a total of 32,304 active accessions of a total of 17 species, held in 73 institutes across 40 countries. Sixteen institutes hold more than 1000 accessions each; a total of 28 hold more than 100 (**Table 3.1**); and a total of 53 hold more than 10. In terms of countries, 8 contain institutes holding a combined total of more than 1000 accessions; a total of 20 countries harbor more than 100 accessions, and a total of 33 maintain more than 10 accessions. Those institutions maintaining the greatest number of *Capsicum* species include: WorldVeg, USDA Plant Genetic Resources Conservation Unit, the Centre for Genetic Resources (Netherlands), the Leibniz Institute of Plant Genetics and Crop Plant Research (IPK) (Germany), two Embrapa institutes (Brazil), and the Institute for Agrobotany (RCA) (Hungary) (all with 7 or more species each). Those institutions maintaining *Capsicum* accessions from the greatest number of countries of origin include: WorldVeg, USDA Plant Genetic Resources Conservation Unit, the Centre for Genetic Resources (Netherlands), and the Leibniz Institute of Plant Genetics and Crop Plant Research (IPK) (Germany).

United Nations Food and Agriculture Organization World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture (WIEWS)

The World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture (WIEWS) is "the information system used by FAO for the preparation of periodic, country-driven global assessments of the status of conservation and use of PGRFA (plant genetic resources for food and agriculture). WIEWS also monitors, on the basis of country reports, the implementation of the Second Global Plan of Action for Plant Genetic Resources for Food and Agriculture, adopted in 2011. National Focal Points, appointed by Governments, may provide relevant information through a dedicated Reporting tool." (FAO 2022). Information on *ex situ* collections in WIEWS is used to measure progress toward Sustainable Development Goal 2 (Zero Hunger) under its Target 2.5. In addition to the data from these national focal points, WIEWS offers accession-level data sourced from the Genesys plant genetic resources portal and from EURISCO (separately), as well as from the Brazilian Agricultural Research Corporation (Embrapa)'s Alelo Genetic Resources Platform. *Ex situ* collections accession-level data in WIEWS also may include basic passport information.

As of the time of writing, the latest year for which *ex situ* collection data is available in WIEWS is 2020; in this dataset, WIEWS reports a total of 47,503 *Capsicum* accessions of a total of 16 species, held in 136 institutes across 79 countries (including international centers separately). These source from national reporting (23,825 accessions [50.2%]), as well as from Genesys (12,559 accessions [27.1%]), EURISCO (8306 accessions [17.5%]), and EMBRAPA-Alelo (2503 accessions [5.3%]). Twenty-two institutes hold more than 1000 accessions each; a total of 52 hold more than 100 (**Table 3.2**); and a total of 97 hold more than 10.

In terms of countries, 12 contain institutes holding a combined total of more than 1000 accessions; a total

Table 3.1. Institutes with *Capsicum ex situ* collections as reported in the Genesys plant genetic resources portal (data from 2022); institutes are listed in descending order based on number of accessions held; only institutes with >100 accessions shown. Countries of origin information does not count unmarked records, thus more countries of origin could potentially be represented in collections than reported.

Institute code	Institute name	Country	Number of *Capsicum* accessions	Number of *Capsicum* species	Number of countries of origin of accessions
TWN001	World Vegetable Center (WorldVeg)	International, located in Taiwan	8372	15	104
USA016	Plant Genetic Resources Conservation Unit, Southern Regional Plant Introduction Station, University of Georgia, USDA-ARS (S9)	United States	4965	13	88
USA974	Seed Savers Exchange (SSE)	United States	2321	6	2
BRA012	Embrapa Hortaliças (CNPH)	Brazil	1934	7	2
BGR001	Institute for Plant Genetic Resources 'K.Malkov' (IPGR)	Bulgaria	1931	3	33
DEU146	Genebank, Leibniz Institute of Plant Genetics and Crop Plant Research (IPK)	Germany	1536	9	57
HUN003	Institute for Agrobotany (RCA)	Hungary	1192	7	22
NLD037	Centre for Genetic Resources, the Netherlands Plant Research International (CGN)	Netherlands	1177	10	74
CRI001	Centro Agronómico Tropical de Investigación y Enseñanza (CATIE)	International, located in Costa Rica	878	6	30
ESP026	Generalidad Valenciana. Universidad Politécnica de Valencia. Escuela Técnica Superior de Ingenieros Agrónomos. Banco de Germoplasma (BGUPV)	Spain	852	6	27
UKR021	Institute of Vegetable and Melon Growing (IOB)	Ukraine	754	1	42
BRA003	Embrapa Recursos Genéticos e Biotecnologia (CENARGEN)	Brazil	702	4	1
ESP027	Gobierno de Aragón. Centro de Investigación y Tecnología Agroalimentaria. Banco de Germoplasma de Hortícolas (CITA-HOR)	Spain	694	3	5
CZE122	Gene bank (CRI)	Czechia	530	2	28
BRA020	Embrapa Clima Temperado (CPACT/EMBRAP)	Brazil	431	7	1
SDN002	Agricultural Plant Genetic Resources Conservation and Research Centre (ARC)	Sudan	398	2	1
ROM019	Research and Development Institute for Vegetables and Floriculture Vidra (ICDLF Vidra)	Romania	387	1	6
ROM007	Suceava Genebank (BRGV Suceava)	Romania	342	4	4
POL003	Plant Breeding and Acclimatization Institute (IHAR)	Poland	334	1	19
ESP004	Centro Nacional de Recursos Fitogenéticos (INIA-CRF)	Spain	315	2	6
PRT001	Portuguese Bank of Plant Germplasm (BPGV-DRAEDM)	Portugal	225	4	6
MDA010	Laboratory for Plant Genetic Resources (LPGR)	Moldova	224	1	8
ARM005	Institute of Botany	Armenia	206	6	3
ARM008	Scientific Center of Vegetables and Industrial Crops (SC VIC)	Armenia	167	1	2
ROM055	Research and Development Station for Vegetables - Bacau (SCDL Bacau)	Romania	138	1	6
MKD001	Faculty of Agriculture, University Ss. Cyril and Methodius	North Macedonia	121	1	1
ARM059	Scientific Center of Agrobiotechnology (SC AB)	Armenia	111	1	10
ARE003	International Center for Biosaline Agriculture (ICBA)	International, located in United Arab Emirates	107	1	9
	Other institutes, each holding < 100 accessions each (N = 45)		960		
Total			**32,304**	**17 (distinct species)**	**137 (distinct countries)**

Table 3.2. Institutes with *Capsicum ex situ* collections as reported in FAO WIEWS (data from 2020); institutes are listed in descending order based on number of accessions held; only institutes with >100 accessions shown. Countries of origin information does not count unmarked records, thus more countries of origin could potentially be represented in collections than reported.

Institute code	Institute name	Country	Number of *Capsicum* accessions	Number of *Capsicum* species	Number of countries of origin of accessions
TWN001	World Vegetable Center	International, located in Taiwan	7853	11	107
USA016	Plant Genetic Resources Conservation Unit, Southern Regional Plant Introduction Station, University of Georgia, USDA-ARS	United States of America	4965	13	88
IND001	National Bureau of Plant Genetic Resources	India	4445	4	27
JPN183	NARO Genebank	Japan	2864	5	Not reported
BGR001	Institute for Plant Genetic Resources 'K.Malkov'	Bulgaria	1918	3	33
DEU146	Information and Coordination Centre for Biological Diversity (IBV)	Germany	1536	9	57
BRA012	Embrapa Hortaliças	Brazil	1370	7	2
TUR001	Plant Genetic Resources Department	Turkey	1318	2	1
HUN003	Centre for Plant Diversity	Hungary	1192	7	22
NLD037	Centre for Genetic Resources, the Netherlands	Netherlands	1154	10	74
MEX006	UACh, Banco Nacional de Germoplasma Vegetal (BANGEV)	Mexico	1152	2	1
MEX208	INIFAP, Centro Nacional de Recursos Genéticos (CNRG)	Mexico	988	5	1
ESP027	Gobierno de Aragón. Centro de Investigación y Tecnología Agroalimentaria. Banco de Germoplasma de Hortícolas	Spain	956	3	9
CRI085	Centro Agronómico Tropical de Investigación y Enseñanza (CATIE)	International, located in Costa Rica	882	6	31
ESP026	Generalidad Valenciana. Universidad Politécnica de Valencia. Escuela Técnica Superior de Ingenieros Agrónomos. Banco de Germoplasma	Spain	854	6	27
UKR021	Institute of Vegetable and Melon Growing	Ukraine	754	1	42
BRA003	Embrapa Recursos Genéticos e Biotecnologia	Brazil	702	4	1
MEX213	CP, Campus Montecillo	Mexico	631	1	1
MEX201	UACh, Centro Regional Universitario Sur (CRUS)	Mexico	565	3	1
MEX228	INIFAP, Campo Experimental Huastecas (CEHUAS)	Mexico	544	1	1
CZE122	Gene bank	Czechia	530	2	28
BOL317	Instituto Nacional de Innovación Agropecuaria y Forestal	Bolivia	487	8	13
BGD206	Lal Teer Seed Limited	Bangladesh	436	2	1
BRA020	Embrapa Clima Temperado	Brazil	431	7	1
PER034	Estación Experimental Agraria Donoso	Peru	413	4	1
SDN002	Agricultural Plant Genetic Resources Conservation and Research Centre	Sudan	398	2	1
ECU023	Departamento Nacional de Recursos Fitogenéticos	Ecuador	388	9	1
ROM019	Research and Development Institute for Vegetables and Floriculture Vidra	Romania	388	1	6
MEX194	Instituto de Investigación y Capacitación Agropecuaria, Acuícola y Forestal del Estado de México (ICAMEX)	Mexico	356	4	1
ROM007	Suceava Genebank	Romania	342	4	4
POL003	Plant Breeding and Acclimatization Institute	Poland	335	1	18
ETH085	Ethiopian Biodiversity Institute	Ethiopia	327	3	3
PER006	Estación Experimental Agraria Santa Rita	Peru	299	1	1

Institute code	Institute name	Country	Number of *Capsicum* accessions	Number of *Capsicum* species	Number of countries of origin of accessions
MEX263	SNICS, Depositario Nacional de Referencia de Semillas (DNRS)	Mexico	260	3	1
BGD003	Bangladesh Agricultural Research Institute	Bangladesh	258	1	1
PAK001	Bio-resources Conservation Institute	Pakistan	257	1	11
COL017	Corporación Colombiana de Investigación Agropecuaria, AGROSAVIA	Colombia	253	5	12
MNG030	Institute of Plant and Agricultural Science	Mongolia	252	1	21
PRT001	Banco Português de Germoplasma Vegetal	Portugal	236	4	6
LKA036	Plant Genetic Resources Centre	Sri Lanka	230	4	1
MDA010	Laboratory for Plant Genetic Resources	Republic of Moldova	226	1	8
ARM059	Scientific Center of Agrobiotechnology	Armenia	219	1	11
MEX069	UAAAN, Centro de Conservación de Semillas Ortodoxas, Región Norte (CC-SO)	Mexico	206	2	1
NGA010	National Centre for Genetic Resources and Biotechnology	Nigeria	194	2	1
ARG1350	Banco Activo de Germoplasma de La Consulta	Argentina	192	3	6
UZB006	Uzbek Research Institute of Plant Industry	Uzbekistan	188	1	28
MEX131	UDG, Centro Universitario de Ciencias Biológicas y Agropecuarias (UDG-CUCBA)	Mexico	185	2	1
TUN029	Banque Nationale de Gènes de Tunisie	Tunisia	154	2	1
ROM055	Research and Development Station for Vegetables - Bacau	Romania	138	1	6
MKD001	Faculty of Agriculture, University Ss. Cyril and Methodius	North Macedonia	121	1	1
ARE003	International Center for Biosaline Agriculture (ICBA)	International, located in United Arab Emirates	107	1	9
EGY087	National Gene Bank	Egypt	104	1	1
	Other institutes, each holding < 100 accessions each (N = 84)		1950		
Total			**47,503**	**16 (distinct species)**	**141 (distinct countries)**

of 39 countries harbor more than 100 accessions, and a total of 63 countries conserve more than 10 accessions. Those institutions maintaining the greatest number of *Capsicum* species include the USDA Plant Genetic Resources Conservation Unit, WorldVeg, the Centre for Genetic Resources (Netherlands), the Information and Coordination Centre for Biological Diversity (IBV) (Germany), the Departamento Nacional de Recursos Fitogenéticos (Ecuador), and the Instituto Nacional de Innovación Agropecuaria y Forestal (Bolivia), two Embrapa institutes (Brazil), and the Centre for Plant Diversity (Hungary) (all with 7 or more species each). It is likely that the German and Hungarian agencies listed here report for those institutes listed in the same countries as having high species richness as documented in the Genesys dataset (**Table 3.1**). Those institutions maintaining *Capsicum* accessions from the greatest number of countries of origin include WorldVeg, the USDA Plant Genetic Resources Conservation Unit, the Centre for Genetic Resources (Netherlands), and the Information and Coordination Centre for Biological Diversity (IBV) (Germany).

Botanic Gardens Conservation International PlantSearch

The Botanic Gardens Conservation International PlantSearch database provides global reporting of plant, seed, and tissue collections primarily from "living plant collections" (i.e. botanic gardens, arboreta, etc.) (BGCI 2022). PlantSearch currently reports information for more than 1.5 million records for over 640,000 taxa held at 1,194 institutions. These records provide basic information simply noting that an institution holds a taxon; specific numbers of accessions and passport data are not currently accessible. Among other purposes, PlantSearch is used to measure progress toward Target 8 of the Global Strategy for Plant Conservation by tracking threatened species representation in botanical collections globally.

For *Capsicum*, PlantSearch reports 866 records for a total of 15 species, held in 135 institutes across 42 countries (BGCI 2018). These institutes are primarily botanic gardens (823 records [95%]), while a few networks (25 [2.9%]), gene/seedbanks (8 [0.9%]), zoos (1 [0.1%]), and other organizations (9 [1%]) are also represented. No institutes in PlantSearch report more than 100 records; 19 institutes report more than 10 species records. In descending order in terms of number of records, these include: Bokrijk Arboretum (Belgium), United States National Arboretum, Eden Project (United Kingdom), Denver Botanic Gardens (United States), Royal Botanic Gardens, Kew (United Kingdom), Conservatoire et Jardin botaniques de la Ville de Genève (Switzerland), Botanische Gärten der Universität Bonn (Germany), Jardi Botanic de Soller (Spain), Longwood Gardens (United States), Botanical and Experimental Garden, Radboud University (Netherlands), Moore Farms Botanical Garden (United States), Jardin Botanique Yves Rocher (France), National Plant Germplasm System - USDA-ARS-NGRL (United States), Botanical Garden, Natural History Museum of Denmark (Denmark), Naples Botanical Garden (United States), Jardins des Plantes de l'Université (France), Cornell Botanic Gardens (United States), National Arboretum Canberra (Australia), and Glasgow Botanic Gardens (United Kingdom). Likewise, in terms of countries, none hold more than 100 records as reported in PlantSearch; a total of 10 hold more than 10 accessions.

Those institutes listed in PlantSearch reported as curating the greatest numbers of species include: the USDA National Plant Germplasm System (13 species), the Botanical and Experimental Garden of Radboud University and the Botanische Gärten der Universität Bonn (11 species each), the U.S. National Arboretum (6 species), and the Conservatoire et Jardin botaniques de la Ville de Genève, Eden Project, Jardin Botanique de la Ville de Caen, Jardins des Plantes de l'Université, and Naples Botanical Garden (5 species each).

Global Biodiversity Information Facility (GBIF)

The Global Biodiversity Information Facility (GBIF) is "an international network and data infrastructure funded by the world's governments and aimed at providing anyone, anywhere, open access to data about all types of life on Earth…the GBIF network of participating countries and organizations, working through participant nodes, provides data-holding institutions around the world with common standards, best practices and open-source tools enabling them to share information about where and when species have been recorded. This knowledge derives from many sources, including everything from museum specimens collected in the 18th and 19th century to geotagged smartphone photos shared by amateur naturalists in recent days and weeks [...].The GBIF network draws all these sources together through the use of data standards, including Darwin Core, which forms the basis for the bulk of GBIF.org's index of hundreds of millions of species occurrence records." (GBIF 2022). GBIF currently offers occurrence information for over 1.9 billion records reported from 1791 publishing institutions worldwide. This information includes many equivalent fields to those of passport data in *ex situ* germplasm collections.

For *Capsicum* records in GBIF, 105,012 occurrences are currently available; these data may be used for a wide range of taxonomic, geographic, ecological and conservation research, and some of the specimens associated with these occurrences may be considered genetic resources, for example as sources of tissue samples usable in genetic analyses. A small proportion of these occurrences (4630 [4.4%]) are identified as a "living specimen"; these may be considered equivalent to an *ex situ* conservation accession. These are held in 86 institutes across at least 93 countries. Aside from institutions already listed in the Genesys, WIEWS, and PlantSearch information described above, institutes reported in GBIF as having more than 10 living specimens of *Capsicum* include the Royal Botanic Garden Edinburgh (United Kingdom) (of 7 species) and the Nordic Genetic Resources Center (NordGen) (Sweden) (1 species).

Capsicum genetic resources survey results

Among the 40 respondents/institutes, 50,132 *Capsicum* accessions are reported to be conserved *ex situ* in 27 countries (**Table 3.3**). Fifteen institutes hold 1000 or more accessions each; a total of 31 hold more than 100; and a total of 39 hold more than 10. In terms of countries, 11 contain institutes holding a combined total of 1000 or more accessions; a total of 20 countries harbor more than 100 accessions, and a total of 26 countries conserve more than 10 accessions. On average, six *Capsicum* species were conserved by the respondents. Three institutions (New Mexico State University, the United States Department of Agriculture, and WorldVeg) conserve more than 15 species of *Capsicum* each; the Centre for Genetic Resources (Netherlands) and Research Centre for Vegetable and Ornamental Crops (Italy) curate 12 species each, the Taiwan Agricultural Research Institute (Taiwan) maintains 11, the National Agriculture and Food Research Organization Genebank (Japan) and Embrapa institutes in Brazil conserve 9 species each, and the Universitat Politècnica de València (Spain) and the Corporación Colombiana de investigación Agropecuaria (AGROSAVIA) (Colombia) curate 8 species each.

Many countries are represented within collections, with an average of 33 countries of origin per collection. Three institutions (the Centre de Ressources Biologiques Légumes, the USDA-ARS Plant Genetic Resources Conservation Unit and WorldVeg) reported more than 100 countries of origin in their collection. Six institutions had a single country of origin for their *Capsicum* collection, with all accessions being collected or originating within country.

Composition of *Capsicum* genetic resource collections

Representation of each *Capsicum* taxon in *ex situ* repositories as reported in global databases and stakeholder surveys is displayed in **Table 3.4**. See section 3.6 below for further information on the Svalbard Global Seed Vault [SGSV] data source. Note that *Capsicum mirum* Barboza (Barboza et al. 2022) was published more recently than the data compiliation effort for this Strategy was completed, and is thus not included in **Table 3.4**.

The emphasis on domesticated *Capsicum* taxa in *ex situ* collections is evident (**Figure 3.1**). For example, of the 50,132 *Capsicum* accessions reported in the stakeholder survey, 40,585 (81%) belonged to the five domesticated species, 722 (1.7%) were members

Table 3.3. Institutes with *Capsicum ex situ* collections from stakeholder surveys (data from 2021); institutes are listed in descending order based on number of accessions held. Institute codes matched to FAO WIEWS institute table.

Institute code	Institute name	Country	Organization designation	Number of *Capsicum* accessions	Number of *Capsicum* species	# of countries of origin of accessions
TWN001	World Vegetable Center	Taiwan	International Research Institute	9171	16	106
TWN006	Taiwan Agricultural Research Institute	Taiwan	Governmental organization	5659	11	-
USA016	United States Department of Agriculture – Agriculture Research Service: Plant Genetic Resources Conservation Unit	United States of America	Governmental organization	4973	19	309
JPN183	National Agriculture and Food Research Organization Genebank	Japan	Governmental organization	3202	9	66
THA008	Tropical Vegetable Research and Development Center (TVRC). Kasetsart University	Thailand	University	3000	5	3
USA974	Seed Savers Exchange	United States of America	Non Governmental Organization	2741	5	-
	Centre de Ressources Biologiques Légumes – Institut national de recherche pour l'agriculture, l'alimentation et l'environnement (INRAE)	France	Governmental organization	2188	5	100
USA307	New Mexico State University Chile Breeding Program	United States of America	University	2117	22	47
ESP026	Universitat Politècnica de València	Spain	University	1935	8	55
ESP004	Centro Nacional de Recursos Fitogenéticos (CRF) – National Institute for Agricultural and Food Research and Technology (INIA), Agencia Estatal Consejo Superior de Investigaciones Científicas (CSIC)	Spain	Governmental organization	1682	6	28
ESP027	Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA)	Spain	Governmental organization	1307	2	1
NLD037	Centre for Genetic Resources, The Netherlands. Wageningen University and Research (WUR)	Netherlands	University	1177	12	75
THA048	Khon Kaen University	Thailand	University	1086	7	12
	Research Centre for Vegetable and Ornamental Crops	Italy	Governmental organization	1000	12	40
VNM049	Plant Resources Center (PRC)	Vietnam	Governmental organization	1000	5	-
BRA003	Embrapa Recursos Genéticos e Biotecnologia	Brazil	Governmental organization	965	9	-

Institute code	Institute name	Country	Organization designation	Number of *Capsicum* accessions	Number of *Capsicum* species	# of countries of origin of accessions
BGR002	Maritsa Vegetable Crops Research Institute	Bulgaria	Governmental organization	932	4	20
CRI085	Tropical Agronomic Research and High Education Center (CATIE)	Costa Rica	International Research Institute	884	7	31
BGR001	Institute of Plant Genetic Resources "K. Malkov"	Bulgaria	Governmental organization	746	5	18
MKD001	Department of Genetics and Plant Breeding Ss. Cyril and Methodius University in Skopje/ Faculty of Agricultural Sciences and Food-Skopje	North Macedonia	University	650	1	1
CZE151	Crop Research Institute	Czech Republic	Governmental organization	530	1	26
	Fruit and Vegetable Research Institute (FAVRI)	Vietnam	Governmental organization	495	3	5
BRA020	Embrapa Clima Temperado	Brazil	Governmental organization	411	8	1
IDN025	Pusat Inovasi Agroteknologi Universitas Gadjah Mada (Agrotechnology Innovation Centre)	Indonesia	University	400	5	3
IND1806	Indian Council of Agricultural Research (ICAR)-Indian Institute of Vegetable Research (IIVR)	India	Governmental organization	400	5	11
COL017	Corporacion Colombiana de investigación Agropecuaria (AGROSAVIA)	Colombia	Governmental organization	337	8	16
ARG1342	Instituto Nacional de Tecnología Agropecuaria (INTA)	Argentina	Governmental organization	197	3	6
TUN029	National Gene Bank of Tunisia (NGBTUN)	Tunisia	Governmental organization	153	1	-
IND006	Indian Council of Agricultural Research (ICAR)- Indian Institute of Horticultural Research (IIHR)- Central Horticultural Experiment Station, Bhubaneswar	India	Governmental organization	142	4	1
	Indonesia Vegetable Research Institute (IVEGRI), Indonesian Agency for Agricultural Research and Development (IAARD), Ministry of Agriculture	Indonesia	Governmental organization	123	2	-
ARE003	International Center for Biosaline Agriculture (ICBA)	United Arab Emirates	International Research Institute	107	1	-
CAN004	Plant Gene Resources of Canada	Canada	Governmental organization	92	3	15
CHL044	Instituto de Investigaciones Agropecuarias	Chile	Governmental organization	79	6	22
THA051	Department of Agriculture Genebank of Thailand	Thailand	Governmental organization	66	4	1
BTN026	National Biodiversity Centre	Bhutan	Governmental organization	60	3	1
SRB002	Institute of Field and Vegetable Crops	Serbia	Governmental organization	58	1	7
VNM079	Southern Fruit Research Institute	Vietnam	Governmental organization	30	1	4
ZAF064	National Plant Genetic Resources Centre (NPGRC)	South Africa	Governmental organization	18	2	-
CHE001	Agroscope	Switzerland	Governmental organization	15	1	5
UUS165	Australian Grains Genebank	Australia	Governmental organization	4	1	-
	Total			**50,132**	**25 (distinct species)**	

Table 3.4. Number of *ex situ* accessions/records held per taxon, per database/dataset. Totals are not provided across rows as considerable duplication of information among datasets is expected.

Taxon	Genesys	FAO WIEWS	BGCI Plant Search	GBIF (living specimens only)	Stakeholder survey	SGSV
C. annuum var. *annuum*	21,636	34,431	575	2913	32,340	5160
C. annuum var. *glabriusculum*	133	166	21	8	367	19
C. baccatum var. *baccatum*	81	83	2	81	63	12
C. baccatum var. *pendulum*	1359	1579	44	116	1,682	212
C. benoistii	0	0	0	0	0	0
C. caatingae	0	0	0	0	1	0
C. caballeroi	0	0	0	0	1	0
C. campylopodium	0	0	0	0	0	0
C. carassense	0	0	0	0	NA	0
C. cardenasii	6	7	3	64	19	3
C. ceratocalyx	0	0	0	0	0	0
C. chacoense	80	118	5	48	157	28
C. chinense	2469	2905	91	219	3071	367
C. coccineum	0	0	0	0	0	0
C. cornutum	0	0	0	0	1	0
C. dimorphum	0	0	0	0	0	0
C. eshbaughii	1	0	0	0	4	0
C. eximium	16	35	3	94	23	9
C. flexuosum	9	9	1	15	7	0
C. friburgense	0	0	0	0	1	0
C. frutescens	2288	3324	61	170	3,095	355
C. galapagoense	9	7	4	3	12	3
C. geminifolium	0	0	0	0	0	0
C. hookerianum	0	0	0	0	0	0
C. hunzikerianum	0	0	0	0	0	0
C. lanceolatum	2	3	1	1	5	0
C. longidentatum	0	0	0	0	0	0
C. longifolium	0	0	0	0	0	0
C. lycianthoides	0	1	0	0	0	0
C. minutiflorum	1	0	1	0	3	0
C. mirabile (syn C. buforum)	1	1	0	0	0	0
C. muticum	0	0	0	0	NA	0
C. neei	0	0	0	0	0	0
C. parvifolium	0	0	0	0	0	0
C. pereirae	0	0	0	0	1	0
C. piuranum	0	0	0	0	0	0
C. pubescens	189	568	26	73	397	31
C. rabenii (syn. *C. praetermissum*)	8	6	0	0	37	1
C. recurvatum	0	0	0	0	1	0
C. regale	0	0	0	0	NA	0
C. rhomboideum	4	6	3	1	7	1
C. schottianum	0	0	2	2	1	1
C. tovarii	5	5	1	1	10	0
C. villosum	0	0	0	0	1	0
hybrid	1	1	0	0	NA	1
unknown/unspecified/other species	4006	4248	22	821	10112	175
Total	**32,304**	**47,503**	**866**	**4630**	**50,132**	**6378**

of wild *Capsicum* species, 119 (0.2%) were labeled with names other than the accepted taxon names of *Capsicum* (as per **Table 2.1**), 1,887 (3.8%) were listed as unknown species, and 6,819 (13.6%) were reported as conserved members of the genus, but not assigned a species name. Mirroring its degree of use worldwide, the domesticated species *C. annuum* comprised the largest collection, with 32,340 accessions conserved globally. The other four domesticated species are conserved to a far lesser extent, with *C. frutescens* (3,095 accessions) being the second most conserved species, followed by *C. chinense* (3,071), *C. baccatum* (1,682) and and lastly *C. pubescens* (397). The global databases follow this same general pattern.

The vast majority of the wild *Capsicum* taxa appear to have no or very little representation in *ex situ* conservation worldwide. Out of the 37–40 wild taxa in the genus, 15 did not have any representation *ex situ* among the survey respondents, and another 13 had fewer than 10 accessions conserved. The global databases paint an even starker picture, with between 25 and 28 taxa completely absent from *ex situ* conservation (depending on the database), and another 6 to 13 represented by fewer than 10 accessions/records. A recent conservation gap analysis for wild *Capsicum* found similar results, with 22 taxa absent from genebanks and other repositories, and another 9 represented by fewer than 10 accessions (Khoury et al. 2019).

As might be expected, the wild progenitor of *C. annuum* – *C. annuum* var. *glabriusculum* – was the most well represented wild taxon in terms of numbers of accessions held, with 367 accessions conserved as per the stakeholder surveys (133 and 166 as per Genesys and WIEWS, respectively). Most of these (254 accessions) were conserved by the National Agriculture and Food Research Organization of Japan as per the surveys; Genesys and WIEWS note substantial collections at USDA. *Capsicum chacoense* Hunz., which represents an important genetic resource for plant breeders and has been widely studied, was the second largest collection among wild species as per the surveys, with 157 accessions. Sixty-three accessions of the wild progenitor *C. baccatum* var. *baccatum* were conserved (81 to 83 in Genesys and WIEWS), nearly half of which were conserved by USDA.

Capsicum rabenii Sendtn. (syn. *Capsicum praetermissum* Heiser & P. G. Sm.) was the fourth most conserved species, with 37 accessions, most of which were conserved at either New Mexico State University (12 accessions) or WorldVeg (10 accessions). Approximately half of the 23 accessions of *C. eximium* Hunz. and the 19 accessions of *C. cardenasii* Heiser & P. G. Sm. were held at New Mexico State University, which houses 12 and 9 accessions, respectively. A total of 12 accessions of *C. galapagoense* Hunz. were reported to be conserved worldwide in the surveys (fewer in the global databases); however, no single institution reported having more than three accessions of this species, with most curating a single accession, and it has been previously reported that at least one, and possibly two, of these accessions likely belong to another species (either *C. annuum* or *C. frutescens* (Parry et al. 2021; Bosland, pers. comm.).

WorldVeg houses three of the 10 accessions of *C. tovarii* Eshbaugh et al. conserved globally, with the other institutions generally having a single accession of this species. Of the seven accessions of *C. flexuosum* Sendtn. reported to be conserved, two each are housed at WorldVeg and USDA. New Mexico State University houses two of the five accessions of *C. lanceolatum* (Greenm.) C. V. Morton & Standl. and two of the three accessions of *C. minutiflorum* (Rusby) Hunz. The Centre for Genetic Resources of The Netherlands

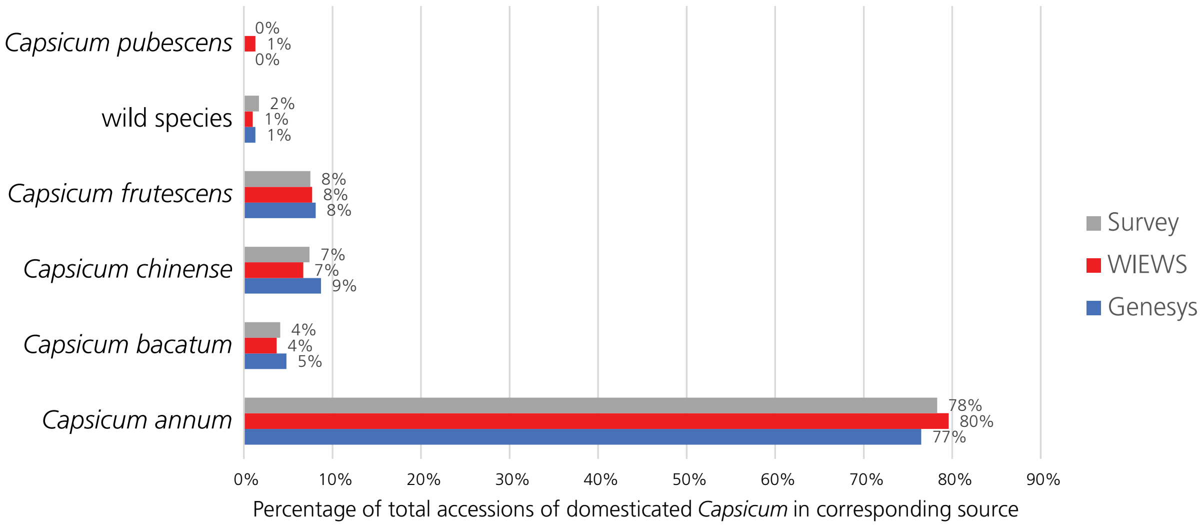

Figure 3.1. Proportions of total world *ex situ* accessions of each of the five domesticated taxa of *Capsicum* as well as the wild taxa (as a single group), as per Genesys, FAO WIEWS, and the stakeholder surveys

houses three of the four accessions of *Capsicum eshbaughii* Barboza. A single accession each of *Capsicum benoistii* Hunz. ex Barboza, *Capsicum caatingae* Barboza & Agra, *Capsicum cornitum* (Hiern) Hunz., *Capsicum friburguense* Bianch. & Barboza, *Capsicum pereirae* Barboza & Bianch., *Capsicum recurvatum* Witas., *Capsicum schottianum* Sendtn., and *Capsicum villosum* Sendtn. var. *muticum* Sendtn. were reported as conserved as per the stakeholder surveys. One accession each of *Capsicum mirabile* Mart. ex Sendtn. (syn. *Capsicum buforum* Hunz) and *Capsicum lycianthoides* Bitter may also be conserved as per Genesys and WIEWS, the first at Embrapa Hortaliças (Brazil) and the second at the Departamento Nacional de Recursos Fitogenéticos (Ecuador).

On average, 24% of collections of wild *Capsicum* were considered by survey respondences to be 100% unique, not duplicated elsewhere, or more than 50% unique, with less than half of the collection being duplicated. Around 13% of collections, on average, were reported to have less than 50% uniqueness, and 11%, on average, was fully duplicated elsewhere.

Improvement type/Biological Status

Improvement type/biological status for *Capsicum* accessions is displayed in **Table 3.5**. Across the global databases and stakeholder surveys, landraces are the dominant form identified as conserved *ex situ*, followed by cultivars and breeding materials. A large proportion (from 42% to 65%, depending on the data source) of accessions do not have a clearly marked improvement type.

For *C. annuum*, from the stakeholder surveys, approximately 37% of accessions was designated as being of unknown improvement type (**Figure 3.2**). Approximately 24% consisted of landraces, followed by advanced or improved cultivars (9%), breeding and research material (7%) and obsolete cultivars (3%). Approximately 2% of the *C. annuum* collection was classified as specialist genetic stock material and 0.3% as wild or weedy species. Similar percentages were evident for the cultivated species in the global databases (Genesys and FAO WIEWS). The low proportion of wild or weedy accessions of *C. annuum* conserved is likely due to the wild progenitor being known and conserved as a separate species. The largest collection of *C. annuum* is housed at WorldVeg, in Taiwan, with 6,266 accessions, followed closely by the Taiwan Agriculture Research and Development Institute, which serves as a safety duplication of WorldVeg. The USDA-ARS Plant Genetic Resources Conservation Unit has the third largest collection of *C. annuum* with 3,446 accesions. Nine respondents (Centro de Investigación y Tecnología Agroalimentaria de Aragón, Centro Nacional de Recursos Fitogenéticos, the French National Research Institute for Agriculture, Food and Environment, the National Agriculture and Food Research Organization of Japan, New Mexico State University, Taiwan Agriculture Research and Development Institute, USDA-ARS Plant Genetic Resources Conservation Unit, Universitat Politècnica de València, and WorldVeg) reported conserving more than 1,000 *C. annuum* accessions. In terms of uniqueness of *C. annuum* collections, on average, 18% of collections were reported by survey respondents to be 100% unique and not duplicated elsewhere, while 40% were more than 50% unique, and 29% were less than 50% unique. Approximately 13% of collections, on average, were reported to be fully duplicated elsewhere.

For *C. baccatum*, from the stakeholder surveys, landraces were by far the largest improvement type, comprising 41% of all accessions, while around 24% of the collection was characterized as being unknown (**Figure 3.2**). In contrast, global databases such as Genesys and FAO WIEWS had up to 82% and 65% of accessions, respectively, unmarked regarding improvement type or in an "other" category, with landraces constituting 7% and 24% of the total, respectively (this still the dominant type among those accessions with information). From the surveys, approximately

Table 3.5. Improvement types/ biological status of *ex situ* accessions, per database/dataset. Improvement type is not clearly reported in PlantSearch or GBIF.

Improvement type/ Biological status	Genesys	FAO WIEWS	Stakeholder survey
Wild	192 (0.6%)	334 (0.7%)	894 (1.8%)
Weedy	1 (0.0%)	1 (0.0%)	32 (0.06%)
Landrace	7977 (24.7%)	17,139 (36.1%)	10,517 (21.0%)
Breeding materials	988 (3.1%)	3726 (7.8%)	2413 (4.8%)
Cultivar	5537 (17.1%)	3738 (7.9%)	3186 (6.4%)
Other	3997 (12.4%)	NA	6 (0.01%)
Specialist genetic stock	NA	NA	637 (1.3%)
Unknown	NA	NA	17,721 (35.3%)
Not specified	13,612 (42.1%)	22,565 (47.5%)	14,726 (29.4%)
Total	**32304**	**47503**	**50132**

5% of *C. baccatum* were designated as being obsolete or traditional cultivars, and 3% advanced or improved cultivars. The wild and weedy populations and breeding or research materials made up approximately 2% of the collection each, and less than 1% of the collection is specialist genetic stock. These proportions align with the global databases. As per the survey information, the largest collection of *C. baccatum* is housed at WorldVeg, with 409 accessions in total, while the Centre de Ressources Biologiques Légumes (129), Embrapa Clima Temperado (122), Embrapa Recursos Genéticos e Biotecnologia (157), the National Agriculture and Food Research Organization of Japan (105), New Mexico State University (123), and the Taiwan Agriculture Research and Development Institute (164) all housed more than 100 accessions. In terms of uniqueness of *C. baccatum* collections, on average, 11% of *C. baccatum* collections were reported to be 100% unique, and not duplicated elsewhere. Approximately 16% of *C. baccatum* collections, on average, were reported to be more than 50% unique and another similar proportion less than 50% unique, while 13% of collections were fully duplicated elsewhere.

For *C. chinense*, from the stakeholder surveys, 56% were designated as unknown in terms of improvement type (**Figure 3.2**). Landraces make up around 11% of the collection and 6% were designated as being obsolete or traditional cultivars. Around 4% were identified as being advanced or improved cultivars and 3% were breeding or research materials, while 1% of the collection is made up of specialist genetic stocks. Less than 0.5% is made up of wild or weedy populations, which could be due to the fact that the wild progenitor of *C. chinense* has not yet been identified, which may also be a contributor to the high proportion of accesions with unknown improvement type. The global databases also show these general trends for the species. As per the survey information, the largest collection of *C. chinense* is housed at WorldVeg with 566 accesions, closely followed by USDA-ARS Plant Genetic Resources Conservation Unit, with 484 accessions and Embrapa Recursos Genéticos e Biotecnologia with 390 accessions. In terms of uniqueness of *C. chinense* collections, on average, 8% of *C. chinense* collections were reported to be 100% unique and not duplicated elsewhere. Around 21% of collections of *C. chinense* were reported to be more than 50% unique, while 16% of collections were less than 50% unique on average. The level of complete duplication was highest for *C. chinense* among the domesticated species collections, with 16% of collections being fully duplicated elsewhere.

For *C. frutescens*, from the stakeholder surveys, 52% of accessions were reported as being of unknown improvement type, while 18% were designated as landraces (**Figure 3.2**). The global databases similarly report up to almost half of accessions being of unknown improvement type, while landraces comprise between 41% (Genesys) and 60% of accessions (FAO WIEWS). Nearly 4% were breeding or research materials and just over 3% were obsolete of traditional cultivars. Specialist genetic stocks and advanced or improved cultivars each represented around 2% accessions. Only 0.5% of the collection consists of wild or weedy populations, again likely due to the wild progenitor of *C. frutescens* being unknown, which could also be a contributing factor to the high proportion of unknown accessions. As per the survey information, WorldVeg conserves the largest collection of *C. frutescens*, with 779 accessions, followed by the National Agriculture and Food Research Organiza-

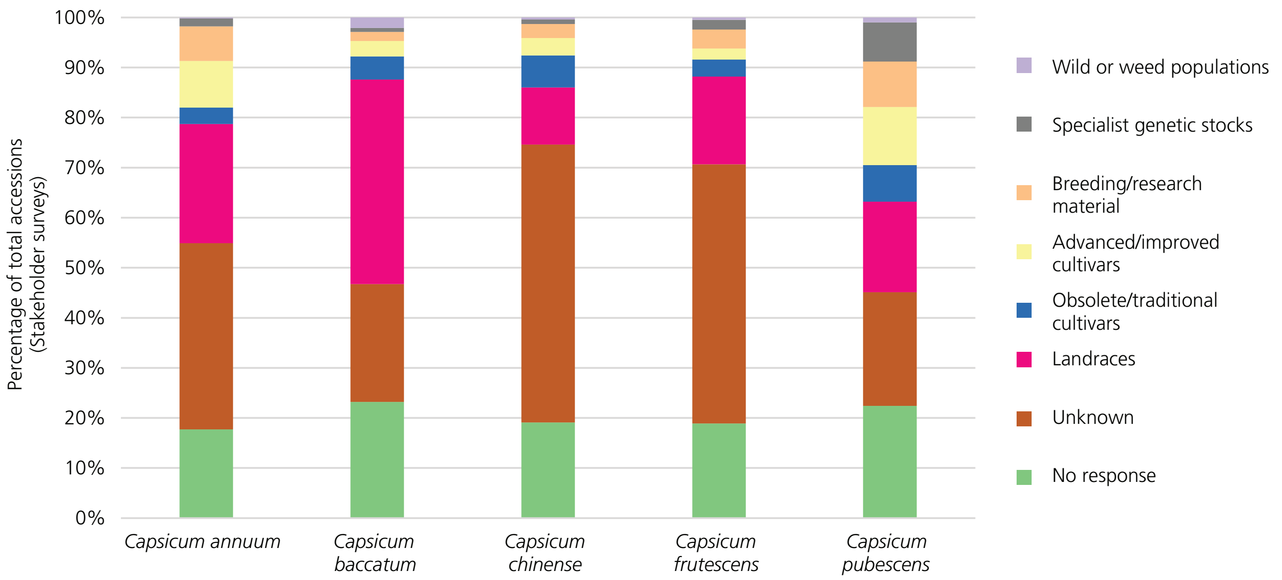

Figure 3.2. Percentage of improvement type/biological status of cultivated chile pepper species collections based on aggregated numbers of accessions, as synthesized from the stakeholder surveys

tion of Japan with 485 accessions. Southeast and East Asia are important secondary centers of diversity for *C. frutescens*, and these two collections could harbor important genetic resources for the species. In terms of uniqueness of *C. frutescens* collections, approximately 11% of collections, on average, were reported to be 100% unique, not being duplicated elsewhere. On average, 18% of *C. frutescens* collections were reported to be more 50% unique, while 21% were reported to be less than 50% unique. It was reported that 13%, on average, of *C. frutescens* collections were fully duplicated elsewhere.

For *C. pubescens*, from the stakeholder surveys, 23% of accessions were listed as being of unknown improvement type (63% in Genesys and 52.6% in FAO WIEWS, for unmarked or "other" types) **(Figure 3.2)**. Approximately 18% consisted of landraces (23% in Genesys and 42% in FAO WIEWS) and 12% were advanced or improved cultivars. Breeding or research materials, specialist genetic stocks, and obsolete or traditional cultivars made up 9%, 8%, and 7%, respectively. Only 1% of the collection were designed as being wild or weedy populations of *C. pubescens*. This species has the smallest global collection among cultivated species; from the survey information, New Mexico State University houses nearly 30% of the entire collection. In terms of uniqueness of *C. pubescens* collections, the level of uniqueness was lower than for the other domesticated species, with 8%, on average, of *C. pubescens* collections being 100% unique and not duplicated elsewhere. Approximately 16% of collections were more than 50% unique, on average, and 8% were reported to be less than 50% unique. On average, 11% of collections of *C. pubescens* were reported to be fully duplicated elsewhere.

Regarding the degree of duplication of accessions (i.e. two or more accessions being identical but having different accession numbers) within (not across) *Capsicum* collections, for all species, around 5% of the institutions reported having no duplication, More than half (54%) of the institutions reported having less than 10% duplication within their collections, while 22% reported having moderate levels of duplication. Approximately 19% of respondents reported having extensive duplication, with more than 30% of the collection being duplicated. The institutions with extensive duplication conserve 13,460 *Capsicum* accessions, in total, which at 30% would be more than 4,000 duplicated accessions of *Capsicum*.

3.2 Past and projected future acquisition of *Capsicum* genetic resources

Genesys and GBIF provide information on the date of collection of accessions. For *Capsicum*, in Genesys, the earliest collection was made in 1899, and the most recent in 2020. For GBIF, the earliest was 1947 and the most recent 2020. FAO WIEWS does not provide date of collection, but from information on date of acquisition, the earliest reported was also 1899 and most recent 2020. In all three datasets, collections/acquisitions were fairly well distributed across decades over the past century.

Across the databases with information on the country of origin of accessions, the number of origin countries represented in *Capsicum ex situ* collections sums to at least 145, with Spain, Bulgaria, United States of America, Hungary, Mexico, Romania, Turkey, Costa Rica, Guatemala, Peru, Brazil, India, Yugoslavia, Italy, Bangladesh, Bolivia, Ecuador, Ethiopia, and Thailand being among the most represented, each with over 500 accessions as reported in at least one database/dataset **(Table 3.6, Figure 3.3)**.

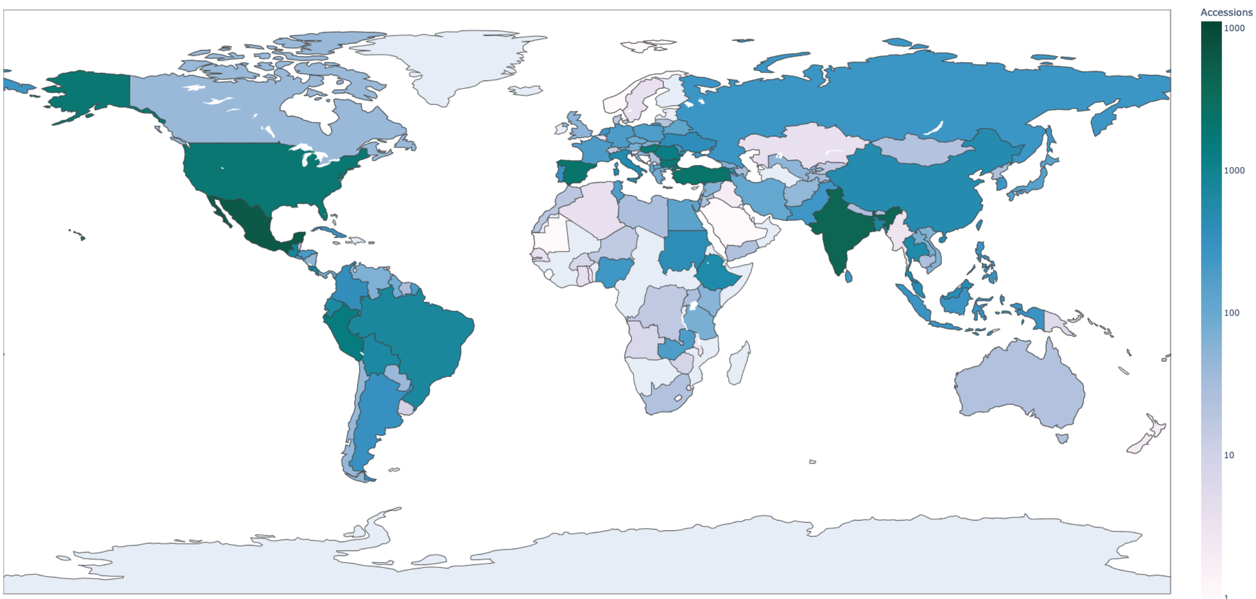

Figure 3.3. Country origin of *Capsicum* accessions as reported in Genesys and FAO WIEWS (combined dataset).

Table 3.6. Countries of origin of *Capsicum* accessions and number of accessions per database.

Country	Genesys	FAO WIEWS	GBIF (living specimens only)	SGSV
Afghanistan	52	45		23
Albania	126	118	55	2
Algeria	4	4	7	1
Angola	7	7	1	2
Argentina	137	330	5	30
Armenia	377	184		1
Australia	22	23	5	9
Austria	73	76	29	42
Azerbaijan	29	29		1
Bahamas	1	1	1	3
Bangladesh	36	754	1	3
Belarus	13	120		
Belgium	3	3	1	2
Belize	17	17		3
Bhutan	30	30	26	8
Bolivia (Plurinational State of)	261	664	449	39
Bosnia and Herzegovina	1	1		23
Brazil	744	716	252	221
British Indian Ocean Territory	1	1		
Bulgaria	1789	1803	63	133
Burkina Faso	7	7	7	1
Burundi			3	4
Cambodia	26	26		1
Cameroon				1
Canada	39	41	18	21
Central African Republic				1
Chile	29	43	5	10
China	449	474	51	104
Colombia	271	368	30	20
Congo, Democratic Republic of the	14	15	11	8
Costa Rica	837	819	19	127
Croatia	49	49		2
Cuba	199	289	2	42
Czechia	77	90	22	8
Czechoslovakia	138	137		56
Denmark	15	15	12	11
Ecuador	274	660	23	35
Egypt	26	135	3	12
El Salvador	200	208	3	90
Eswatini		3		
Ethiopia	245	546	13	78
Fiji	9	9		3
France	458	183	23	231
Georgia	63	67		14
German Democratic Republic	10	10		2
Germany	164	179	44	84
Ghana	4	4	2	3
Greece	81	81	2	3
Grenada	3	3		1

Country	Genesys	FAO WIEWS	GBIF (living specimens only)	SGSV
Guam		1		
Guatemala	803	802	237	265
Guyana	18	81	2	7
Honduras	203	199	12	68
Hungary	1621	1705	213	303
India	684	4178	10	214
Indonesia	278	279	7	42
Iran (Islamic Republic of)	140	107	16	79
Iraq	2	2		
Israel	118	88		39
Italy	502	500	25	132
Jamaica	8	9	2	3
Japan	136	149	43	57
Jordan	13	12	1	
Kazakhstan	4	4		
Kenya	57	55		2
Korea (Democratic People's Republic of)	26	26		3
Korea, Republic of	203	247		668
Kyrgyzstan	4	15	7	4
Lao People's Democratic Republic	74	74		38
Lebanon	10	6		6
Lesotho		1		
Libya	21	27	10	10
Lithuania	20	21		
Malawi	3	3		1
Malaysia	444	437		79
Maldives	84	79	76	32
Mauritania	1	1		
Mauritius	1	1	2	1
Mexico	1098	6083	556	187
Micronesia (Federated States of)	1	1		
Moldova, Republic of	199	207	15	5
Mongolia	4	22	3	2
Morocco	16	18	7	
Myanmar	3	3		1
Nepal	22	27	42	4
Netherlands	237	251	76	90
Netherlands Antilles	2	2		
New Zealand		2		
Nicaragua	55	48	15	27
Niger	8	16		
Nigeria	64	240	3	13
North Macedonia	123	123		
Northern Mariana Islands	1	2	1	2
Norway	1	1		
Pakistan	50	231	8	9
Palestine, State of			6	
Panama	73	77	4	8
Papua New Guinea	6	6		4
Paraguay	40	41	36	6

Country	Genesys	FAO WIEWS	GBIF (living specimens only)	SGSV
Peru	757	1448	143	111
Philippines	221	268	4	76
Poland	184	184	134	5
Portugal	246	287	8	18
Puerto Rico	2	25	2	16
Romania	971	976	38	71
Russian Federation	121	247	12	15
Sao Tome and Principe		1		
Saint Helena				1
Saudi Arabia		1		
Senegal	4	4		3
Serbia	26	26	18	1
Sierra Leone	1	1		
Slovakia	65	65	11	8
Slovenia	3	3	1	1
Solomon Islands	2	2		1
South Africa	5	23	1	1
Spain	2070	2214	540	170
Sri Lanka	71	244		17
Sudan	408	408	23	7
Suriname	34	29	4	6
Sweden	4	2	5	
Switzerland	14	14	4	12
Syrian Arab Republic	64	58	26	19
Taiwan	129	359	8	93
Tajikistan	20	24		
Tanzania, United Republic of	42	74	1	10
Thailand	497	535	79	110
Togo	2	2	18	1
Trinidad and Tobago	14	13		6
Tunisia	28	182	4	13
Turkey	894	2230	17	289
Uganda	9	28		5
Ukraine	384	388	21	2
United Kingdom	54	51	3	27
United States of America	1627	1852	173	701
Uruguay	8	10		2
USSR (Soviet Union)	151	154		25
Uzbekistan	25	50	44	22
Vanuatu	3	3		1
Venezuela (Bolivarian Republic of)	69	68	10	13
Viet Nam	66	62	57	14
Virgin Islands (British)	4	3		
Yemen	24	25	9	21
Yugoslavia	549	556		22
Zaire	1			1
Zambia	97	181	93	26
Zimbabwe	9	8	1	5
Unknown			2	177
Not reported	7434	8218	493	303
Total	**32,304**	**47,503**	**4630**	**6378**

As reported in the stakeholder surveys, during the last 10 years, an average of 240 *Capsicum* accessions have been acquired by institutions conserving these crops. Seven institutions have acquired at least 500 accessions of *Capsicum* within the last 10 years. In total, across the institutions responding to the surveys, 8,406 *Capsicum* accessions have been acquired during the last decade. During the same period, 508 accessions of *Capsicum* were lost from the collections, with an average of 24 accessions per institution. In total, 72 accessions were removed from the collections because they were identified as being duplicates, leading to an average of nearly 4 *Capsicum* accessions per institution.

From the stakeholder surveys, national priorities were clear for many collections. For example, approximately 70% of *C. annuum* accessions were collected in the same country as the institution, with 24 institutions reporting that more than half of their *C. annuum* accessions were collected or originated within their own country. Approximately 21%, on average, of *C. annuum* was reported to be collected or originated regionally, and 27% was collected or originated internationally, excluding the region the institution was located in, with four institutions stating that more than 50% of their *C. annuum* collection originated internationally. Nearly 23% of *C. annuum*, on average, was of unknown origin, with two institutions reporting that more than half of their collection was of unknown origin.

The Genesys and FAO WIEWS databases provide information on the collecting (or acquisition) source (**Table 3.7**). While the great majority of accessions are not classified or clearly specified, those records with information indicate that the largest sources include institutes/genebanks, farms, wild habitats, and seed companies.

The vast majority of respondents to the stakeholder surveys perceived gaps in their *Capsicum* collections. The most common gap reported was for species or taxa, with more than 77% of institutions reporting a perceived or known species/taxa gap in their *Capsicum* collection. Nearly 75% of respondents reported that there were known or perceived genetic diversity gaps in their *Capsicum* collection. Similarly, 74% of respondents reported perceived or known ecogeographic gaps within their *Capsicum* collection. Approximately 65% of respondents reported having known or perceived varietal diversity and trait gaps in their *Capsicum* collections. In addition, 19% of respondents reported other gaps for their *Capsicum* collections, besides genetic, taxonomic, ecogeographic, varietal or for specific traits.

Approximately 48% of respondents reported efforts or plans to try to fill gaps in their *Capsicum* collections, with most targeting collections in certain under-represented regions and germplasm exchanges as a means to do so. As expected, funding for gap filling was mentioned by several respondents (5) as a major limitation to further acquisition.

Nearly half of survey respondents predicted a limited expansion (5–10% increase) in the size of their *Capsicum* collections over the next 10 years and another 24% of respondents anticipate a substantial increase of more than 10% in the size of their collections over the next decade. Only 7% of respondents projected a decrease in their collections, with 2% owing the reduction to collection rationalization, such as removing duplicates, and 5% reporting that lack of funding or facilities will result in a collection size reduction. The size of the *Capsicum* collection is anticipated to stay approximately the same over the next decade for 20% of the institutions responding to the survey (**Figure 3.4**).

A "diversity tree" (van Treuren et al. 2009) has been developed for *Capsicum* genetic resources based on stakeholders' delineations of the taxonomic, genetic, and geographic structure within the genus. This tree is a stratification of the *Capsicum* genepool into groups and subgroups; the Crop Trust has adapted this idea to visualize and understand the coverage of a crop genepool in *ex situ* conservation. The interactive is available for visualization in the Genesys *Capsicum* crop page.

Matching current *ex situ* accessions as reported in a combined Genesys and FAO WIEWS dataset to the diversity tree suggests that *Capsicum annuum* var. *annuum* from West and Central Africa is particularly poorly represented in *ex situ* collections, likewise in South Asia, Myanmar, Nepal and Bhutan are underrepresented, and in Southeast Asia, Cambodia and Laos. In South America, Venezuela, Paraguay, Uruguay, Suriname and Chile have a low absolute number of accessions (**Table 3.8**). Some states in Mexico were found to

Table 3.7. Acquisition source and number of accessions per database. Sources sorted in descending order in terms of number of accessions (of specified acquisition sources), by the Genesys database.

Acquisition source	Genesys	FAO WIEWS
Institute/Genebank	1944 (6.0%)	3470 (7.3%)
Farm	1648 (5.1%)	7192 (15.1%)
Seed company	696 (2.2%)	565 (1.2%)
Wild habitat	487 (1.5%)	3116 (6.6%)
Market or shop	87 (0.3%)	421 (0.9%)
Weedy habitat	2 (0.0%)	21 (0.0%)
Other	3432 (10.6%)	0 (0.0%)
Not specified	24,008 (74.3%)	32,718 (68.9%)
Total	**32,304**	**47,503**

Table 3.8. Summary of existing accessions held *ex situ*, as reported in a combined Genesys and FAO WIEWS dataset, in the end groups of the *Capsicum annuum* var. *annuum* section of the *Capsicum* diversity tree. Data from stakeholder surveys is not included.

Capsicum annuum* var. *annuum	**End group**	**Number of accessions**
Central Africa		8
Eastern and Southern Africa		407
West Africa		58
North Africa, Southern Europe, Middle East		
	North Africa	373
	Southern Europe	3221
	Middle East	189
Eastern Europe/West Asia		
	Eastern Europe	6054
	Turkey	2178
	Caucasus	566
Central Asia		
East Asia	China	449
East Asia	Japan	152
East Asia	North Korea	26
East Asia	South Korea	237
East Asia	Taiwan	349
South Asia		
South Asia	Bangladesh	211
South Asia	Bhutan	30
South Asia	India	3970
South Asia	Myanmar	3
South Asia	Nepal	15
South Asia	Pakistan	229
Southeast Asia		
Southeast Asia	Cambodia	7
Southeast Asia	Indonesia	151
Southeast Asia	Laos	24
Southeast Asia	Malaysia	208
Southeast Asia	Philippines	169
Southeast Asia	Thailand	330
Southeast Asia	Vietnam	41
Oceania		32
Caribbean and Central America		
	Belize	10
	Costa Rica	244
	Cuba	138
	Dominican Republic	0
	El Salvador	140
	Guatemala	504
	Haiti	0
	Honduras	115
	Jamaica	3
	Nicaragua	32
	Panama	12
	Puerto Rico	9
	USA	1579
Mexico		4504
	Aguascaliente	147
	Baja California	4
	Baja California Sur	15
	Campeche	29
	Chiapas	148
	Chihuahua	10
	Coahuila	29
	Colima	7
	Durango	118
	Guanajuato	5
	Guerrero	27
	Hidalgo	86
	Jalisco	25
	Michoacan	19
	Morelos	227
	Mexico	83
	Nayarit	15
	Nuevo Leon	30
	Oaxaca	445
	Puebla	277
	Queretaro	82
	Quintano Roo	24
	San Luis Potosi	121
	Sinaloa	1
	Tabasco	16
	Tamaulipas	118
	Tlaxcala	79
	Veracruz	210
	Yucatan	110
	Zacatecas	196
South America		
	Argentina	204
	Bolivia	35
	Brazil	201
	Chile	14
	Colombia	93
	Ecuador	222
	French Guiana	0
	Paraguay	2
	Peru	169
	Suriname	2
	Uruguay	2
	Venezuela	10
	North, West and Central Europe	706

be less well represented than others, but it should be noted that 1,774 accessions listed as from Mexico had neither coordinates or state of origin information.

A similar assessment conducted for *Capsicum chinense* suggests that the Central Africa and West Africa secondary regions of diversity are not well represented in *ex situ* collections (**Table 3.9**). Also, Southeast Asia, East Asia and Oceania have a low number of accessions conserved *ex situ*. However, out of the 3,257 accessions of *C. chinense* recorded in Genesys and WIEWS, 1,396 (42% of the total) do not have information on the country of origin (of these 790 are held at BRA003 and BRA012). This lack of data is a strong limitation on assessing how well *ex situ* collections cover the geographic distribution of this crop (here used as a proxy for genetic diversity).

Accessions of *C. frutescens* from China, Japan and Taiwan are scarcely represented in the combined Genesys-WIEWS dataset (**Table 3.10**). It is likely, however, that this is because accessions from China are stored in Chinese genebanks and that the data is not shared in these databases. Similarly, there is a large number of accessions stored at NARO with unknown country of origin, and some of these are likely to be from Japan. In Southeast Asia, Cambodia, Indonesia and Myanmar are also under-represented (although a search at NARO database found that JPN183 stores 62 accessions from Cambodia).

Table 3.9. Summary of existing accessions held *ex situ*, as reported in a combined Genesys and FAO WIEWS dataset, in the end groups of the *Capsicum chinense* section of the *Capsicum* diversity tree. Data from stakeholder surveys is not included.

***Capsicum chinense* Jacq**	**End group**	**Number of accessions**
Africa	Eastern Africa and Southern Africa	12
	Central Africa	8
	Western Africa	9
The Americas	Mexico	149
	Central America	138
	Caribbean	52
	South America (excluding Brazil and Peru)	438
	Brazil	208
	Peru	521
Oceania		1
Asia	East Asia	6
	South Asia	305
	Southeast Asia	14
Unknown origin		1396

The analysis also found that *ex situ* accessions of *C. pubescens* were mostly collected in Peru, while Mexico, the Central American countries, and Ecuador, Colombia, and Bolivia are not as well represented in *ex situ* collections.

The majority of accessions of *Capsicum annuum* var. *glabriusculum* are from Mexico (**Table 3.11**). However, this taxon is found throughout Central America and south to Brazil. Therefore, a better representation of its distribution range in *ex situ* collections will require a larger number of accessions collected outside of Mexico. Also, at a finer geographical level, the coverage within Mexico may be less than ideal. Considering that this taxon was likely domesticated in Mexico, analysis at this level of scale would be worthwhile, but the data available to the authors of this strategy did not allow for detailed analysis at this finer level.

A recent conservation gap analysis for wild *Capsicum* species considered 35 (95%) of these taxa of high priority for further collecting for *ex situ* conservation, including the two known putative crop progenitors (Khoury et al. 2019). Among these were 23 taxa with no (zero) reported *ex situ* representation in the available germplasm databases, and another

Table 3.10. Summary of existing accessions held *ex situ*, as reported in a combined Genesys and FAO WIEWS dataset, in the end groups of the *Capsicum frutescens* section of the *Capsicum* diversity tree. Data from stakeholder surveys is not included.

***Capsicum frutescens* L.**	**End group**	**Number of accessions**
Africa (total)		563
	Nigeria	28
Americas		
	Central America	514
	Mexico	101
	South America	351
Asia		
	China	5
	Japan	0
	Taiwan	5
	South Asia	497
	Cambodia	18
	Indonesia	13
	Laos	50
	Malaysia	84
	Myanmar	0
	Philippines	53
	Thailand	61
Other origins		272
Unknown origin		736

eight with fewer than ten accessions, and thus very limited genetic diversity accessible for crop breeding and other research. When examining *ex situ* representation in terms of the climatic niches of the taxa, *C. annuum* var. *glabriusculum*, *C. baccatum* var. *baccatum*, and *C. chacoense* (i.e., the only wild taxa with more than 10 germplasm occurrences) were determined to be relatively well represented. The rest of the taxa, with no or very few occurrences, were clearly very poorly represented.

3.3 Structure, management, and condition of *Capsicum* collections

The Genesys and FAO WIEWS databases provide some information on the conditions under which *ex situ* accessions are stored. In Genesys, 68% of accessions were marked as stored as seed (the rest were not specified). Of the accessions with information on storage term (44% of all accessions), long-term storage conditions were provided for 61% of these accessions; medium-term for 60%, and short-term conditions for 0.6% (note that seed can be held in more than one storage type within each institution).

In FAO WIEWS, 97% of accessions were marked as stored as seed, 1% as stored in the field, and less than 0.1% as stored *in vitro*; for only 3% of accessions were storage conditions not specified. Of the accessions with information on storage term (96% of all accessions), long-term storage conditions were provided for 67% of these accessions and medium-term for 60% (note that seed can be held in more than one storage type within each institution); short-term storage conditions were not specified.

It has been observed that seeds of some wild species, including *C. lanceolatum*, are highly recalcitrant to storage and rapidly become unviable in cold storage (Barchenger and Bosland, 2019). New Mexico State University maintains live plants of several recalcitrant wild *Capsicum* species to ensure they are not lost (P.W. Bosland, pers. comm.).

Table 3.11. Summary of existing accessions held ex situ, as reported in a combined Genesys and FAO WIEWS dataset, in the end groups of the *Capsicum annuum* var. *glabriusculum* section of the Capsicum diversity tree. Data from stakeholder surveys is not included.

***Capsicum annuum* var. *glabriusculum* (Dunal) Heiser & Pickersgill**	**End group**	**Number of accessions**
Mexico		
	Mexico (no coordinates)	38
	Aguascaliente	0
	Baja California	0
	Baja California Sur	0
	Campeche	0
	Chiapas	2
	Chihuahua	2
	Coahuila	0
	Durango	0
	Guanajuato	0
	Guerrero	0
	Hidalgo	0
	Jalisco	0
	Michoacan	0
	Morelos	0
	Mexico	1
	Nayarit	0
	Nuevo Leon	0
	Oaxaca	15
	Puebla	0
	Queretaro	0
	Quintana Roo	0
	San Luis Potosi	0
	Sinaloa	9
	Sonora	9
	Tabasco	0
	Tamaulipas	0
	Veracruz	15
	Yucatan	0
	Zacatecas	0
Central America		
	Belize	0
	Costa Rica	6
	El Salvador	4
	Guatemala	13
	Honduras	0
	Nicaragua	3
	Panama	0
Colombia		0
USA		5
	Arizona	lack of coordinates
	Florida	lack of coordinates
	Louisiana	lack of coordinates
	New Mexico	lack of coordinates
	Texas	lack of coordinates
Caribbean		0
Unknown origin		54

From the stakeholder surveys, on average, the proportion of the *Capsicum* collections maintained under short-, medium-, and long-term storage was 68%, 86%, and 81%, respectively. In total, 24 institutions maintained long-term storage of *Capsicum*, 26 maintained collections under medium-term storage, and 17 have collections stored short-term. The average temperature for long-, medium-, and short-term storage facilities for the *Capsicum* collection was -13.3, 4.4, and 13.3 °C, respectively. The average seed moisture content of *Capsicum seeds* was 7.1%, and ranged from 3 to >10%, although four institutions reported not determining seed moisture content prior to storage. Sealed aluminum packs were the most common packaging used for *Capsicum* seed conservation, at 47% of institutions, followed by paper envelopes (35%), plastic containers (25%), sealed and vacuum-packed aluminum packs (23%), glass containers (10%); 7.5% of institutions used another type of packaging.

More than half (56%) of the institutions responding to our surveys use the Genebank Standards developed by FAO/IPGRI (1994) in managing their collection and to minimize the loss of genetic integrity in *Capsicum* accessions during storage and regeneration (**Table 3.12**). In addition, 44% of respondents follow the guidelines established by Rao et al. (2006) for seed conservation, and 22% use the earlier version by Hanson (1985). More than 36% of respondents use their organization's own operational manual and 27% have developed Standard Operating Procedures (SOP) for key processes in their institution. Approximately 17% of respondents use a Quality Management System (QMS) for day to day operations. More than 7% of institutions report having no written procedure or protocol in place for managing their *Capsicum* collection.

More than 80% of survey respondents have established a genebank management system or have written protocols for the regeneration (88%), conservation (84%), characterization (81%), and distribution (81%) of germplasm (**Figure 3.5**). Nearly 71% of respondents have a genebank management system or written protocols in place for the acquisition of germplasm as well as for information management. Established protocols are in place for more than half (56%) of the institutions for safety duplication of accessions and for germplasm health. However, fewer institutions have a procedure in place for dealing with duplicated (44%) or misidentified (37%) accessions within the collections.

The vast majority of institutions report having separate work areas for dirty and clean seed handling procedures (83%), suitable field site for regeneration and multiplication (83%), greenhouse or glasshouse facilities for regeneration and multiplications (78%), dedicated laboratory and trained staff for seed viability testing (76%), and separate work areas for seed packaging for storage and distribution (73%) (**Figure 3.6**). However, only 56% of the respondents report having access to a low temperature seed dryer, and

Table 3.12. Percent of institutions responding to the stakeholder surveys using management procedures and protocols. Institutions may use more than one protocol, thus percentages do not sum to 100%.

Management procedure/protocol	Percent of institutions
FAO/IPGRI 1994. Genebank Standards.	55.5%
Rao et al. 2006. Handbooks for Genebanks No. 8: Manual of Seed Handling in Genebanks. Bioversity International.	43.9%
Organization's own "Operational Genebank Manual"	36.3%
Written and verified Standard Operating Procedures (SOPs) for key processes	26.8%
Hanson 1985. Practical Manuals for Genebanks No. 1: Procedures for Handling Seeds in Genebanks. IBPGR.	22.0%
A Quality Management System (QMS)	17.1%
Other	7.3%
No written procedures or protocols	7.3%

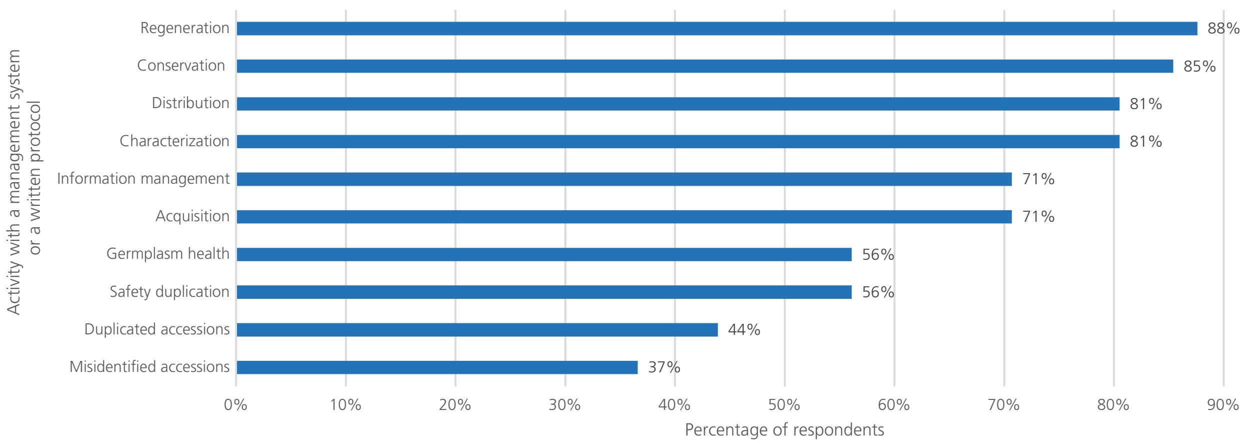

Figure 3.5. Percent of respondents to the stakeholder surveys having management systems or written protocols for genebank activities.

only 29% have a laboratory and staff for seed health testing.

Several core collections and other germplasm (sub)sets were described by the survey respondents, especially in Asia and Europe. Recently, the G2PSol *Capsicum* collection was developed, which is maintained for distribution in Europe by the Institut national de la recherche agronomique (INRAE) in France and in Asia by the World Vegetable Center (WorldVeg) in Taiwan. This was developed through sequencing nearly 15,000 *Capsicum* accessions housed across five large genebanks in Europe, plus WorldVeg. The G2PSol core collection has been widely evaluated in multiple locations for numerous traits of interest and currently efforts are underway to identify loci contributing to those traits using genome wide association studies (GWAS).

Similarly, CGN in the Netherlands has a core selector tool, based on the use of Diversity Trees, where users can develop their own core collections of the germplasm available there. A morphological core collection, consisting of 10% of the total collection, has been developed by the Taiwan Agricultural Research and Development Institute. Genetic subsets were reported by Universitas Gadjah Mada (Agrotechnology Innovation Centre) in Indonesia for bacterial diseases, for tropical diseases by the Fruit and Vegetable Research Institute in Vietnam, and for *Chilli leaf curl virus* (ChiLCV; *Begomovirus*) by ICAR-Indian Institute of Vegetable Research. Khon Kaen University in Thailand maintains a subset of *Capsicum* with diverse levels of various phytochemicals. The Institute of Plant Genetic Resources "K. Malkov" in Bulgaria maintains five subsets of *Capsicum* for earliness, productivity, dry matter content, vitamin C content and sugar content. Ss. Cyril and Methodius University in Northern Macedonia have developed a corkiness (scaring or minor striations on the surface of the pepper skin, which represents a quality trait in some market segments) subset.

In terms of biotic constraints to storage and maintenance of *Capsicum* collections, stakeholder survey respondents listed fungal disease (27% of respondents), viruses (20%) and the arthropod pests bruchids (13%) and skin bugs (7%) (**Figure 3.7**). A third of respondents reported that no biotic constraints to *Capsicum* seed storage exist for their institution.

3.4 Status of regeneration and multiplication of *Capsicum* genetic resources

Global genetic resource databases do not provide specific information on the regeneration and multiplication status or needs of accessions of *Capsicum*. From the stakeholder surveys, for *C. annuum*, the average proportion of the collection that requires urgent regeneration was 38%, which can be extrapolated to more than 12,000 accessions worldwide. Six

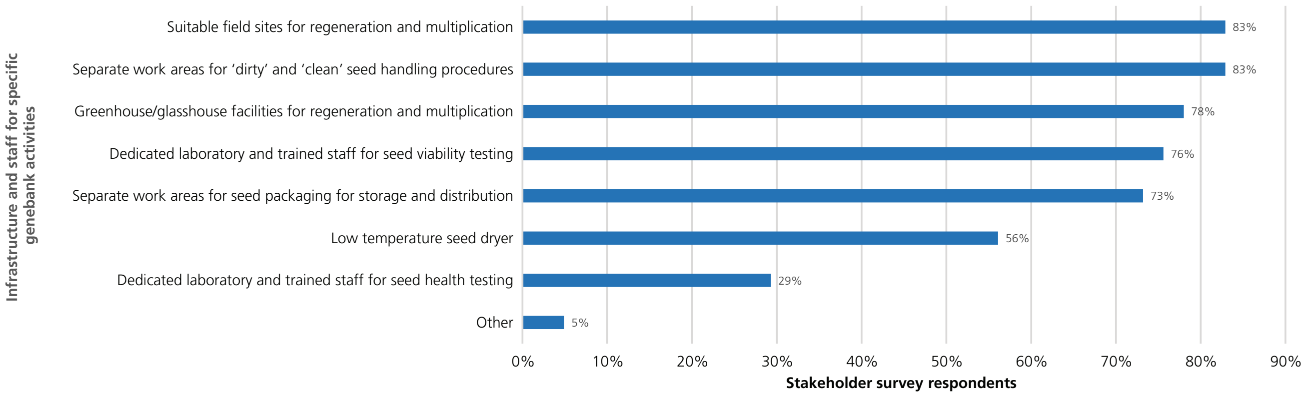

Figure 3.6. Percent of respondents to the stakeholder surveys having infrastructure and staff for specific genebank activities.

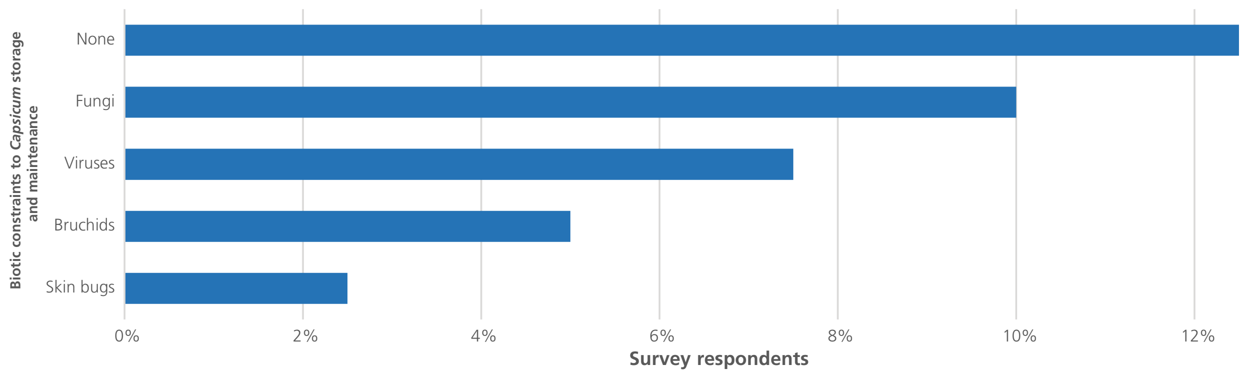

Figure 3.7. Number of stakeholder survey respondents (n = 40) listing biotic constraints to *Capsicum* storage and maintenance.

institutions reported that 100% of their *C. annuum* collection required urgent regeneration and one institute reported 80%, with an additional six institutions reporting that at least 50% of their *C. annuum* collection needs to be regenerated urgently (**Figure 3.8**). A very similar situation exists for the other domesticated species and the wild *Capsicum* species, each with approximately 34% of accessions requiring urgent regeneration, on average. For the other domesticated species, five institutions reported that at least 50% of the collection requires urgent regeneration, with three reporting that 100% of the collection requires urgent regeneration. Likewise, five institutions reported that at least 50% of the collection of wild species of *Capsicum* is in need of urgent regeneration, of which four reported at least 80% of the collection.

The average regeneration interval for *Capsicum* collections was reported to be nearly 12 years, and ranged from 2 years to 50 years (**Figure 3.9**). The average interval for germination testing (determining % germination across a subset of individuals in an accession) was nearly 5 years; however, there was a wide range for germination testing intervals, with nearly half of respondents testing more frequently than every 5 years, and around 35% of respondents conducting germination tests every 10 years or longer. The intervals for seed viability (testing if alive or dead) testing were generally similar for germination testing, averaging every 4.5 years, with 55% of respondents testing every 5 years. Health testing was done on average every 2 years, approximately, although these data are likely highly dynamic and may not be representative across *Capsicum* collections worldwide. Several institutions provided feedback that health testing was done as necessary, with frequency based on requests for germplasm, emerging pests and diseases, and changing phytosanitary requirements.

There was an array of biotic constraints to regeneration and multiplication reported by the stakeholder survey respondents, and these constraints were more numerous than those listed for storage and distribution activities. The most common constraint was viruses, with nearly a quarter of respondents reporting viral diseases are an issue (**Figure 3.10**). The most common response for this category of constraints was simply “viruses”, but respondents also reported *Pepper yellow leaf curl virus* (PepYLCV; *Begomovirus*) (1 respondent), *Tomato brown rugrose fruit virus* (ToBRFV; *Tobamovirus*) (2), *Chilli leaf curl virus* (ChiLCV; *Begomovirus*) (2) and *Tomato spotted wilt virus* (TSWV; *Tospovirus*) (1). A small percentageof respondents reported that anthracnose (caused by *Colletotrichum* spp.), thrips, fungi, whitefly, general bacterial diseases and bacterial wilt were major constraints to their regeneration or multiplication of *Capsicum*.

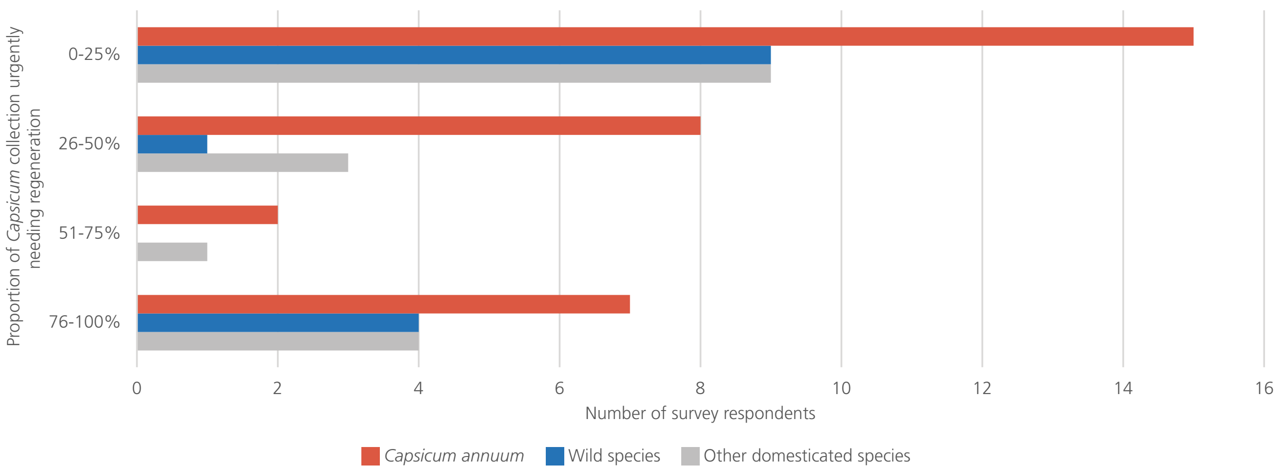

Figure 3.8. Number of survey respondents (n = 40) reporting the proportion of their *Capsicum* collections urgently needing regeneration, per taxon grouped into three categories (*C. annuum*, other domesticated species, and wild species).

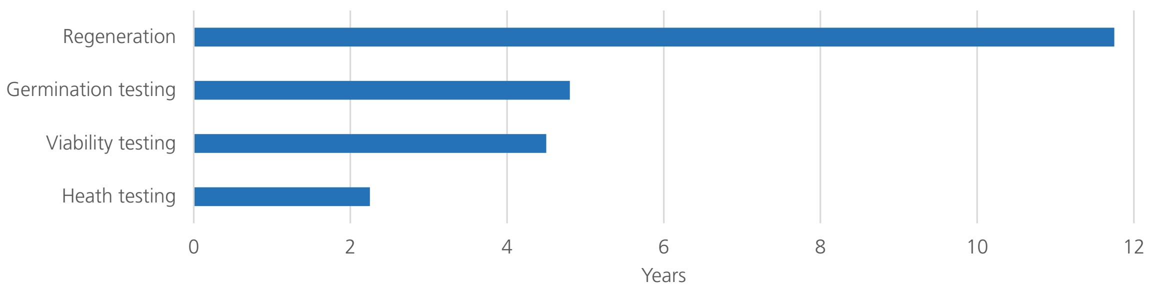

Figure 3.9. Intervals for testing and for regeneration of *Capsicum* accessions, averaged across stakeholder survey respondents (n = 40).

3.5 Status of characterization and evaluation of *Capsicum* genetic resources

Global genetic resources databases do not provide specific information on characterization or evaluation of *Capsicum* accessions. The Genesys database does offer access to a morphological characterization dataset for 74 accessions of *Capsicum* held by CATIE (from 2008–2010 and 2011–2012. Various national genebank information systems may offer characterization and evaluation data for *Capsicum* (not covered here).

From the stakeholder surveys, on average, 60% of the accessions of the domesticated/cultivated *Capsicum* species conserved by respondents have some agro-morphological (phenotypic) characterization data, while 30% of the accessions of the wild *Capsicum* species have these data. Approximately 9% of both the cultivated and the wild accessions have been genotyped using molecular markers or other sequencing techniques (**Figure 3.11**). Only 18% of domesticated/cultivated accessions and 10% of wild accessions have been phenotyped for biotic stresses, and only 4% of the domesticated/ cultivated accessions and 1% of the wild accessions, on average, for abiotic stress tolerance.

There was a large variation among respondents for the traits characterized. Approximately 13% of respondents reported phenotyping at least some portion of their *Capsicum* collection for drought tolerance (**Figure 3.12**). Only 4%, on average, of *Capsicum* collections reported phenotyping for abiotic stress tolerance, while 13% have phenotyped for tolerance to water deficit stress. Beyond drought, the most common stresses phenotyped were biotic, with 11% of respondents phenotyping for bacterial wilt (caused by *Ralstonia* spp.), 8% screening for *Phytophthora capsici* resistance, and 8% for pests and diseases in general. Thrips, an important arthropod pest, has been a focus for screening the *Capsicum* collections of 5% of respondents. In addition, 5% of respondents have phenotyped their collections for tolerance to *Chilli leaf curl virus* (ChiLCV; *Begomovirus*), anthracnose (caused by *Colletotrichum* spp.), and viral diseases in general , as well as abiotic stresses including salinity, waterlogging, and heat/high temperature. Various other fungal, bacterial, and viral diseases, as well as aphids, were reported to be of focus of phenotyping by approximately 3% of respondents.

Wild *Capsicum* species have not had extensive characterization or evaluation (van Zonneveld et al. 2015, Mongkolporn and Taylor 2011), aside from a few reports of disease resistance (e.g., Kenyon et al. 2014), unlike the wild relatives of tomato (*Solanum lycop-*

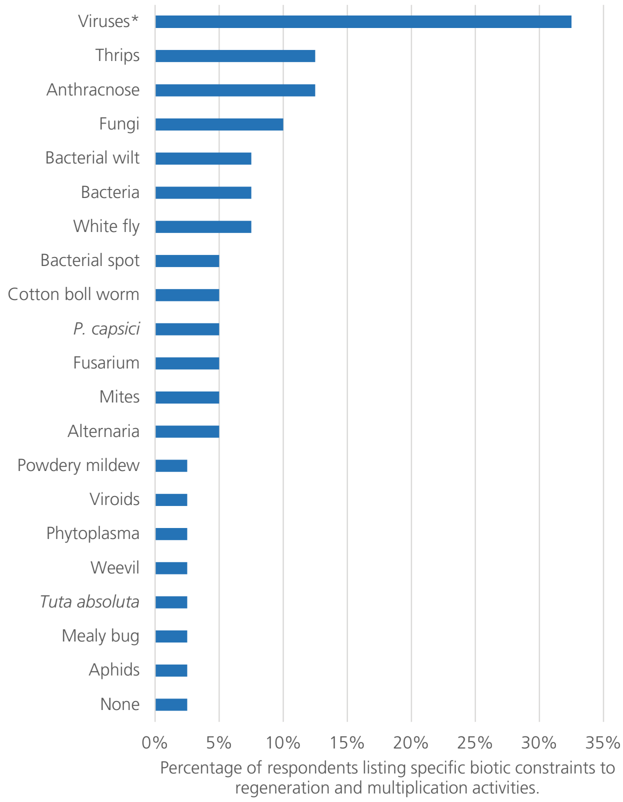

Figure 3.10. Number of responses in survey listing specific biotic constraints to regeneration and multiplication activities. *The response of viruses also included responses of Pepper yellow leaf curl *virus* (PepYLCV; *Begomovirus*)[1], Tomato brown rugose fruit virus (ToBRFV; *Tobomovirus*)[2], Chilli leaf curl virus (ChiLCV; *Begomovirus*)[2] and Tomato spotted wilt virus (TSWV; *Tospovirus*) [1].

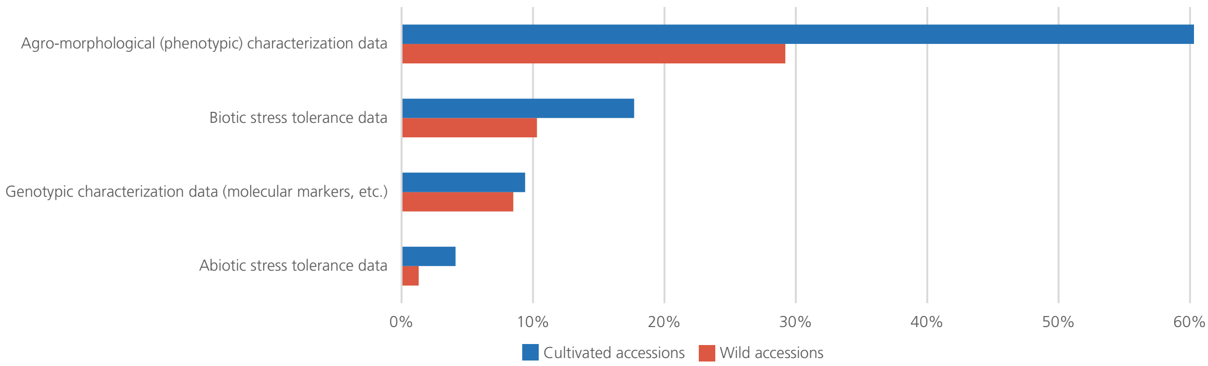

Figure 3.11. Percent of *Capsicum* collection having characterization or evaluation data, on average across stakeholder survey respondents, for domesticated species and for wild species accessions.

ersicum L.) (Lin et al. 2014) and potato (*S. tuberosum* L.) (Hirsch et al. 2013), some of the other important crops in the Solanaceae (Khoury et al. 2019). Tolerance of wild *Capsicum* to abiotic stresses such as salinity, drought, flooding, and heat, all recognized challenges in the production of the crop taxa (Aloni et al. 2001; De Pascale et al. 2003; Gajanayake et al. 2011; Han et al. 1996; Maas and Hoffman 1977; Rao and Li 2003), has not been widely investigated.

A recent ecogeographic assessment of wild *Capsicum* found substantial variation in their climatic niches across species (Khoury et al. 2019, see Annex V with supplementary information from Khoury et al. 2019). Taxa with occurrences in the locations with the highest maximum temperatures in the warmest month of the year included *C. chacoense*, *C. annuum* var. *glabriusculum*, *C. baccatum* var. *baccatum, C. coccineum,* and *C. minutiflorum*. Those found in locations with the lowest temperatures in the coldest month included *C. cardenasii*, *C. caballeroi*, *C. eximium*, *C. friburgense*, and *C. flexuosum*. Those taxa with occurrences in sites with the highest precipitation in the wettest month included *C. lanceolatum*, *C. lycianthoides*, *C. schottianum*, and *C. coccineum*, while those occurring in areas with the lowest precipitation in the driest month included *C. hookerianum*, *C. eximium*, *C. cardenasii*, *C. chacoense*, *C. eshbaughii*, *C. galapagoense*, *C. longidentatum*, *C. neei*, *C. parvifolium*, *C. tovarii*, and *C. caatingae*.

While some of these are distant relatives to the cultivated peppers (with a base chromosome number of 13 rather than 12), a number of the taxa with outstanding potential adaptations are putative progenitors or relatively close relatives, including *C. annuum* var. *glabriusculum*, *C. baccatum* var. *baccatum, C. cardenasii*, *C. chacoense*, *C. eshbaughii, C. eximium*, and *C. galapagoense*. Temperature, precipitation, and other variables also varied considerably within the ranges of some of the more widespread taxa, including *C. annuum* var. *glabriusculum*, *C. baccatum* var. *baccatum*, and *C. rhomboideum*, and for the Andean taxa *C. lycianthoides*, *C. geminifolium, C. dimorphum*, and *C. coccineum*, as well as for *C. lanceolatum*. Thus, populations within these taxa may differ significantly with regard to their ecological adaptations and potential traits to offer to crop improvement.

While ecogeographic information associated with germplasm accessions can help narrow the potential pool of useful germplasm targeted by plant breeders, these data cannot displace the need for direct phenotypic validation of adaptations, such as for abiotic or biotic stress tolerance. Further phenotypic characterization of collections under diverse environmental conditions and using manipulative experiments (e.g., imposing moisture stress or inoculating with pathogens) are needed for *Capsicum* accessions.

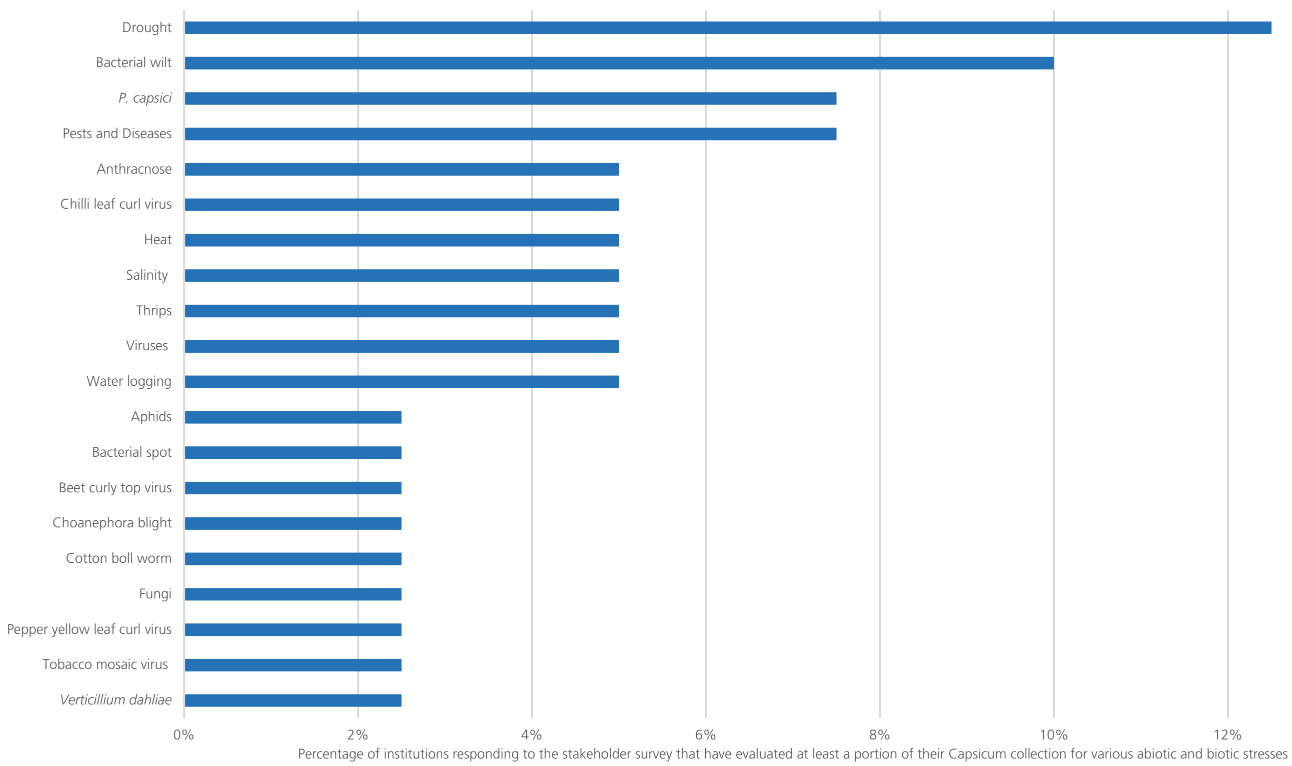

Figure 3.12. Number of responses of institutions responding to the stakeholder survey that have evaluated at least a portion of their Capsicum collection for various abiotic and biotic stresses (n=40).

3.6 Status of safety duplication of *Capsicum* genetic resources

The Genesys and FAO WIEWS databases provide some information on duplication of *Capsicum ex situ* accessions. In Genesys, 11,864 out of 32,304 accessions (36.7%) are specifically noted as currently safety duplicated. At least 3,764 of these are duplicated at the Svalbard Global Seed Vault (SGSV). Other important back-up sites include the USDA National Laboratory for Genetic Resources Preservation, the Centro Nacional de Recursos Fitogenéticos (Spain), Warwick Genetic Resources Unit (UK), and the RDA genebank (Republic of Korea).

In FAO WIEWS, 8,297 out of 47,503 accessions (17.5%) are specifically noted as currently safety duplicated. At least 871 of these are held at the SGSV; other important back-up sites include the National Plant Genetic Resources Centre (Taiwan), the Centro Nacional de Recursos Fitogenéticos (Spain), Warwick Genetic Resources Unit (UK), and Embrapa Hortaliças (Brazil).

The Seed Portal of the Svalbard Global Seed Vault (Nordgen 2022) provides direct information on accessions deposited there. Numbers of *Capsicum* accessions per taxon safety duplicated at Svalbard are listed in **Table 3.4**, while numbers of accessions per country of origin are listed in **Table 3.6**.

From the stakeholder surveys, approximately 21% of institutions have completed safety duplication of their collection in at least one other genebank, while 47% have partial safety duplication (**Figure 3.13**). Four institutions reported having more than 95% of their *Capsicum* collection safety duplicated, and an additional four institutions have at least 50% of their collection of *Capsicum* duplicated. More than 26% of institutions have no safety duplication of their *Capsicum* collection and an additional 5% are unaware of the status of safety duplication.

On average, 41% of the *Capsicum* accessions conserved by the survey respondents have been safety duplicated at one or multiple other institutions (this corresponds to an estimated total of 13,654 accessions). Nearly a quarter of respondents have their safety duplication integrated in another collection within their county and approximately a quarter of respondents have safety duplications at the SGSV. Approximately 15% of institutions have their *Capsicum* collection safety duplicated in a "black box" system within their country, and 12% have safety duplication in a black box outside of their country. In addition, 12% of respondents integrate their safety duplication of *Capsicum* into another collection outside of their country. Among the institutions having safety duplications, 83% have established formal agreements outlining the terms and obligations of safety duplication and approximately 21% of institutions serve as safety duplication sites for other collections. Notably, nearly a quarter of respondents report facing constraints to duplication of *Capsicum*

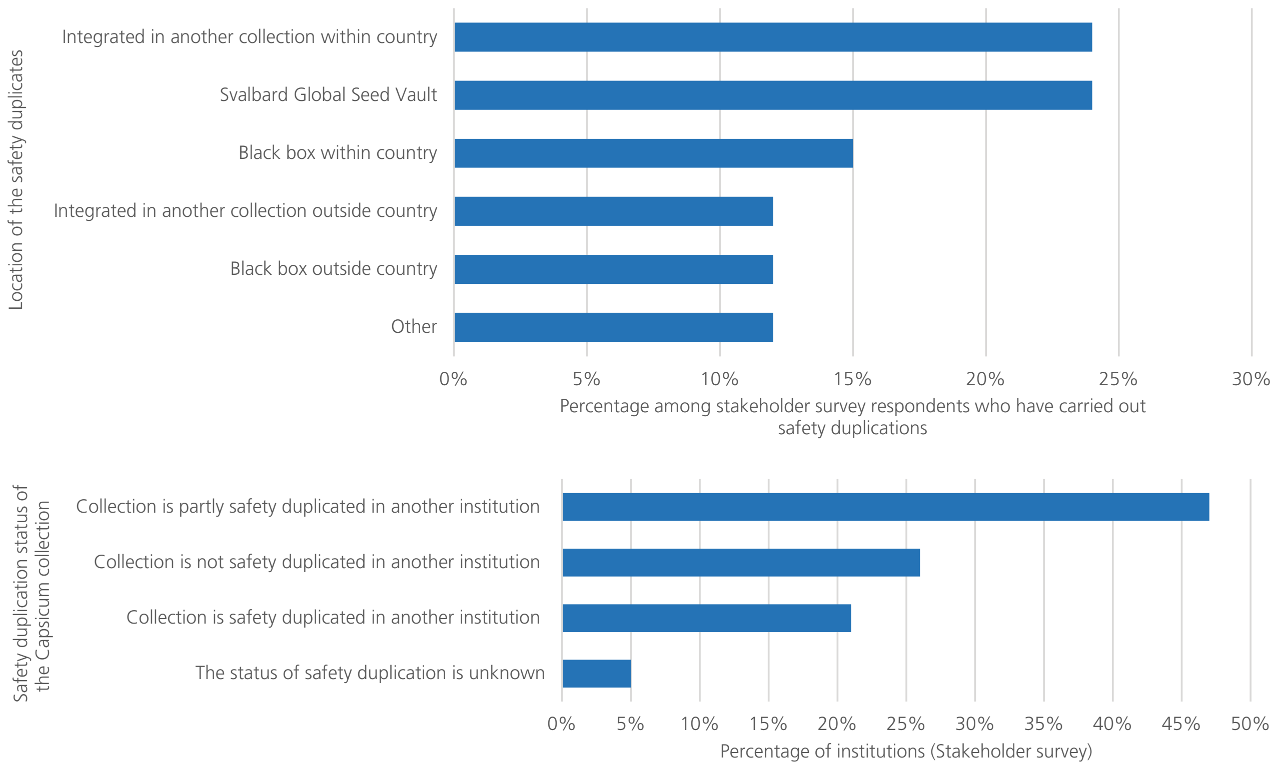

Figure 3.13. Safety duplication status of the *Capsicum* collection (top) and location of the safety duplicates among those respondents who have carried out safety duplications (bottom).

accessions outside of their country, potentially limiting their ability to fully safeguard their collections.

3.7 Documentation and information sharing on *Capsicum* genetic resources

As described in sections 3.1 and 3.5, Genesys, FAO WIEWS, PlantSearch, and GBIF provide different aspects of global documentation of *Capsicum* genetic resources. These databases currently offer access to basic taxonomic, institutional, and passport (provenance) information; some, such as Genesys, aspire to provide characterization and evaluation data as well. Genesys currently offers access to a morphological characterization dataset for 74 accessions of *Capsicum* held by CATIE (from 2008–2010 and 2011–2012). The FAO WIEWS database offers information on the overall degree of documentation of genetic resources in national institutions, including for characterization and evaluation data, but these are not currently specified per crop/genus. Various national genebank information systems may offer documentation data pertinent for *Capsicum*; these are not covered here.

Additional insights on the status, availability, and accessibility of information in national and subnational *Capsicum* collections can be gained from the stakeholder surveys. Approximately 60% of respondents to the surveys reported not having an adequate computerized database to manage the collection and share accession data, and, further, that their current system did not meet the needs of the institution or of the users of the collection. Approximately 21% of respondents who have a searchable electronic platform (computerized database) for storing and retrieving accession-level data, use the freely available Germplasm Resource Information Network (GRIN)-Global. Other specialist software mentioned by respondents include the Integrative Germplasm Information Management System (iGMS), the Alelo Portal, the SADC Plant Genetic Resource Centre Documentation Information System (SDIS), OLGA, and others. Microsoft Access and Excel were reported to be used by 32% of respondents for storing and retrieving data.

Passport data is present within an accession-level database for 83% of institutions responding to the survey, while 73% of institutions have taxonomic data for their collection (**Figure 3.14**). Characterization data and associated images exist in the accession level database for the *Capsicum* collections surveyed in 59% and 51% of the institutions, respectively. Approximately 42% of institutions have evaluation data for their *Capsicum* collection and maintain distribution data in their database. Genotypic data has been collected and maintained in an accession-level database by 27% of respondents, and more than 7% of respondents maintain other types of data for the collection.

Nearly 60% of the respondents make accession-level data publicly available, while 27% reported that this information is private (**Figure 3.15**). Accession-level data for the *Capsicum* collection can be accessed through a searchable online database, from outside the institution, for 32% of respondents. An additional 42% of respondents make accession-level data available through a written catalog or only when a potential user contacts the *Capsicum* curator. Nearly 27% of institutions reported that accession-level data is

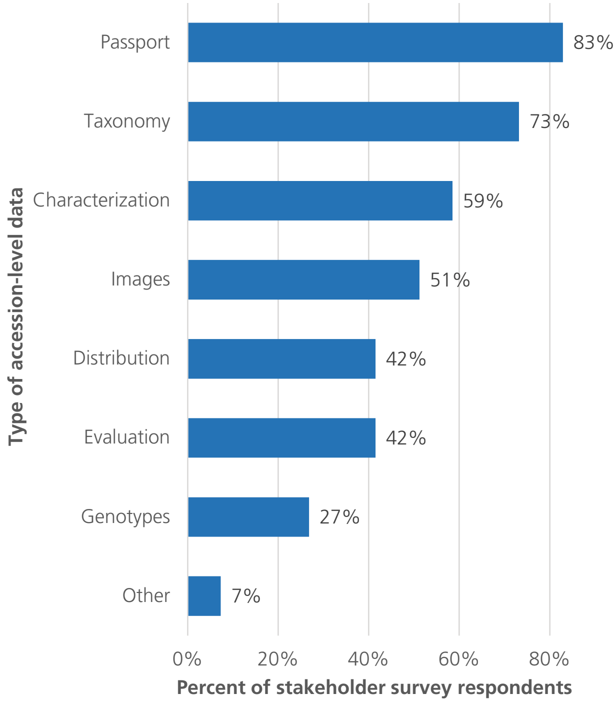

Figure 3.14. Percent of stakeholder survey respondents holding different types of accession-level data for their *Capsicum* collections

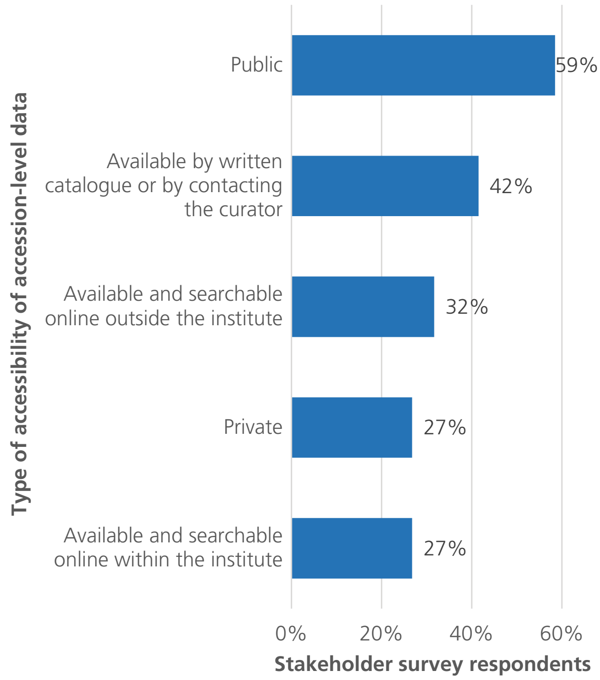

Figure 3.15. Percent of stakeholder survey respondents and type of accessibility of accession-level data for their Capsicum collections

available and searchable online from within the institution. For the institutions that make accession-level data accessible, 32% allow the data to be accessed internationally, 28% make it available nationally, and 22% have regional-specific access (**Figure 3.16**).

3.8 Access to, distribution of, and use of *Capsicum* genetic resources

Capsicum crops are a particular area of focus for WorldVeg and CATIE, who make germplasm collections and breeding materials freely available internationally. These crops are not currently considered mandate species in CGIAR centers. Regarding access to *Capsicum* genetic resources, the crop is not currently listed in Annex 1 as covered under the Multilateral System (MLS) of Access and Benefit Sharing of the International Treaty on Plant Genetic Resources for Food and Agriculture (FAO 2002).

The global databases Genesys and FAO WIEWS do provide some insight into the degree to which *Capsicum* collections are in any case included within the MLS, as Parties to the ITPGRFA may voluntarily place their collections within the system, or treat their accessions under equivalent terms, regardless of whether or not they are specifically listed in Annex 1. From Genesys, it appears that 1687 (5% of total) *Capsicum* accessions are listed as included in the MLS, 9676 (30%) specifically not in the MLS, and 20,941 (65%) are not specified. For FAO WIEWS, 10,256 (22%) *Capsicum* accessions are listed as included in the MLS and 37,247 (78%) are blank (either not in MLS or not specified). It is clear that these fields in the respective databases are not comprehensively filled, thus considerable uncertainty remains as to the access status of *Capsicum* accessions.

In terms of distributions of *Capsicum* germplasm under the auspices of the ITPGRFA, its Global Information System, using data tracking the use of standard Material Transfer Agreements (SMTAs) from 2012 to 2019, reports 7,992 exchanges of *Capsicum* in this time period (999 transfers per year, on average). This data may be confounded by the use of the term 'pepper' in reporting, which may also indicate transfers of *Piper* L. species, although the vast majority of exchanges are in fact likely to be of *Capsicum*. These transfers make *Capsicum* among the most exchanged of vegetable crops in the MLS, others being cabbages and other brassicas, lettuce, tomatoes, spinach, beets, and eggplant (Khoury et al. 2022). Likewise, information reported through FAO WIEWS about the number of accessions and the number of samples distributed from 2012 to 2019 by national genebanks indicates that *Capsicum* is among the most distributed of vegetable crops (with a total of 9,646 accessions and 35,170 samples distributed) (Khoury et al., 2022).

Similarly, FAO WIEWS information on the number of farmers' varieties/landraces distributed by national or local genebanks to farmers (either directly or through intermediaries) lists *Capsicum* among the most distributed vegetables, only topped by crops in the genus *Cucurbita* L.).

Among the institutions that returned the stakeholder surveys, 61% distribute their *Capsicum* accessions in addition to conserving them. Among these institutions, 58% distribute accessions nationally and internationally to all or most countries, while nearly 40% distribute *Capsicum* germplasm only to users within their own country, and 3% distribute to users only in certain countries (**Figure 3.17**).

Of those respondents who distribute *Capsicum* accessions, 64% report doing so under institutional material transfer agreements or other bi-lateral agreements, while 42% distribute material following the ITPGRFA (i.e., using the SMTA) (**Figure 3.18**). Further, 24% of institutions distribute following the Nagoya Protocol for the Convention on Biological Diversity and 6% distribute under another agreement. Notably, 18% of institutions report distributing germplasm without any terms or conditions.

In general, accessing *Capsicum* germplasm is largely free of cost for users among the institutions responding to the surveys. Approximately 27% of institutions charge users the costs of shipping, 17% charge users for the costs of phytosanitary testing or quarantine, and 15% charge a fee for accessing the accessions themselves. The ITPGRFA stipulates that

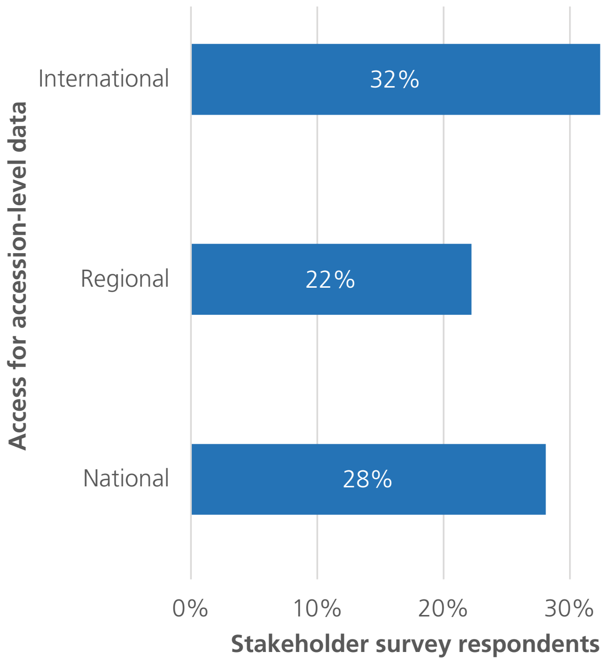

Figure 3.16. Percent of stakeholder survey respondents and geographic access for accession-level data for their *Capsicum* collections. Data are for those collections making their accession-level data accessible (n=34).

any fees charged shall not exceed the minimum costs involved. Amounts charged for accessions and the minimum costs involved in making *Capsicum* accessions available to users were not included as questions in the stakeholder surveys.

Based on data from the previous three years, in total, for the institutions responding to our survey, 5,032 accessions of the domesticated or cultivated species were distributed to users within their own nation (**Figure 3.19**). More than 800 accessions of the wild *Capsicum* species were distributed nationally. The number of institutions distributing *Capsicum* accessions internationally was around 60% of those distributed nationally. A total of 3,847 accessions of domesticated *Capsicum* species and 473 accessions of wild *Capsicum* species were distributed internationally. For both national and international distributions, and both cultivated and wild accession types, distributions across institutions displayed a very uneven spread, with the majority distributing very little, and a few institutions distributing the majority. The USDA-ARS Plant Genetic Resources Conservation Unit was the largest distributor of *Capsicum* among the respondents both nationally and internationally, and for both wild and domesticated species.

The largest group of users of the distributed *Capsicum* accessions, as reported by stakeholders in the surveys, were academic researchers and students at universities, making up more than 40% of recipients, on average (**Figure 3.20**). Public sector breeding programs, on average, made up the second largest named category of recipients (26%), followed by research institutions (22%), and governmental departments as well as farmers or farmer organizations, each accounting for 19% of distributions. Private sector breeding programs accounted for 13% of *Capsicum* recipients, which was slightly higher than non-governmental organizations (11%) and other genebanks (9%), on average. Interestingly, the overall second largest group of *Capsicum* recipients were identified as "other". It is unclear what category of users makes up such a large proportion of recipients of *Capsicum*, and whether this number relates more to lack of information than to a previously under-recognized user category.

Approximately one-third of institutions have observed a notable increase in the number of *Capsicum* accessions distributed over the past 5 to 10 years (**Figure 3.21**). Similarly, 33% of respondents reported that they anticipate an increase in *Capsicum* distributions over the next 5 to 10 years. Nearly half (49%) of institutions responding to the survey reported observing a relatively stable number of distributions of *Capsicum* of the past decade, while 18% observed a decrease. Approximately 63% of respondents anticipated that during the next 5 to 10 years the number of *Capsicum* accessions distributed to users would remain stable. Very few (3%) institutions expect to observe a decrease in the number of distributions of *Capsicum* over the next decade. Global SMTA distributions of *Capsicum* between 2012 and 2019 are relatively stable across years, although with somewhat fewer distributions in the most recent three years.

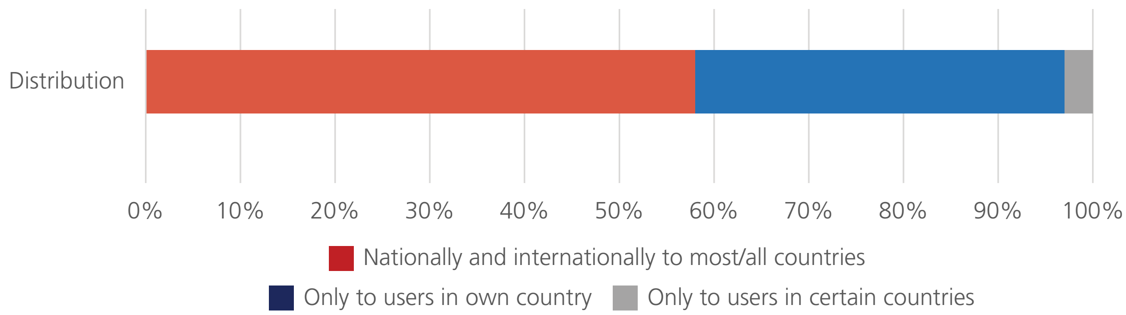

Figure 3.17. Distribution arrangements for *Capsicum* collections, reporting the percent of institutions and their distribution arrangement status. Data includes only those collections making their accessions accessible (n=33) that answered the stakeholder survey.

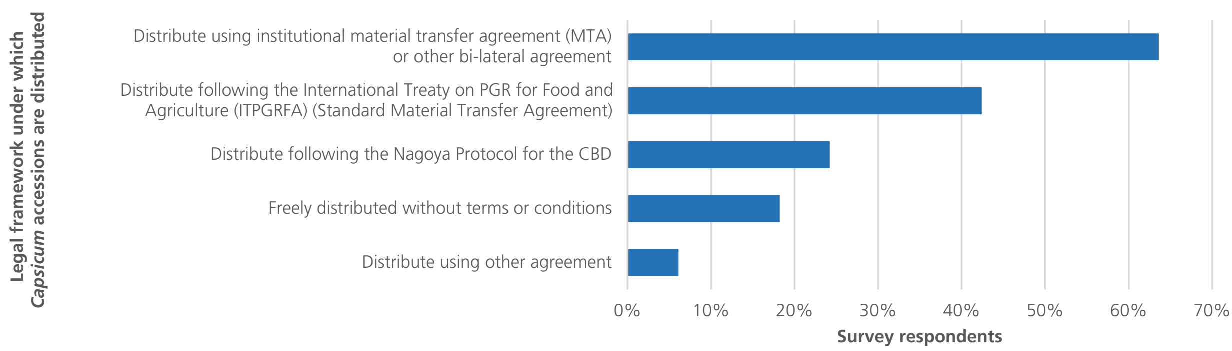

Figure 3.18. Legal framework under which *Capsicum* accessions are distributed, according to survey respondents (n=33).

In terms of biotic constraints to distributing *Capsicum* samples, approximately 43% of stakeholder survey respondents reported viruses as major limiting challenges, including Tomato brown rugose fruit virus, and 7% reported viroids (**Figure 3.22**). Fungal diseases were reported by 14% of respondents to be seed distribution constraints. Notably, 36% of respondents reported that there were no pests or diseases limiting distribution; however, this value is similar to the percentage of institutions that distribute germplasm only within their own country, which would likely have minimal or no phytosanitary requirements.

3.9 Risks and vulnerabilities regarding the *ex situ* conservation and use of *Capsicum* genetic resources

Approximately 27% of stakeholder survey respondents report having had a formal risk assessment performed and a management plan developed for their institutions. In the surveys, respondents provided a self-as-

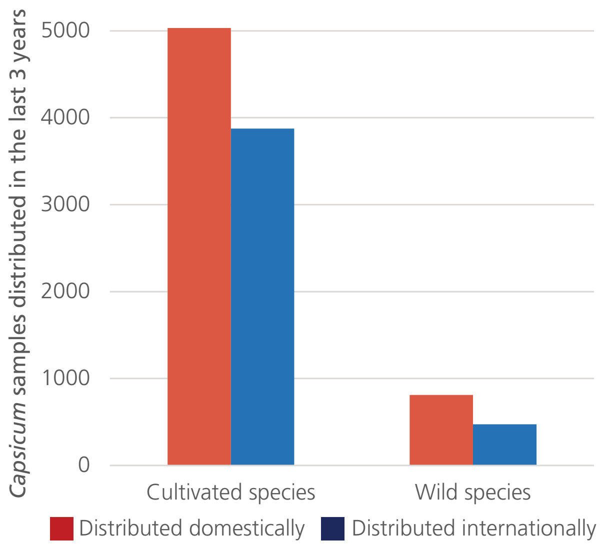

Figure 3.19 Total number of Capsicum samples distributed nationally and internationally during the past three years, as reported by survey respondents, for cultivated and wild accessions.

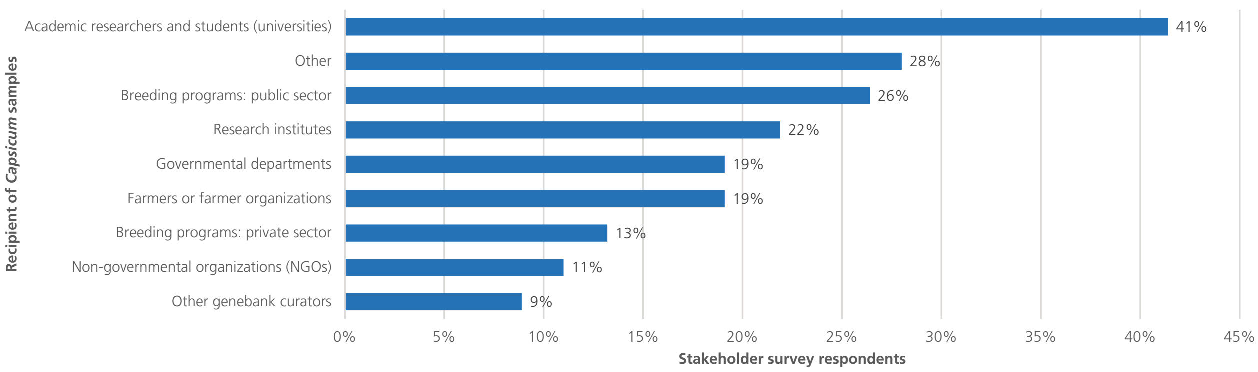

Figure 3.20. Recipient types of *Capsicum* samples distributed by stakeholder survey respondents, on average across respondents.

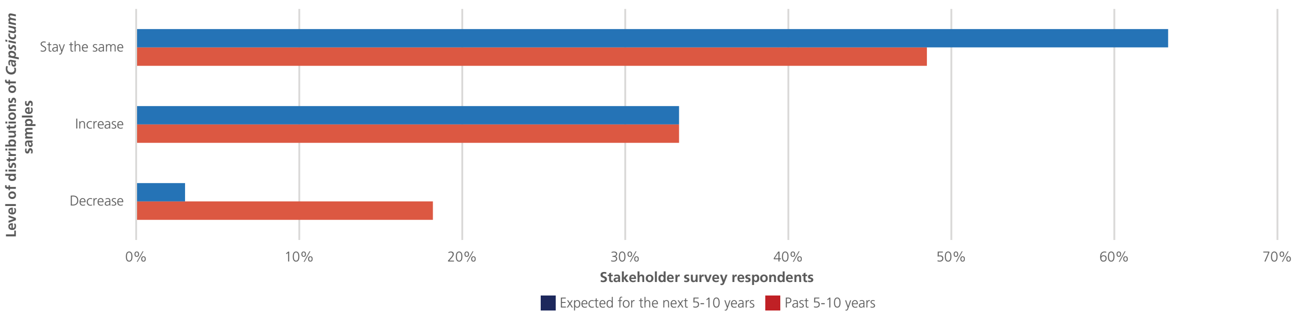

Figure 3.21. Level of distributions of *Capsicum* samples in the past 5 to 10 years, as well as expected level for the next 5 to 10 years.

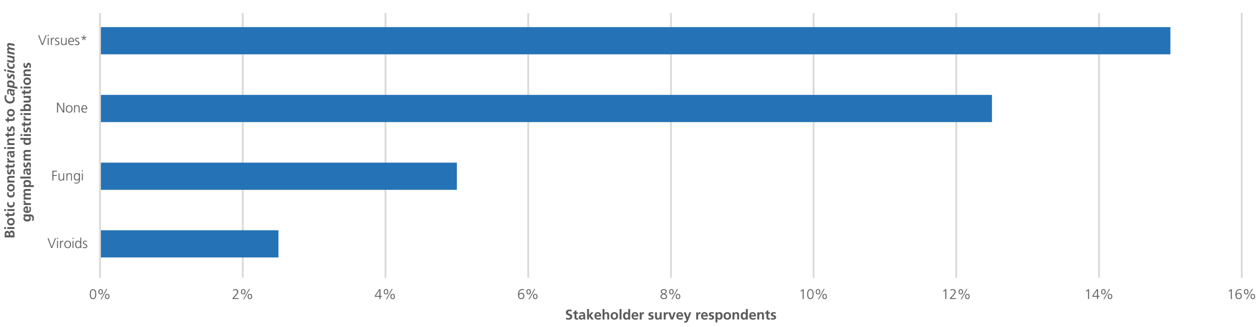

Figure 3.22. Number of stakeholder survey respondents listing biotic constraints to *Capsicum* germplasm distributions (n=40).

sessment for several risk factors associated with their *Capsicum* collection, based on the current situation and how the future is expected to be. The risk factor assessment used a three-point scale, where 1 indicated an inadequate situation, 2 indicated an adequate situation, and 3 indicated an excellent situation. On average, the funding for routine operations and maintenance of the *Capsicum* collection was reported to be largely inadequate currently (1.4 on average) and this was not expected to significantly improve in the future (1.7) (**Figure 3.23**). Similarly, staff retention was generally reported to be inadequate, currently (1.5), but in the future staff retention is anticipated to become nearly adequate (1.7). On average, there were three major areas in which respondents were quite positive for the future. The first area was feedback from users, which was rated as insufficient (1.5) currently, but anticipated to improve to better than adequate (2.1) in the future. Similarly, use by breeders and interest by donors was perceived to be currently nearly adequate (1.7 and 1.5, respectively), with this to improve to be better than adequate (2.1 and 2.1, respectively) in the future. Both the current access to germplasm information, such as passport data, and genetic variability in the collection needed by users were rated as nearly adequate, on average, (1.9 and 1.9, respectively) and these were anticipated to improve slightly in the future (2.4 and 2.3, respectively).

Lack of funding and human resources or capacity were the most common vulnerabilities identified that significantly threaten the global *Capsicum* collection, each cited by approximately 23% of respondents (**Figure 3.24**). Nearly 60% of institutions have seen a decrease in their budget over the past five years, while 29% have seen no change in their budget over the past years and 5% of institutions have experienced increases. Nearly 19% of institutions reported that the regeneration backlog and loss of seed viability or germination rate were significant threats to the collection. Inadequate facilities (12%) and lack of safety duplications (6%) were found to be the third and fourth most common threat identified by the institutions conserving *Capsicum*. Less than 4% of respondents reported that bureaucracy, emerging pests and diseases, inadequate representation or lack of diversity, cross-pollination or outcrossing, data management, or local conditions that are not suitable for *Capsicum* as significant vulnerabilities of the collection.

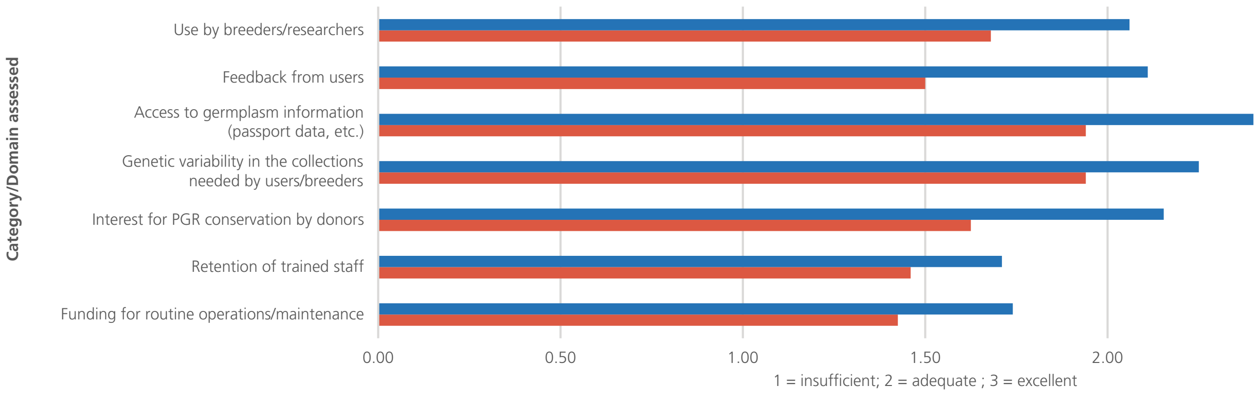

Figure 3.23. State of funding, staffing, donor interest, genetic diversity, access, user feedback, and use of collections, currently and in the future, on average across stakeholder survey respondents (n = 31).

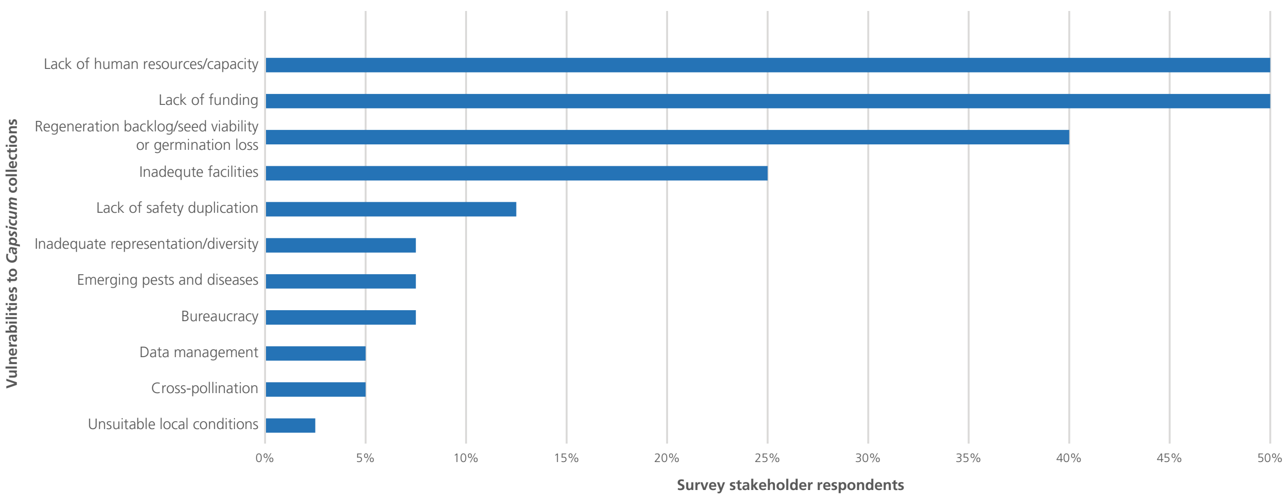

Figure 3.24. Number of stakeholder survey respondents listing different vulnerabilities to Capsicum collections (n=40).

3.10 Networks and other collaborative initiatives on *Capsicum* genetic resources

Relatively little information on genetic resource networks or other collaborative initiatives focused on *Capsicum* was garnered through the survey and consultations. Those past and current networks and other collaborative initiatives pertinent to *Capsicum* genetic resources, as recognized by the participants of the stakeholder meetings, are discussed below.

- The G2P-SOL phenotypic and genotypic network aims at increasing the knowledge about and use of the seeds from tens of thousands of genetic accessions of the four major Solanaceous food crops (potato, tomato, pepper and eggplant) that are stored in genebanks worldwide. This has project based funding from the European Union. Although focused on Europe, WorldVeg is also involved.
- The European Cooperative Programme for Plant Genetic Resources (ECPGR) is a collaborative programme among many European countries aimed at ensuring the long-term conservation and facilitating the increased utilization of plant genetic resources in Europe, including for *Capsicum*. Pepper was selected as a vegetable of significant interest to establish an European Evaluation (EVA) network. The EVA Pepper network builds on partners' experience from recent or ongoing Horizon2020 projects LIVESEEDS, BRESOV and G2PSOL as well as the ECPGR Solanaceae Working Group.
- The Simposio de Recursos Genéticos para América Latina y el Caribe (SIRGEALC) has provided a platform historically for curators of Latin American genebanks to exchange ideas and resources. According to the information we received as part of the survey's respondents and stakeholder meetings processes, this is currently not running.
- The Plant Genetic Resources Management Working Group of the African Union coordinates activities related to genetic resources across parts of Africa and includes international centers such as WorldVeg.
- The Taiwan Seed Industry Exchange Platform was established during 2017 to strengthen ties with Taiwan seed companies and public organizations working in vegetable improvement. The platform facilitates information exchange between WorldVeg's researchers and vegetable breeders in Taiwan and fosters special initiatives to serve the interests of Taiwanese companies. Platform membership is free and members receive regular updates and an annual newsletter, as well as invitations to events. There is a dedicated contact person at WorldVeg who can respond to any requests in Mandarin. One of the initiatives of the platform is to collaborate in regenerating WorldVeg genebank accessions, which is done using the facilities and staff of Taiwan seed companies. The platform has resulted in a significant reduction in the number of accessions in the backlog at WorldVeg.
- The first Indonesian genebank dedicated to horticultural crops, particularly vegetables, was recently established through a collaboration between the tropical vegetable seed company East-West Seed and Universitas Gadjah Mada (UGM), a public research institution in Yogyakarta. The genebank, which stores and preserves genetic resources of various vegetable crops, is located at the Agro Technology Innovation Center of UGM. *Capsicum* is one of the target species of the genebank and is currently the largest collection housed there. In addition to financial support from the private sector, the genebank receives technical assistance and backstopping from WorldVeg. The UGM genebank is expected to grow more through the voluntary seed contribution of both private and public institutions.
- The Association of Southeast Asian Nations (ASEAN) and WorldVeg have a longstanding network, AARNET, with the mission to coordinate and facilitate development and implementation of projects on vegetables in ASEAN member countries, as well as facilitate information exchange, technology transfer and training on vegetable production related fields.
- The Taiwan-Africa Vegetable Initiative (TAVI) is a project being coordinated by WorldVeg to conserve and use African vegetable biodiversity to address malnutrition by increasing the production and consumption of nutritious vegetables in Eswatini, Tanzania, Madagascar, and Benin.Over three years, project partners expect to collect 4,800 landraces and crop wild relatives from 25 species in the four countries, which are "hotspots" of vegetable biodiversity in Africa. TAVI is currently guiding upgrades to improve seed handling and storage at Eswatini's National Plant Genetic Resources Centre (NPGRC) and the genebank at the WorldVeg Eastern and Southern Africa facility in Tanzania to accommodate the new seed lots.
- Through funding from the Ministry of Foreign Affairs of Taiwan, WorldVeg has recently established a network to enhance international cooperation in vegetable research and development in Latin America and the Caribbean. In addition to promoting vegetable diversity and strengthening national programs, the project also supports the rescue of *Capsicum* and other species collected in the region and provide safety duplication for CATIE at the WorldVeg. To date, 210 cucurbit, 10 tomato, 270 amaranth, and 72 *Capsicum* accessions originating in Latin America have been conserved through this project.


Photo: World Vegetable Center

4 *IN SITU* CONSERVATION OF *CAPSICUM* GENETIC RESOURCES

Established protected areas and other open spaces in the Americas likely offer some degree of habitat conservation for some wild *Capsicum* populations (Khoury et al. 2019) and, to a much more limited degree, possibly some landraces, although both are only extremely rarely prioritized in management plans (Khoury et al. 2020). Confirmation of the persistence of such populations, and of population sizes likely to be viable under current and projected future pressures, require further validation and continued monitoring. Robust long-term conservation of these populations will likely require active management plans to ensure persistence in the contexts of climate change, invasive species, and competing management priorities (Khoury et al. 2020). There is only one land area currently known to us where active monitoring and management plans have been established to facilitate long-term conservation specifically for wild *Capsicum: the U.S. Forest Service Wild Chile Botanical Area in Rock Corral Canyon, Coronado National Forest, Arizona, USA*. Although not widely published (Barchenger and Bosland, 2019), the emerging evidence that seed of some wild species, such as *C. lanceolatum* and possibly others, cannot be stored short- or long-term, further highlights the importance of such protected areas in conservation of the genetic diversity of *Capsicum*.

Recent conservation assessments are lacking for much of the *Capsicum* genus. The IUCN Red List of Threatened Species currently lists eight taxa. *C. annuum* (Aguilar-Meléndez et al. 2019), *C. caatingae* (BGCI & IUCN SSC Global Tree Specialist Group 2019), *C. eximium* (Mendoza and Madrinan 2020), *C. frutescens* (Azurdia et al., 2017b), and *C. rhomboideum* (Azurdia et al. 2017c) are listed as of Least Concern (LC), although populations of *C. frutescens* are decreasing due to agriculture, livestock ranching, and wild harvesting. *C. eshbaughii* (Mendoza 2020), *C. lanceolatum* (Azurdia et al. 2017a), and *C. tovarii* (Gonzales Arce 2020) are listed as Endangered (EN).

The majority of the wild *Capsicum* are endemics or are otherwise restricted to specific environments. These include: *C. caatingae*, *C. campylopodium*, *C. cornutum*, *C. friburgense*, *C. hunzikerianum*, *C. longidentatum*, *C. mirabile*, *C. pereirae*, *C. recurvatum*, *C. schottianum*, *C. villosum* var. *muticum*, and *C. villosum* var. *villosum* in coastal Brazil; *C. caballeroi*, *C. cardenasii*, *C. ceratocalyx*, *C. eshbaughii, C. minutiflorum,* and *C. neei* in Bolivia; *C. galapagoense* in the Galapagos Islands; *C. benoistii*, *C. hookerianum*, *C. longifolium*, and *C. piuranum* in mainland Ecuador and/or northern Peru; and *C. tovarii* in central-southern Peru (Khoury et al. 2019).

A recent ecogeographic conservation assessment for wild *Capsicum* generated preliminary Red List designations for the taxa based on their range sizes and number of known populations (Khoury et al. 2019). This indicated that *C. benoistii*, *C. ceratocalyx*, *C. eshbaughii*, *C. friburgense*, *C. piuranum*, and *C. villosum* var. *muticum* could be candidates for designation as Critically Endangered (CR), and *C. cardenasii*, *C. galapagoense*, and *C. hunzikerianum* as Endangered (EN) (although a number of populations of the last two taxa occur in protected areas). Further, *C. caballeroi, C. campylopodium*, *C. cornutum, C. hookerianum, C. longidentatum, C. longifolium, C. minutiflorum, C. neei, C. pereirae,* and *C. tovarii* may be considered as Vulnerable (VU); *C. coccineum*, *C. lanceolatum, C. mirabile, C. recurvatum, C. schottianum,* and *C. villosum var. villosum* possibly as Near Threatened (NT); and the remaining taxa, including the two putative progenitors, as of Least Concern (LC).

Habanero hybrid. Photo: World Vegetable Center

5 ENHANCING THE CONSERVATION AND USE OF *CAPSICUM* GENETIC RESOURCES

This section summarizes the current state of knowledge on *Capsicum* genetic resources and discusses priority actions to enhance their conservation and use.

Capsicum diversity, genetic resource collections, and acquisition priorities

Fundamental information on the taxonomy, ecogeographic distribution, and patterns of diversity in *Capsicum* is likely quite well established at this point. The genus is well understood; several new wild species have been described in recent years and species boundaries and synonymy further clarified (Barboza and Bianchetti 2005; Barboza et al. 2011, 2019, 2020, 2022; Khoury et al. 2019). It is possible that one or more additional taxa may remain to be discovered. If so, these are likely to be species of limited ranges and exposed to threats including habitat destruction, invasive species, climate change, and others. They are also likely to be very poorly represented *ex situ*. Of particular interest, not only for taxonomic studies but also for genetic resources implications, would be the identification of the progenitors of cultivated *C. chinense*, *C. frutescens*, and *C. pubescens*, if they still persist. A second priority with genetic resources implications would be the completion of crossability and phylogenetic studies across all *Capsicum* taxa, which will be important for clearer establishment of clades, complexes, and genepool classifications within the genus. Within the cultivated taxa, some further elucidation of patterns of varietal and genetic diversity is needed, for example for *C. annuum* in South and Southeast Asia, *C. chinense* in West and Central Africa and in parts of Asia, and *C. frutescens* in Africa and Asia.

Substantial *Capsicum* genetic resources are conserved *ex situ* in international, national, and subnational genebanks, universities, botanic gardens, seed conservation organizations, and other institutions worldwide, with over 50,000 accessions in total. It is not currently clear, or straightforward to clarify, what proportion of these represent distinct and unique accessions, although the stakeholder surveys conducted during the development of this strategy indicate that many collections are considered to be highly distinct/unique, at least in terms of the accessions within (not across) these collections. Further collaboration in comparing accessions at the nomenclatural, phenotypic, and genetic levels will be needed to arrive at a clearer understanding of the distinctness of accessions and degree of duplication both within and among collections.

From the global databases as well as the stakeholder surveys, several collections stand out in terms of numbers of accessions, species-level diversity, and/or diversity in countries of origin of samples. These include WorldVeg, the USDA Plant Genetic Resources Conservation Unit (USA), the Centre for Genetic Resources (Netherlands), the Leibniz Institute of Plant Genetics and Crop Plant Research (IPK)/Information and Coordination Centre for Biological Diversity (IBV) (Germany), Embrapa (Brazil), New Mexico State University (USA), the Institute for Agrobotany (RCA)/Centre for Plant Diversity (Hungary), the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), the Departamento Nacional de Recursos Fitogenéticos (Ecuador), the Instituto Nacional de Innovación Agropecuaria y Forestal (Bolivia), the Research Centre for Vegetable and Ornamental Crops (Italy), the Taiwan Agricultural Research Institute (Taiwan), the National Agriculture and Food Research Organization Genebank (Japan), the Universitat Politècnica de València (Spain), the Corporación Colombiana de investigación Agropecuaria (AGROSAVIA) (Colombia), and the Centre de Ressources Biologiques Légumes, Institut national de recherche pour l'agriculture, l'alimentation et l'environnement (INRAE) (France). These are clearly diverse collections, and attention should be paid to their long-term security and the availability and accessibility of their *Capsicum* accessions for use.

This list should not be considered complete, however; from the stakeholder survey responses it is evident that *Capsicum* collections worldwide are not fully reported in global databases such as Genesys, FAO WIEWS, PlantSearch, and GBIF; likewise, the information contained within these databases may not be fully updated or accurate. Moreover, the stakeholder surveys returned during this strategy process were not comprehensive of all *Capsicum* collections worldwide, with particularly notable gaps for collections in Mexico and other parts of Mesoamerica as well as South America, and important secondary regions of diversity in Asia such as China, Korea, and India. One simple and seemingly resolvable roadblock encountered in the survey process that certainly led to less-than-optimal response rates was that contact information – at least through electronic means (i.e. email address) – for a substantial proportion of *Capsicum* collections listed in global databases and also on institutional websites are no longer functioning or active. It is therefore difficult to easily contact *Capsicum* colleagues in many *ex situ* facilities; paper mail may be the only option for some. A further impediment to more comprehensive responses to the survey may have been not offering the survey in languages other than English and Spanish, and failing to communicate by email and through relevant networks in all of the languages spoken by *Capsicum stakeholders*. Further updating and availability of contact information for *Capsicum* collections is important to the further development of this strategy.

Regarding taxonomic representation of *Capsicum* in *ex situ* conservation, the cultivated taxa are clearly much better represented than the wild species, as with most crop genepools, and likely comprise around 97–99% of all *Capsicum* accessions worldwide. Representation across cultivated taxa generally reflects the global importance and geographic spread of the taxa. However, even among the cultivated taxa there are regions and countries that are less well represented in *ex situ* collections (based on the data available to us). For C. *annuum* var. *annuum,* West and Central Africa are poorly represented in *ex situ* collections, likewise, in South Asia, Myanmar, Nepal and Bhutan are underrepresented, and in Southeast Asia, Cambodia and Laos. In South America, Venezuela, Paraguay, Uruguay, Suriname and Chile appear to be not well represented as well. For *C. chinense,* the available data suggests that Central Africa and West Africa, Southeast Asia, East Asia and Oceania are not well represented in *ex situ* collections. For *C. frutescens,* in Southeast Asia, Indonesia and Myanmar seem to be particularly under-represented *ex situ*; similarly, for Taiwan in East Asia. For *C. pubescens*, the data suggest that further collecting is needed in Mexico, Central America, Bolivia, and Colombia.

Conversely, the wild species are generally extremely poorly represented *ex situ*, with only a few exceptions, i.e. *C. annuum* var. *glabriusculum*, *C. chacoense*, and potentially *C. baccatum* var. *baccatum* in terms of absolute number of accessions; *C. cardenasii* may also be considered fairly well represented in the context of coverage across its geographic range (Khoury et al. 2019). Further collecting of the remaining wild species, as well as of geographic and ecological gaps in even these aforementioned wild relatives, is clearly needed to improve their representation in *ex situ* conservation and their availability and accessibility for research, including for plant breeding. Further collecting within taxonomic hotspots, namely Brazil, Andean countries, and parts of Mesoamerica are of particular importance and may provide an opportunity for efficient collecting of multiple taxa and ecotypes (Khoury et al. 2019).

Information reported in the global databases on the biological status of *Capsicum* genetic resources is highly incomplete, with nearly 50% of accessions unspecified, while stakeholder surveys indicate that an even higher proportion of accessions may not be clearly specified. This lack of information is likely to limit the exploration of the unspecified accessions for genetic resource purposes, thus further efforts to complete these data, as possible, would be useful. From the available information from the global databases and surveys, landraces appear to have the most accessions, followed by cultivars and breeding materials. It is not currently clear or straightforward to assess to what degree these total numbers represent extant diversity in farmers' fields and in breeding programs. It is very likely that breeding programs not reported in the global databases or stakeholder surveys currently work with a range of breeding materials and potentially cultivars, landraces, and other types of material, and which are not conserved for the long-term in *ex situ* facilities. Alongside further assessments of the comprehensiveness of conservation of landraces (and wild relatives) *in situ*, collaborations with breeding programs to ensure the long-term conservation of materials of interest is warranted.

Gaps in collections were identified by the vast majority of stakeholder survey respondents, including at species/taxa, genetic, ecogeographic, varietal, trait, and other levels. Most respondents also foresee expansions of their collections in the coming decade, mainly by collecting in under-represented regions and through germplasm exchange. Funding for gap-filling was mentioned by several respondents as a major limitation to these aspirations.

The *Capsicum* community engaged in this strategy identified a series of ways by which further acquisition may proceed, toward the larger goal of greater representation of *Capsicum* diversity within *ex situ* collections globally. Collaboration to this end is key, including by international and regional institutions partnering with national genebanks to jointly conduct field collecting. Recognizing current policy challenges to bilateral exchange of *Capsicum* genetic resources, international facilitation by organizations such as the Crop Trust may be extremely helpful in negotiating such partnerships and in organizing funding, which would hopefully come from relevant national as well as international and other sources.

Structure, management, and conditions of *Capsicum* collections

From the global databases and stakeholder surveys, it appears that long-term storage infrastructure exists for the great majority of *Capsicum* collections, while medium- and short-term conditions supplement the long-term infrastructure. This is good news. Further efforts should certainly be made to ensure presence in long-term infrastructure for all distinct accessions, either at their current sites or through duplication at institutions with the appropriate infrastructure. Likewise, further efforts to improve storage materials (e.g. aluminum packets) and processes (i.e. temperature and humidity standards) should be made for collections not currently following optimum practices. For many collections, pests and diseases provide challenges to storage and maintenance, and further efforts to limit their negative impacts are important. All these maintenance priorities have financial implications; in some cases, it may be more expedient to duplicate distinct accessions to international or other *Capsicum* collections rather than to implement all ideal changes at all institutions.

The body of literature on storage life of *Capsicum* seed is limited. There are apparently genotypic effects involved in seed viability in short-, medium-, and long-term storage conditions, with some species requiring conservation as live plants. There are additional factors that contribute to viability of the seed in storage, many of which are associated with the growing conditions of the mother plant. In addition, the various treatments that have been employed to reduce or eliminate pathogens from the seeds may also result in reduced viability. There is a clear and pressing need to study the multitude of factors contributing to loss of viability for all *Capsicum* species in storage and to develop a set of standards to ensure best practices. This should include research on alternatives to traditional cold storage of seed, such as through in vitro and cryopreservation. A collaborative effort across genebanks and users would be most useful to develop and disseminate new and improved protocols.

Regeneration and multiplication of *Capsicum* genetic resources

Almost 40% of *Capsicum* accessions worldwide presently require urgent regeneration according to stakeholder survey respondents, with some institutions reporting 100% of accessions requiring urgent regeneration. A reasonable interval of 12 years on average for regeneration exists across respondents, assuming adequate long-term storage conditions are implemented, although the extremes range from 2 to 50 years, neither of which are likely ideal for long-term maintenance of genetic diversity. The multiple biotic factors constraining regeneration efforts include viruses (especially ToBRFV), bacteria, fungi, and insect pests; in combination, these present major challenges to regeneration and maintenance.

Further efforts – and corollary resources – are clearly needed to reduce the number of accessions urgently needing regeneration. Again, collaborations may be useful, as exemplified by WorldVeg's regeneration activities conducted as a partnership between the genebank and the plant breeding program. Such a model may not work as easily in institutions without breeding programs, although some examples now exist of external breeding programs – including private companies – productively collaborating with genebanks to accomplish regeneration (as exemplified by collaborations arranged by the Centre for Genetic Resources, The Netherlands and WorldVeg with private companies). Collaboration with farmers may be another promising avenue to accomplish regeneration and multiplication (and incidentally also foster use); this approach has been used for *Capsicum* by the Instituto de Investigaciones Agropecuarias, Chile. As a more global approach, a large project such as the "Global System Project", funded by the Bill & Melinda Gates Foundation and managed by the Crop Trust over a decade ago, at that time with focus on staple cereals, pulses, and starchy crops, could make a major impact in reducing backlogs in regeneration (as well as characterization and safety duplication), if such a project could be created for *Capsicum* and other important horticultural/vegetable crops. Alternatively, duplication of *Capsicum* accessions at international or other repositories where regeneration may be more feasible, and subsequent reduction of collections in less well resourced institutions may need to be considered.

Characterization and evaluation of *Capsicum* genetic resources

As mentioned above, further data gaps remain to be filled to correctly record basic characters on accessions such as their taxonomy and biological status, as well as collecting/acquisition source and other passport data. A stakeholder participant also mentioned that locality data – especially coordinates – are often inaccurate for older accessions; this fundamental data gap may not be completely solvable without new collecting, but some efforts could be made to improve locality data in databases.

From the stakeholder surveys, it appears that a substantial proportion of *Capsicum* accessions, have been characterized for phenotypic characters. This is good news for their potential value for crop breeding, and further efforts should be made to complete characterization of collections. Stakeholder meeting participants did note, though, that there may be a disconnect between the basic characters recorded by genebanks and those of most importance to crop breeders, thus more interaction, including potentially an update of the characterization guidelines for *Capsicum* genetic resources, may be in order.

Much less data currently exists for evaluation for biotic and abiotic stresses, and for genotyping. Meeting participants noted that funding for evaluation and genotyping was less easily found than for phenotypic or basic characterization. Further, participants noted that evaluation in multiple environments was important for a better understanding of resistance to biotic and abiotic constraints. Unfortunately, screening for these stresses is expensive and challenging, as is "cleaning" the accessions if important diseases are found. New (seed-bourne) diseases inevitably remain to be discovered. Relatively few *Capsicum* collections currently can and in the future will be able to continue to afford continuous screening for these (increasing) biotic pressures.

As with acquisition and regeneration, collaborations to characterize and evaluate *Capsicum* collections may therefore be among the most promising ways forward, in particular between *ex situ* facilities on one side and both public and private breeding programs on the other; collaboration with the private sector is becoming more common in Europe. As a more global approach, a large project such as the previously mentioned "Global System Project" could make a major impact in characterizing *Capsicum* accessions while also reducing regeneration backlogs and addressing safety duplication deficiencies, if such a project could be created for *Capsicum*. Alternatively, duplication of *Capsicum* accessions at international or other repositories where resources for characterization and evaluation are more available may be considered, if data was sure to flow back to the genebanks.

Safety duplication of *Capsicum* genetic resources

As *Capsicum* accessions can be conserved as seed, existing facilities appear to be capable of providing safety duplication of chile pepper collections globally, including at the Svalbard Global Seed Vault (SGSV) and at WorldVeg and CATIE, as well as at national genebanks such as the USDA National Laboratory for Genetic Resources Preservation (USA), the Centro Nacional de Recursos Fitogenéticos (Spain), Warwick Genetic Resources Unit (UK), RDA's genebank (Republic of Korea), the National Plant Genetic Resources Centre (Taiwan), and Embrapa Hortaliças (Brazil). Some of these facilities currently mainly provide safety duplication for other institutions within the same country, although they may be able to provide wider services to surrounding countries or those further afield.

The global databases indicate that 18% [i.e. 8297 accessions] (FAO WIEWS) or 37% [i.e 11,864 accessions] (Genesys) of *Capsicum* accessions globally are currently safety duplicated, although major data gaps exist in this information, thus the true extent may be considerably higher. The SGSV currently holds over 6,000 *Capsicum* accessions; this may represent around 13% of total worldwide assuming a global collection of around 50,000 accessions. The stakeholder surveys indicate that around 41% of accessions on average are already safety duplicated, although considerable variation exists across institutions, with more than one quarter of institutions having no safety duplication of their *Capsicum* collection and an additional 5% unaware of the status of safety duplication.

Further work on safety duplication of *Capsicum* accessions is clearly essential to secure these genetic resources for the long-term. Additional resources are likely needed to enable adequate fresh seed for safety duplication. Further policy improvements may also be important, as nearly a quarter of survey respondents face (administrative/policy) constraints to duplication outside of their country. An international project such as the "Global System Project" could make a major impact in addressing safety duplication deficiencies, if such a project could be created for *Capsicum*.

Documentation and information sharing on *Capsicum* genetic resources

As mentioned above, further efforts are needed to provide up-to-date information on *Capsicum* collections through global databases such as Genesys and FAO WIEWS. Such efforts will go a long way toward a clearer understanding of the state of *ex situ* conservation of *Capsicum* genetic resources worldwide, as well as facilitate communication on access to these resources and other collaborative activities. Fundamental passport data on collections (i.e. taxonomy, biological status, etc.) can be made more complete, while enhancing the availability of passport and characterization information will also make the collections of greater potential use value.

The stakeholder survey responses indicate that while major *Capsicum* collections may have adequate computerized databases to manage their collections, many other institutions have inadequate software and computer infrastructure. On the other hand, it appears that considerable passport, taxonomy, and characterization data on *Capsicum* collections have already been generated, while there is less evaluation, genetic, and other pertinent data. This is typical of crop collections worldwide. The availability of these data to outside users, such as breeding programs, also appears sufficient for major collections, but at least a quarter of respondents noted that data on collections was only available within institutes or was private, which may be a limitation to wider use of these genetic resources.

As with acquisition, regeneration, characterization, and safety duplication, collaboration on documentation and information management may help to resolve current limitations, although national and international policies on genetic resources and associated information may be constraints in some cases. A variety of free tools and programs, for example the GRIN-Global software for collections management, are available, including with support and ongoing curation, and these are increasingly linkable with global databases such as Genesys. Further capacity building on the value and operation of these tools may aid in further adoption.

Use of *Capsicum* genetic resources

The substantial collections of *Capsicum* in international and regional centers such as WorldVeg and CATIE, as well as in public genebanks particularly in North America and in Europe, enable a global system of facilitated and international access to *Capsicum* genetic resources, including online information/ordering systems and free or low cost distributions. Due to the mandates of these institutions, these *Capsicum* genetic resources are largely accessible under the SMTA of the ITPGRFA, foregoing the need for bilateral negotiations under the Nagoya Protocol in most cases, even though *Capsicum* is not listed in Annex 1 of the Treaty. These are likely among the reasons why *Capsicum* genetic resources are distributed at a relatively high rate, compared to many other fruit and vegetable crops.

For other *ex situ* repositories, facilitated and international access to *Capsicum* genetic resources is currently much more limited, with concomitant low annual distributions. This lack of access was noted by stakeholders as a major challenge within the *Capsicum* genetic resources community. This said, substantial within-country distributions are occurring in some countries and regions, supporting national and sub-national research efforts. Distributions are anticipated to increase or stay the same in the coming decade, across most respondents to the stakeholder survey.

It appears that several user types are working with *Capsicum* genetic resources, including (in descending order of number of distributions) academics, public breeding programs, research institutions, government departments, farmer organizations, private industry, non-governmental organizations, and other genebanks. The *Capsicum* stakeholder community has noted that further use of wild species is a priority and that this requires efforts to excite researchers and crop breeders about their potential value. Also, further efforts to organize collections for more efficient exploration, such as through core collections and trait-based subsetting, are important to increase their use.

Improving access to *Capsicum* genetic resources is not simple or straightforward, as it is often linked to national and institutional policy which is largely outside the responsibilities and power of *Capsicum* genetic resources practitioners. All efforts to motivate more open sharing of these resources are important, including by advocating for the inclusion of *Capsicum* within Annex 1 of the ITPGRFA, based on its clear international importance. Steps to reduce constraints caused by pests and diseases, in particular viruses, are also important to the potential to increase the availability of *Capsicum* genetic resources (for more on this topic see Dombrovsky and Smith 2017; Kenyon et al. 2014).

Other vulnerabilities and the need for further collaboration

In addition to the challenges to the conservation and use of *Capsicum* genetic resources already mentioned in previous sections, stakeholders identified lack of funding, lack of staff capacity, and inadequate facilities as major factors limiting the ability of many collections to perform optimally. None of these are simple to resolve in a global context of limited and often declining funding for biodiversity conservation and agricultural research.

Collaborations offer some potential to mitigate these enormous and fundamental challenges, particularly through capacity building. Further efforts should be made to share information, tools, and methods for the conservation of *Capsicum* resources, while reductions in unnecessary duplication of efforts could also be explored. For these steps to be taken, members of the global *Capsicum* genetic resources community need more opportunities to get to know one another and to build an atmosphere of trust and collaboration. Global-level projects focused on creating and strengthening networks within the *Capsicum* community, as well as building capacities and addressing the management and acquisition, regeneration, characterization and evaluation, safety duplication, documentation, and access constraints discussed above, will likely be very useful, if not essential, to further progress. Smaller steps could be taken through online communications, newsletters, directories of organizations, etc.

In situ conservation of *Capsicum* genetic resources

Dedicated *in situ* conservation efforts for cultivated and wild *Capsicum* are currently extremely limited worldwide. Meanwhile, it is clear that many wild species are narrow endemics and likely headed toward extinction given ongoing loss of their habitats and the increasing impacts from climate change. The lowest hanging fruit for improving the conservation of the wild species is through the confirmation of the persistence of such populations, and of population sizes likely to be viable under current and projected future pressures, within existing protected and other open space areas, and subsequently through the development of active management plans for populations within these areas. This requires increased collaboration between agricultural research, genetic resources,natural resources, and land management communities. Large scale efforts toward the expansion of natural areas conservation, including such global initiatives as 30x30 and Half-Earth, would, if implemented, likely enhance *in situ* conservation of wild *Capsicum*. Recognizing the roles and the rights of Indigenous and traditional peoples within such initiatives, including by permitting access to wild *Capsicum* populations for harvest, will be essential (Khoury et al. 2021).

Threats to landraces are less well understood but should be assumed to be real and increasing in most regions. Improving *in situ* (on farm) conservation of these resources is challenging as farmers necessarily balance several priorities critical to their livelihoods, the conservation of genetic diversity being only one (if at all). This said, the evidence base for successful collaborations in on-farm conservation is growing; options appropriate to location and culture should be identified based on participatory processes (Khoury et al. 2021).

REFERENCES

Aguilar-Meléndez A, Azurdia C, Cerén-López J, Menjívar J, Contreras A (2019) *Capsicum annuum* (amended version of 2017 assessment). The IUCN Red List of Threatened Species 2019: e.T100895534A143826567. (Accessed 23 February 2022)

Aguilar-Meléndez A, Morrell PL, Roose ML, Kim SC (2009) Genetic diversity and structure in semiwild and domesticated chiles (*Capsicum annuum*; Solanaceae) from Mexico. *Amer. J. Bot.* 96(6): 1190–1202.

Albrecht E, Zhang D, Saftner RA, Stommel JR (2011) Genetic diversity and population structure of *Capsicum baccatum* genetic resources. *Genet. Resour. Crop Evol.* 59: 517–538.

Albrecht E, Zhang D, Mays AD, Saftner RA, Stommel JR (2012) Genetic diversity in *Capsicum baccatum* is significantly influenced by its ecogeographical distribution. *BMC Genetics* 13: 68.

Aloni B, Peet MM, Pharr M, Karni L (2001) The effect of high temperature and high atmospheric CO_2 on carbohydrate changes in bell pepper (*Capsicum annuum*) pollen in relation to its germination. *Physiologia Plantarum* 112: 505–512.

Andrews J (1984) *Peppers. The Domesticated Capsicums*. University of Texas Press.

Azurdia C, Aguilar-Meléndez A, Menjívar J, Cerén-López J, Contreras A (2017a). Capsicum lanceolatum (errata version published in 2018). The IUCN Red List of Threatened Species 2017: e.T107657869A135208239. http://dx.doi.org/10.2305/IUCN.UK.2017–3.RLTS.T107657869A107657872.en. (Accessed 23 February 2022)

Azurdia C, Aguilar-Meléndez A, Cerén-López J, Contreras A, Menjívar J (2017b) *Capsicum frutescens*. The IUCN Red List of Threatened Species 2017: e.T110057309A110057536. (Accessed 23 February 2022)

Azurdia C, Aguilar-Meléndez A, Cerén-López J, Contreras A, Menjívar J (2017c) *Capsicum rhomboideum*. The IUCN Red List of Threatened Species 2017: e.T107659536A107659540. (Accessed 23 February 2022)

Baba VY, Rocha KR, Gomes GP, de Fatima Ruas C, Ruas RM, Rodrigues R, Goncalves LSA (2016) Genetic diversity of *Capsicum chinense* accessions based on fruit morphological characterization and AFLP markers. *Genet. Resources Crop Evol.* 63: 1371–1381.

BACI: International Trade Database at the Product-Level (1995–2019) (2021) Accessed 16 February 2022.

Barboza GE, Agra MF, Romero MV, Scaldaferro MA, Moscone EA (2011). New endemic species of *Capsicum* (Solanaceae) from the Brazilian Caatinga: Comparison with the re-circumscribed *C. parvifolium*. *Systematic Botany* 36: 768–81.

Barboza GE, Bianchetti L (2005) Three new species of *Capsicum* (Solanaceae) and a key to the wild species from Brazil. *Systematic Botany* 30: 863–871.

Barboza GE, Carrizo García C, Leiva González S, Scaldaferro M, Reyes X (2019) Four new species of *Capsicum* (Solanaceae) from the tropical Andes and an update on the phylogeny of the genus. *PLoS One* 14: e0209792.

Barboza GE, de Bem Bianchetti L, Stehmann JR (2020) *Capsicum carassense* (Solanaceae), a new species from the Brazilian Atlantic Forest. *PhytoKeys* 140: 125–138.

Barboza GE, Carrizo García C, de Bem Bianchetti L, Romero MV, Scaldaferro M (2022) Monograph of wild and cultivated chili peppers (*Capsicum* L., Solanaceae). PhytoKeys 200: 1–423.

Baral JB, Bosland PW (2002) An updated synthesis of the *Capsicum* genus. *Capsicum Eggplant Newsletter* 21: 11–21.

Barchenger DW, Bosland PW (2019) Wild chile pepper (*Capsicum* spp.) of North America. In: Greene S L, Williams KA, Khoury CK, Kantar MB, Marek LF (Eds.), *North American Crop Wild Relatives, Volume 2: Important Species.* Springer International Publishing AG, pp. 225–242.

Bioversity International (2015) FAO/Bioversity Multi-Crop Passport Descriptors V.2.1 [MCPD V.2.1] Accessed 13 February 2022.

BGCI (2018) PlantSearch. Accessed 21 September 2018.

BGCI (2022) PlantSearch. Accessed 13 February 2022.

BGCI & IUCN SSC Global Tree Specialist Group (2019) *Capsicum caatingae*. The IUCN Red List of Threatened Species 2019: e.T149211901A149211903. (Accessed 19 September 2019)

Bosland PW, Baral J (2007) 'Bhut Jolokia'—The world's hottest known chile pepper is a putative naturally occurring interspecific hybrid. *HortScience* 42: 222–224.

Bosland PW, Votava EJ (2012) *Peppers: vegetable and spice capsicums. 2nd ed.* CAB International, Oxfordshire, U.K.

Carrizo Garcıa C, Barfus MHJ, Sehr EM, Barboza GE, Samuel R, Moscone EA, Ehrendorfer F (2016) Phylogenetic relationships, diversification and expansion of chili peppers (*Capsicum*, Solanaceae). *Annals of Botany* 118: 35–51.

Carrizo García C, Fernández L, Kapetanovic V, Reyes X (2020) Rare Bolivian wild chile *Capsicum eshbaughii* (Solanaceae) located again: open ending on its identity and conservation. *Plant Systematics Evol.* 306: 85.

Colonna V, D'Agostino N, Garrison E, Albrechtsen A, Meisner J, Facchiano A, Cardi T, Tripodi P (2019) Genomic diversity and novel genome-wide association with fruit morphology in *Capsicum*, from 746k polymorphic sites. *Sci Rep* 9: 10067.

Davenport WA (1970) Progress report on the domestication of *Capsicum* (chile peppers). *Proceedings of the Association of the American Geographers* 2: 46–47.

de la Vega G (1609) *Comentarios reales de los Incas*. English translation by HV Livermore, published in 1966. University of Texas Press, Austin, TX USA.

De Pascale S, Ruggiero C, Barbieri G, Maggio A (2003) Physiological responses of pepper to salinity and drought. *Journal of the American Society for Horticultural Science* 128: 48–54.

DeWitt D (2020) *Chile peppers: A global history*. University of New Mexico Press, Albuquerque.

DeWitt D, Bosland PW (1993) *The Pepper Garden*. Ten Speed Press, Berkeley, CA.

Durán FD (1588) *The history of the Indies of New Spain*. English translation by D Heyden, published in 1964. University of Oklahoma Press, Norman, OK USA.

Dombrovsky, A., Smith, E. (2017) Seed transmission of Tobamovirus: Aspect of Global Disease Distribution. in: Jimenez-Lopez, J.C. *Seed Biology,* 2017. Accessed 16 August 2022

Emboden WA Jr. (1961) A preliminary study of the crossing relationships of *Capsicum baccatum*. *Butler University Botanical Studies* 14: 1–5.

Eshbaugh WH (1970) A biosystematic and evolutionary study of *Capsicum baccatum* (Solanaceae). *Brittonia* 22: 31–43.

Eshbaugh WH (2012) The taxonomy of the genus *Capsicum*. In: Russ VM (ed.), *Pepper: Botany, production, and uses.* CABI, pp. 14–28.

FAO (2002) *The International treaty on plant genetic resources for food and agriculture*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

FAO (2022a) FAOSTAT. Accessed 1 February 2022

FAO (2022b). United Nations Food and Agriculture Organization World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture (WIEWS). Data from most recent year (2020) Accessed 9 February 2022.

Flynn DO, Giraldez A (1994) China and the Manila galleons. Japanese industrialization and the Asian economy. In: Latham J, Kawakatsu, H. (Eds.), *Japanese Industrialization and the Asian Economy*. Routledge, London and New York, pp. 71–90.

Gajanayake B, Trader BW, Reddy KR, Harkess RL (2011) Screening ornamental pepper cultivars for temperature tolerance using pollen and physiological parameters. *HortScience* 46: 878–884.

Global Biodiversity Information Facility (GBIF) (2022) GBIF occurrence downloads, doi 10.15468/dl.7fvner (all occurrences) and 10.15468/dl.yu5924 (living specimens only) (accessed 9 February 2022)

Global Crop Diversity Trust (2022) Genesys global portal of plant genetic resources for food and agriculture. Accessed 9 February 2022.

Gonzales Arce P (2020) Capsicum tovarii. The IUCN Red List of Threatened Species 2020: e.T100895995A100896004. https://dx.doi.org/10.2305/IUCN.UK.2020–3.RLTS.T100895995A100896004.en. (Accessed 23 February 2022)

González-Jara P, Moreno-Letelier A, Fraile A, Piñero D, García-Arenal F (2011) Impact of human management on the genetic variation of wild pepper, *Capsicum annuum* var. *glabriusculum*. PLoS ONE 6(12): e28715.

Guzman I, Bosland PW, O'Connell MA (2011) Heat, color, and flavor compounds in *Capsicum* fruit. In: Gang DR (Ed.), *The biological activity of phytochemicals*. Springer, New York N.Y., pp. 109–126.

Halász Z (1963) *Hungarian paprika through the ages*. Corvina Press, Budapest, Hungary.

Halikowski Smith S (2015) In the shadow of a pepper-centric historiography: understanding the global diffusion of *Capsicums* in the sixteenth and seventeenth centuries. *Journal of Ethnopharmacology* 167: 64–77.

Han XB, Li RQ, Wang JB, Miao C (1996) Effect of heat stress on pollen development and pollen viability of pepper. *Acta Horticulturae Sinica* 23: 359–364.

Heiser CB Jr. (1969) *Nightshades, the paradoxical plants.* WH Freeman, San Francisco.

Heiser CB (1976) Peppers *Capsicum* (Solanaceae). In: Simmonds NW (Ed.), *Evolution of Crop Plants*. Longman, London, UK, pp. 265–268.

Heiser CB Jr., Smith PG (1948) Observations on another species of cultivated peppers, *Capsicum pubescens* R & P. *Proceedings of the American Society for Horticultural Science* 52: 331–335.

Hernández-Verdugo S, Luna-Reyes R, Oyama K (2001). Genetic structure and differentiation of wild and domesticated populations of *Capsicum annuum* (Solanaceae) from Mexico. P*lant Systematics and Evolution* 226(3–4): 129–42.

Hill TA, Ashrafi H, Reyes-Chin-Wo S, Yao JQ, Stoffel K, Truco MJ, Kozik A, Michelmore RW, Van Deynze A (2013) Characterization of *Capsicum annuum* genetic diversity and population structure based on parallel polymorphism discovery with a 30K unigene pepper genechip. *PLoS One* 8(2): e56200.

Hirsch CN, Hirsch CD, Fletcher K, Coombs J, Zarka D, Van Deynze A, et al. (2013) Retrospective view of North American potato (*Solanum tuberosum* L.) breeding in the 20th and 21st centuries. *G3* 3: 1003–1013.

Ibiza VP, Blanca J, Canizares J, Nuez F (2012) Taxonomy and genetic diversity of domesticated *Capsicum* species in the Andean region. *Genet. Resour. Crop Evol.* 59: 1077–1088.

IBPGR (1983) *Genetic resource of Capsicum - A global plan of action.* IBPGR Secretariat, Rome, Italy.

Islam, AHMS, Schreinemachers P, Kumar S (2020) Farmers' knowledge, perceptions, and management of chili pepper anthracnose disease in Bangladesh. *Crop Protection* 133: 105139.

Jarrett RL, Barboza GE, da Costa Batista FR, Berke T, Chou Y-Y, Hulse-Kemp A, et al. (2019) *Capsicum* - an abbreviated compendium. *Journal of the American Society for Horticultural Science* 144: 3–22.

Jarvis A, Williams K, Williams D, Guarino L, Caballero PJ, Mottram G (2005) Use of GIS for optimizing a collecting mission for a rare wild pepper (*Capsicum flexuosum* Sendtn.) in Paraguay. *Genet Resour Crop Evol*. 52(6): 671–82.

Jha TB, Bhowmick BK (2021) Unravelling the genetic diversity and phylogenetic relationships of Indian *Capsicum* through fluorescent banding. *Genet. Resour. Crop Evol.* 68: 205–225.

Kahane R, Hodgkin T, Jaenicke H, Hoogendoorn C, Hermann M, Keatinge JDH, et al. (2013) Agrobiodiversity for food security, health, and income. *Agronomy for Sustainable Development* 4: 671–693.

Kantar MB, Anderson JE, Lucht SA, Mercer K, Bernau V, Case KA, et al. (2016) Vitamin variation in *Capsicum* spp. provides opportunities to improve nutritional value of human diets. *PLoS ONE* 11: e0161464.

Kehie M, Kumaria S, Devi KS, Tandon P (2016) Genetic diversity and molecular evolution of Naga King Chili inferred from internal transcribed spacer sequence of nuclear ribosomal DNA. *Meta Gene* 7: 56–63.

Kenyon L, Kumar S, Tsai WS, Hughes Jd'A (2014) Virus diseases of peppers (*Capsicum* spp.) and their control. In: Loebenstein G, Katis N (Eds.), *Advances in Virus Research 90*, Academic Press, Burlington, Cambridge, MA, USA, pp. 297–354.

Khoury CK, Brush S, Costich DE, Curry HA, de Haan S, Engels J, Guarino L, Hoban S, Mercer KL, Miller A, Nabhan GP, Perales HR, Richards C, Riggins C, and Thormann I (2021) Crop genetic erosion: understanding and responding to loss of crop diversity. *New Phytologist* 233(1): 84–118.

Khoury CK, Carver D, Barchenger DW, Barboza G, van Zonneweld M, Jarret R, Bohs L, Kantar MB, Uchanski M, Mercer K, Nabhan GP, Bosland PW, and Greene SL (2019) Modeled distributions and conservation status of the wild relatives of chile peppers (*Capsicum* L). *Diversity and Distributions* 26(2): 209–225.

Khoury CK, Carver D, Greene SL, Williams KA, Achicanoy HA, Schori M, León B, Wiersema JH, and Frances A (2020) Crop wild relatives of the United States require urgent conservation action. *Proc Natl Acad Sci USA* 117(52): 33351–33357.

Khoury CK, Sotelo S, Hawtin G, Halewood M, Lopez Noriega I, Lusty C, Gallo P, and Rengifo VE (2022) *Thematic Background Study on Germplasm Exchange for The Third Report on the State of the World's Plant Genetic Resources for Food and Agriculture*. Food and Agricultural Organization of the United Nations, Rome: FAO (in press).

Kim S, Park M, Yeom S-I, Kim Y-M, Lee JM, Lee H-A, et al (2014) Genome sequence of the hot pepper provides insights into the evolution of pungency in *Capsicum* species. *Nature Genetics* 46(3): 270–8.

Kraft KH, Jesús Luna-Ruíz J, Gepts P (2012) A new collection of wild populations of *Capsicum* in Mexico and the southern United States. *Genetic Resources and Crop Evolution* 60(1): 225–32.

Lee HY, Ro NY, Jeong HJ, Kwon JK, Jo J, Ha Y, Jung A, Han JW, Venkatesh J, Kang BC (2016) Genetic diversity and population structure analysis to construct a core collection from a large *Capsicum* germplasm. *BMC Genetics* 17(1): 142.

Lin T, Zhu G, Zhang J, Xu X, Yu Q, Zheng Z, et al. (2014) Genomic analyses provide insights into the history of tomato breeding. *Nature* 46: 1220–1226.

Lopez-Castilla L del C, Garruna Hernandez R, Castillo Aguilar C de la C, Martinez-Hernandez A, Ortiz-Garcia MM, Andueza-Noh RH (2019) Structure and genetic diversity of nine important landraces of *Capsicum* species cultivated in the Yucatan Peninsula, Mexico. Agronomy 9(7): 376.

Lozada DN, Bosland PW, Barchenger DW, Haghshenas-Jaryani M, Sanogo S, Walker S (2022) Chile pepper (*Capsicum*) breeding and improvement in the "multi-omics" era. *Frontiers in Plant Science* (in press).

Luna-Ruiz JDJ, Nabhan GP, Aguilar-Meléndez A (2018) Shifts in plant chemical defenses of chile pepper (*Capsicum annuum* L.) due to domestication in Mesoamerica. *Frontiers in Ecology and Evolution* 6: 48.

Maas EV, Hoffman GJ (1977) Crop salt tolerance, current assessment. *Journal of Irrigation and Drainage Division* 103: 115–134.

McBryde FW (1933) Sololá: A Guatemalan town and Cakchiquel market-center. Middle America Research Series Pub. 5, Pamphlet 3. Tulane University, New Orleans LA, USA.

McBryde FW (1944) Cultural and historical geography of Southwest Guatemala. Pub. 4. Institute of Social Anthropology, Smithsonian Institution, Washington DC, USA.

Mendoza F, JM (2020) *Capsicum eshbaughii*. The IUCN Red List of Threatened Species 2020: e.T100895749A100895752. (accessed 23 February 2022)

Mendoza F, JM, Madrinan S (2020) *Capsicum eximium*. The IUCN Red List of Threatened Species 2020: e.T100895763A100895779. (accessed 23 February 2022)

Mongkolporn D, Taylor PWJ (2011) Capsicum. In: Kole C (Ed.), *Wild crop relatives: Genomic and breeding resources*. Springer, Berlin-Heidelberg.

Moreira AFP, Ruas PM, de Fatima Ruas C, Baba VY, Giordani W, Arruda IM, Rodrigues R, Goncalves LCA (2018) Genetic diversity, population structure and genetic parameters of fruit traits in C*apsicum chinense*. *Sci. Hort.* 236: 1–9.

Nabhan GP (1985) Native crop diversity in Aridoamerica: Conservation of regional gene pools. *Econ. Bot.* 39: 387–399.

Nankar AN, Todorova V, Tringovska I, Pasev G, Radeva-Ivanova V, Ivanova V, et al. (2020a) A step towards Balkan *Capsicum annuum* L. core collection: Phenotypic and biochemical characterization of 180 accessions for agronomic, fruit quality, and virus resistance traits. *PLoS ONE* 15(8): e0237741.

Nankar AN, Tringovska I, Grozeva S, Todorova V, Kostova D (2020b). Application of high-throughput phenotyping tool Tomato Analyzer to characterize Balkan *Capsicum* fruit diversity. *Sci. Hort.* 260: 108862.

Nargele RP, Mitchell J, Hausbeck MK (2016) Genetic diversity, population structure, and heritability of fruit traits in Capsicum annuum. *PLoS ONE* 11(7): e0156969.

Nicolaï M, Cantet M, Lefebvre V, Sage-Palloix A-M, Palloix A (2013) Genotyping a large collection of pepper (Capsicum spp.) with SSR loci brings new evidence for the wild origin of cultivated *C. annuum* and the structuring of genetic diversity by human selection of cultivar types. *Genet Resour Crop Evol* 60: 2375–2390.

Nordgen (2022) Svalbard Global Seed Vault Seed Portal. Accessed 9 February 2022.

Noss CF, Levey DJ (2014) Does gut passage affect post-dispersal seed fate in a wild chili, *Capsicum annuum*? *Southeastern Naturalist* 13: 475–483.

Pacheco-Olvera A, Hernández-Verdugo S, Rocha-Ramirez V, Gonzalez-Rodriguez A, Oyama K (2012) Genetic diversity and structure of pepper (*Capsicum annuum* L.) from Northwestern Mexico analyzed by microsatellite markers. *Crop Sci.* 52: 231–241.

Parry, Catherine, Yen-Wei Wang, Shih-wen Lin, and Derek W. Barchenger. Reproductive Compatibility in Capsicum Is Not Necessarily Reflected in Genetic or Phenotypic Similarity between Species Complexes. Edited by Dengcai Liu. *PLOS ONE* 16, no. 3 (March 24, 2021): e0243689.

Parry C, Wang Y-W, Lin S, Barchenger DW (2021) Reproductive compatibility in *Capsicum* is not necessarily reflected in genetic or phenotypic similarity between species complexes. *PLoS ONE* 16: e0243689.

Pereira-Dias L, Vilanova S, Fita A, Prohens J, Rodríguez-Burruezo A (2019) Genetic diversity, population structure, and relationships in a collection of pepper (*Capsicum* spp.) landraces from the Spanish centre of diversity revealed by genotyping-by-sequencing (GBS). *Hortic Res* 6(1): 54.

Perry L, Dickau R, Zarrillo S, Holst I, Pearsall DM, Piperno DR, et al. (2007) Starch fossils and the domestication and dispersal of chili peppers (*Capsicum* spp. L.) in the Americas. *Science* 315: 986–988.

Perry L, Flannery KV (2017) Precolumbian use of chili peppers in the Valley of Oaxaca, Mexico. *Proceedings of the National Academy of Sciences* 104: 11905–9.

Pickersgill B (1966) The variability and relationships of *Capsicum chinense* Jacq. PhD. Dissertation, Indiana University, Bloomington.

Pickersgill B (1969) The archaeological record of chili peppers (*Capsicum* spp.) and the sequence of plant domestication in Peru. *American Antiquity* 34: 51–64.

Pickersgill B (1971) Relationships between weedy and cultivated forms in some species of chili peppers (genus *Capsicum*). *Evolution* 25: 683–691.

Pickersgill B (1977) Taxonomy and the origin and evolution of cultivated plants in the New World. *Nature* 268: 591–595.

Pickersgill B (1980) Some aspects of interspecific hybridization. In: *Capsicum. Unpublished and preliminary report at the IVth Eucarpia Capsicum working group meetings in Wageningen, The Netherlands*.

Pickersgill B (1984) Migration of chili peppers, *Capsicum* spp., in the Americas. In: Stone D (Ed.), *Pre-Columbian Plant Migration*. Peabody Museum of Archaeology and Ethnology, Harvard University, Cambridge, pp. 106–122.

Portis E, Acquadro A, Comino C, Lanteri S (2004) Effect of farmers' seed selection on genetic variation of a landrace population of pepper (*Capsicum annuum* L.), grown in North-West Italy. *Genetic Resources and Crop Evolution* 51(6): 581–590.

Purseglove JW (1968) *Tropical crops. Dicotyledons 2*. Longmans, London, UK.

Rai VR, Kumar R, Kumar S, Rai A, Kumar S, Singh M, Singh SP, Rai AB, Paliwal R (2013) Genetic diversity in *Capsicum* germplasm based on microsatellite and random amplified microsatellite polymorphism markers. *Physiol. Mol. Biol. Plants* 19: 575–586.

Rao R, Li Y (2003) Management of flood effects on growth on vegetable and selected field crops. *HortTechnology* 13: 610–616.

Russell-Wood AJR (1998) *The Portuguese Empire, 1415–1808: A World on the Move.* The Johns Hopkins University Press, Baltimore.

Scaldaferro MA (2019) Molecular cytogenetic evidence of hybridization in the "purple corolla clade of the genus *Capsicum* (*C. eximium* × *C. cardenasii*). *Plant Biosystems*: 1–7.

Smith CE (1967) Plant remains. In: Byes DS (Ed.), *The prehistoric history of the Tehuacan Valley vol. 1. Environment and subsistence*. University of Texas Press, Austin, TX, pp. 220–225.

Solomon AM, Han K, Lee JH, Lee HY, Jang S, Kang BC (2019) Genetic diversity and population structure of Ethiopian *Capsicum* germplasms. *PLoS one* 14(5): e0216886.

Tong N, Bosland PW (1999) *Capsicum tovarii*, a new member of the *Capsicum baccatum* complex. *Euphytica* 109: 71–77.

Tripodi P, Rabanus-Wallace MT, Barchi L, Kale S, Esposito S, Acquadro A, et al. (2021) Global range expansion history of pepper (*Capsicum* spp.) revealed by over 10,000 genebank accessions. *Proc. Natl. Acad. Sci. USA* 118(34): e2104315118.

USDA ARS NPGS (2019) GRIN Global Taxonomy, Crop Relatives in GRIN-Global Taxonomy. (Accessed 2 February 2022)

USDA NASS (2017) Census of Agriculture. Accessed 2 February 2022.

van Zonneveld M, Ramirez M, Williams DE, Petz M, Meckelmann S, Avila T, et al. (2015) Screening genetic resources of *Capsicum* peppers in their primary center of diversity in Bolivia and Peru. *PLoS ONE* 10(9): e0134663.

van Zonneveld M, Larranaga N, Blonder B, Coradin L, Hormaza JI, Hunter D (2018) Human diets drive range expansion of megafauna-dispersed fruit species. *Proceedings of the National Academy of Sciences* 115: 3326–3331.

van Treuren R, Engels JMM, Hoekstra R, van Hintum TJL (2009) Optimization of the composition of crop collections for ex situ conservation. Plant Genetic Resources 7(02): 185.

Villalon-Mendoza H, Medina-Martinez T, Ramirez-Meraz M, Solis Urbina SE, Maiti R (2014) Factors influencing the price of chile piquin wild chili (*Capsicum annuum* L. var. *glabriusculum*) of north-east Mexico. *International Journal of Bio-resource and Stress Management* 5: 128–131.

Votava EJ, Baral JB, Bosland PW (2005) Genetic diversity of chile (*Capsicum annuum* var. *annuum* L.) landraces from Northern New Mexico, Colorado, and Mexico. *Econ. Bot.* 59(1): 8–17.

Votava EJ, Nabhan GP, Bosland PW (2002) Genetic diversity and similarity revealed via molecular analysis among and within an *in situ* population and *ex situ* accessions of chiltepín (*Capsicum annuum* var. *glabriusculum*). *Conservation Genetics* 3:123–129.

Wall MM, Bosland PW (1998) Analytical methods for color and pungency of chiles (*Capsicums*). In: Wetzel D, Charalambous G (Eds.), *Instrumental methods in food and beverage analysis*. Elsevier B.V., Amsterdam, Netherlands, pp. 347–373.

Walsh BM, Hoot SB (2001) Phylogenetic relationships of *Capsicum* (Solanaceae) using DNA sequences from two noncoding regions: The chloroplast atpB-rbcL spacer region and the nuclear waxy introns. *International Journal of Plant Sciences* 162: 1409–1418.

World Vegetable Center (2019) *International Vegetable Breeding: A Strategy to Create Development Impact at Scale.* World Vegetable Center, Shanhua, Taiwan. Publication No. 19: 838.

Yamamoto S, Nawata E (2005) *Capsicum frutescens* L. in Southeast and East Asia, and its dispersal routes into Japan. *Econ. Bot.* 59: 18.

Yamamoto S, Nawata E (2009) Use of *Capsicum frutescens* L. by the indigenous peoples of Taiwan and the Batanes islands. *Econ. Bot.* 63: 43–59.

Zhang XM, Zhang ZH, Gu XZ, Mao SL, Li XX, Chadœuf J, Palloix A, Wang LH, Zhang BX (2016) Genetic diversity of pepper (*Capsicum* spp.) germplasm resources in China reflects selection for cultivar types and spatial distribution. *J. Integrative Ag.* 15(9): 1991–2001.

Zhong Y, Cheng Y, Ruan M, Ye Q, Wang R, Yao Z, Zhou G, Liu J, Yu J, Wan H (2021) High-throughput SSR marker development and the analysis of genetic diversity in *Capsicum frutescens*. *Horticulturae* 7(7): 187.

ANNEXES

Annex I: *Capsicum* genetic resource collections survey (template)

Introduction

The Global Crop Diversity Trust (the 'Crop Trust') is an international non-profit organization, whose mission is to conserve and make available crop genetic diversity in perpetuity, thus ensuring global food security. As part of this mission, the Crop Trust has supported the development of 27 crop-specific conservation strategies to date, available on the Crop Trust website. These strategies comprehensively assess the status of crop conservation globally, with a particular emphasis on *ex situ* collections, and identify key priority actions needed to preserve crop diversity effectively and efficiently for the future. New strategies are currently under development for additional crops, including chili pepper (*Capsicum* spp.). The chili pepper global conservation strategy is being coordinated by the World Vegetable Center (Dr. Derek Barchenger) and the San Diego Botanic Garden (Dr. Colin Khoury), commissioned by the Crop Trust. This strategy will guide future investments into the conservation of chili pepper, which will benefit existing and future smallholder farmers through the supply of more resilient chili pepper varieties.

The strategy will critically depend on input and feedback from chili pepper specialists and collection curators. As such, the following questionnaire has been designed to connect with collection curators worldwide, in order to make a baseline assessment of the current *ex situ* conservation status of *Capsicum* genetic resources. Respondents of this survey will be invited to participate in a virtual workshop to contribute to the global *Capsicum* conservation strategy.

As the curator and/or manager of a genebank or other form of *Capsicum ex situ* collection, the information you provide will be vital to our global assessment. The collection data we receive via the questionnaire will be used to address not only the extent of *Capsicum* genetic diversity conserved *ex situ* worldwide, but also how securely it is conserved and if there are any collection gaps. The questionnaire contains 65 questions and should take approximately 60 minutes to complete.

Participation in this survey is voluntary. By returning the completed questionnaire we assume that you have consented to participate in the study. All data will be kept confidential and personal identifying information will be removed from the data before sharing of any data.

Respondents will be invited to provide comments on the draft strategy and will be invited to participate in a (virtual) meeting to discuss priority actions for the conservation of *Capsicum* PGR. Please complete the survey at your earliest convenience, but no later than 30 September 2021. Any questions/concerns on how to complete the questionnaire, or feedback on the strategy itself, can be directed to Colin (c.khoury@cgiar.org) and Derek (derek.barchenger@worldveg.org).

Thank you in advance for your participation in this important initiative!

ORGANIZATION INFORMATION

1. Organization holding/maintaining the *Capsicum* collection:

Name of Organization |Address | City/Town | State/Province | ZIP/Postal Code | Country | Website

2. Curator in charge of the *Capsicum* collection:

Name | Job Title | Telephone | Email

3. Name of respondent to this questionnaire (if not as above) (optional):

Name | Function/Job Title | Telephone | Email

4. Is the organization in charge of the *Capsicum* collection the legal owner of the collection?

(Y/N) If not, who is the owner?

5. Describe the organization (select one):

Governmental organization
University
Private organization
NGO or charity
Other (please specify)

6. Does the genebank or collection operate under a national conservation strategy, policy, or plan?

(Y/N) If yes, please specify.

7. Who has influence on genebank priorities (*e.g.*, objectives, species focus, activities)? (Select all that apply).

The curator(s) of the collection
The organization/department management
A governing committee
A stakeholder committee
Other (please specify)

THE CAPSICUM COLLECTION

8. Basic information on the *Capsicum* collection:

Year of establishment
Total number of *Capsicum* accessions (today)
Total number of *Capsicum* species (today)
Total number of *Capsicum* accessions currently available for distribution

9. The main objectives of the collection include (select all that apply):

Long-term conservation
Working collection for public breeding/research program
Working collection for private breeding/research program
Academic or educational use
Reference collection
Other (please specify)

10. For the cultivated species, *Capsicum annuum, C. baccatum, C. chinense C. frutescens,* and *C. pubescens,* indicate the number of accessions by germplasm type:

Total number of accessions	*C. annuum*	*C. baccatum*	*C. chinense*	*C. frutescens*	*C. pubescens*
Landraces					
Obsolete/traditional cultivars					
Advanced/improved cultivars					
Breeding/research materials					
Specialist genetic stocks					
Wild or weedy populations					
Unknown					
Other					
Total					

11. Please indicate the total number of accessions of wild *Capsicum* species (NOT listed in table above) in your collection

Species	Total number of accessions
Capsicum annuum var. *glabriusculum*	
Capsicum baccatum var. *baccatum*	
Capsicum benoistii	
Capsicum caatingae	
Capsicum caballeroi	
Capsicum campylopodium	
Capsicum cardenasii	
Capsicum ceratocalyx	
Capsicum chacoense	
Capsicum coccineum	
Capsicum cornutum	
Capsicum dimorphum	
Capsicum eshbaughii	
Capsicum eximium	
Capsicum flexuosum	
Capsicum friburgense	
Capsicum galapagoense	
Capsicum geminifolium	
Capsicum hookerianum	
Capsicum hunzikerianum	

Species	Total number of accessions
Capsicum lanceolatum	
Capsicum longidentatum	
Capsicum longifolium	
Capsicum lycianthoides	
Capsicum minutiflorum	
Capsicum mirabile	
Capsicum neei	
Capsicum parvifolium	
Capsicum pereirae	
Capsicum piuranum	
Capsicum praetermissum	
Capsicum recurvatum	
Capsicum rhomboideum	
Capsicum schottianum	
Capsicum tovarii	
Capsicum villosum var. *muticum*	
Capsicum villosum var. *villosum*	
Capsicum sp. (unknown species)	
Other *Capsicum* species not listed above	

12. To what extent do you consider the *Capsicum* accessions in your collection to be unique and not duplicated elsewhere (excluding safety duplication)? Please mark one field per row.

	100% unique	More than 50% unique	Less than 50% unique	Fully duplicated elsewhere
Cultivated/domesticated Capsicum annuum				
Cultivated/domesticated Capsicum baccatum				
Cultivated/domesticated Capsicum chinense				
Cultivated/domesticated Capsicum frutescens				
Cultivated/domesticated Capsicum pubescens				
Crop wild relatives (i.e., other Capsicum spp.)				

13. Across the entire *Capsicum* collection, approximately how many countries of origin are represented

14. Describe the geographic origins of the collection by indicating the proportion (%) of cultivated *Capsicum annuum* accessions that were collected/obtained (total should sum to 100%):

Nationally | Regionally (excluding own country) | Internationally (excluding own region) | Unknow

15. Are there any known or perceived gaps in your *Capsicum* collection (check all that apply):

Genetic diversity gaps
Varietal diversity gaps
Species/taxa gaps
Ecogeographic gaps
Trait gaps
Other gaps

16. If there are collection gaps, as indicated in Q15, how and when do you plan to fill these gaps, if at all (optional)?

17. To what extent do you consider duplication within your *Capsicum* collection to be a problem? (select one)

No duplication within the collection
Low amounts of duplication (< 10%)
Moderate amounts of duplication (10-30%)
Duplication is extensive (> 30%)

18. Indicate the number of *Capsicum* accessions that have been:

Acquired in the past 10 years?
Lost from the collection in the past 10 years?
Removed as they were identified as duplicates?

EX SITU CONSERVATION FACILITIES

19. Indicate the proportion (%) of *Capsicum* accessions that are maintained under the following conditions: (Note: if accessions are maintained under multiple conditions, total may exceed 100%.)

Short-term storage
Medium-term storage
Long-term storage
Safety duplications at one or multiple other genebanks

For the following questions in this section (Q20-Q30), you need answer only for the storage conditions applicable for your collection (safety duplicates in other repositories are addressed in another section).

20. Please describe the storage facilities:

	Short-term storage	Medium-term storage	Long-term storage
Type of facility (warehouse, cold chamber, freezer, etc.)			
Conservation method (seed, *in vitro*, etc.)			
Temperature (°C)			
Relative humidity (%)			

21. What type of packaging is used for seed conservation? (check all that apply)

	Short-term storage	Medium-term storage	Long-term storage
Sealed aluminum packs			
Sealed, vacuum-packed aluminum packs			
Plastic containers			
Glass containers			
Paper envelopes or bags			
Cloth bags			
Other (please specify)			

22. Please provide information on *Capsicum* seed drying prior to storage. If no drying is done, please respond with "none".

	Short-term storage	Medium-term storage	Long-term storage
Moisture percentage			
Method of drying			
Instrument used to determine moisture content			

23. Do the genebank facilities include (check all that apply):

Separate work areas for 'dirty' and 'clean' seed handling procedures
Separate work areas for seed packaging for storage and distribution
Dedicated laboratory and trained staff for seed viability testing
Dedicated laboratory and trained staff for seed health testing
Low temperature seed dryer
Suitable field sites for regeneration and multiplication
Greenhouse/glasshouse facilities for regeneration and multiplication
Other (please specify)

GERMPLASM MANAGEMENT

24. Have you established a genebank management system or written procedures/protocols for (check all that apply):

	Yes	No	N/A
Acquisition			
Conservation (storage, maintenance, etc.)			
Regeneration			
Characterization			
Distribution			
Safety duplication			
Information management			
Misidentified accessions			
Duplicated/repeated accessions			
Germplasm health (viability testing, phytosanitary, etc.)			

25. The genebank uses written procedures and protocols from (check all that apply):

No written procedures or protocols
Hanson 1985. Practical Manuals for Genebanks No. 1: Procedures for Handling Seeds in Genebanks. IBPGR.
FAO/IPGRI 1994. Genebank Standards.
Rao et al. 2006. Handbooks for Genebanks No. 8: Manual of Seed Handling in Genebanks. Bioversity International.
Organization's own "Operational Genebank Manual"
Written and verified Standard Operating Procedures (SOPs) for key processes
A Quality Management System (QMS)
Other (please specify)

26. Please describe your quality control activities for conserved seeds:

	Frequency	Protocols/Methods
Germination testing		
Viability testing		
Health testing (presence of pathogens, viroids or viruses)		

27. What is the normal regeneration interval (in years) to maintain the viability of your *Capsicum* collection?

28. What proportion (%) of your *Capsicum* collection requires urgent regeneration (apart from the normal routine regeneration)?

Cultivated *Capsicum annuum*
Other domesticated *Capsicum* species
Crop wild relatives (other *Capsicum* spp.)

SAFETY DUPLICATION

29. Are accessions safety duplicated at another genebank(s)?

Yes
Partly
No
Don't know
If you answered Yes or Partly, please complete the following questions (Q34–Q36). If No, skip these questions.

30. Please indicate the proportion (%) of *Capsicum* accessions safety duplicated by arrangement: (Note: if accessions are safety duplicated at more than one location, total may exceed 100%.)

Svalbard Global Seed Vault
Black box outside country
Integrated in another collection outside country
Black box within country
Integrated in another collection within country
Other

31. Please list the institution(s) where your germplasm is safety duplicated.

32. Do all safety duplication sites have formal agreements to establish terms and obligations?

(Y/N)

33. Are there constraints to duplicating the collection outside your country?

(Y/N)? If yes, please specify.

34. Are there *Capsicum* accessions from other collections that are safety duplicated at your facilities?

(Y/N) If yes, please provide the name(s) of the original collection holder(s) and the number of accessions?

DOCUMENTATION AND INFORMATION MANAGEMENT

35. Do you use a searchable electronic platform (computerized database) for storing and retrieving accession-level data? (Y/N) If yes, what software is used?

36. The accession-level information is (check all that apply):

Public
Private
Available by written catalogue or by contacting the curator
Available & searchable online within the institute
Available & searchable online outside the institute

37. The accession-level database provides the following information (check all that apply):

Passport
Taxonomy
Characterization
Evaluation
Genotypes
Images
Distribution
Other (please specify)

38. What proportion (%) of the *Capsicum* collection has:

Passport data
Coordinate (geo-referenced) data

39. If you use a computerized database to manage the collection and share accession data, is it adequate to meet the needs of both the genebank and users? (Y/N) If inadequate, are there plans to upgrade or improve this system?

40. Are the accession-level data describing your collection available in other, external databases?

	Yes	Partly	No	If Yes/Partly, specify the database(s):
National				
Regional				
International				

CHARACTERIZATION AND EVALUATION

41. In your database, what proportion (%) of cultivated and wild accessions have:

	Cultivated accessions	Wild accessions
Agro-morphological (phenotypic) characterization data		
Genotypic characterization data (molecular markers, etc.)		
Abiotic stress tolerance data		
Biotic stress tolerance data		

42. If abiotic/biotic stresses have been at least partially assessed, please list the specific stresses that have been evaluated.

43. Please describe any core collections or other trait-specific subsets of accessions that have been established for the *Capsicum* collection?

DISTRIBUTION

44. Do you distribute accessions from your *Capsicum* collection? (Y/N) If no, why not?

If you answered Yes to the previous question (Q50), please complete the remaining questions in this section (Q50-Q59). If you answered No, you may skip to the next section.

45. Are you able to distribute accessions of your *Capsicum* collection (check one):

Only to users in own country
Only to users in certain countries (i.e., regionally)
Nationally and internationally, to most/all countries

46. What best describes the conditions that must be met for distribution (check any that apply):

Freely distributed without terms or conditions
Institutional material transfer agreement (MTA) or other bi-lateral agreement
The Nagoya Protocol for the CBD
The International Treaty on PGR for Food and Agriculture (ITPGRFA) (Standard Material Transfer Agreement)
Other (please specify)

47. For the following categories, how many samples are typically distributed annually (average of last 3 years)? Answer where applicable. (Note: wild materials include wild progenitors as well as other *Capsicum* species.)

	Nationally	Internationally
Cultivated accessions		
Wild accessions		

48. How have your distributions changed over the last 5–10 years? (check one)

Increase | Stay the same | Decrease

49. How do you expect your distributions to change over the next 5–10 years? (check one)

Increase | Stay the same | Decrease

50. Are there factors that currently limit, or may limit in future, the distribution and use of materials maintained in your collection?

51. Of your annual distributions, what kind of users have received germplasm from your collection? Please estimate the proportion (%) of total distribution over the last 5 years (total should sum to 100%):

Farmers or farmer organizations
Governmental departments
Other genebank curators
Academic researchers and students (universities)
Research institutes
Breeding programs: public sector
Breeding programs: private sector
Non-governmental organizations (NGOs)
Other

52. Do you charge fees for the following services? (Y/N)

The cost of accessions
The cost of shipping
The cost of phytosanitary/quarantine processes

53. How do germplasm users influence the management of the collection? (check all that apply)

Through feedback on available materials/distributions
Through formal consultations
Through participation in the governing body of the genebank
Other (please specify)

54. How are the accessions available for distribution publicized?

LONG-TERM COLLECTION VULNERABILITY

55. Does your organization provide most or all of the recurrent costs for maintaining the Capsicum collection? (Y/N) If not, who are your other significant funders?

56. How has the budget for conservation of the collection changed over the last 5 years? (check one)

Increased | Stable | Decreased

57. If it has decreased, please describe any other funds sourced to make up the shortfall?

58. Has there been a formal risk assessment performed and management plan developed for the genebank/collection? (Y/N) If yes, how recently?

59. What do you consider to be the 3 most significant vulnerabilities or threats to the Capsicum collection?

60. What are the primary disease/pathogen or pest concerns for:

Seed storage | Distribution | Regeneration/multiplication

61. How do you predict the size of the collection to change in the next 10 years? (check one)

Stay approximately the same size
Limited expansion (5-10%)
Substantial increase (>10%)
Decrease owing to collection rationalization
Decrease due to lack of funding/facilities

62. Please indicate the current and expected situation of your Capsicum collection with respect to the following risk factors, where 1 = excellent, 2 = adequate, 3 = insufficient, N/A = not applicable:

	Current situation	Expected situation (2025 onwards)
Funding for routine operations/maintenance		
Retention of trained staff		
Interest for PGR conservation by donors		
Genetic variability in the collections needed by users/breeders		
Access to germplasm information (passport data, etc.)		
Feedback from users		
Use by breeders/researchers		

NETWORKS AND PARTNERSHIPS

63. Does your genebank collaborate with other collection holders? If yes, please describe the form of your collaborations (check all that apply):

	Collecting	Conservation	Research	Safety duplication	Training	Other
Other national *ex situ* collection						
Other regional or international *ex situ* collection						
In situ conservation sites						
On farm conservation sites						
Community seedbanks						
Protected sites for wild relatives						
Other (please specify)						

64. Do you participate (or have you participated in the last 10 years) in a plant genetic resource network (including germplasm holders and/or users)? (Y/N) If yes, please describe the network & provide a URL if applicable.

FINAL CONSIDERATIONS

65. Please add any further comments you may have in regard to your *Capsicum* collection and/or this questionnaire. Recommendations for the chili pepper conservation strategy are also welcome.

Annex II: *Capsicum* genetic resource collections survey respondent information

Name of Organization	Address	City/Town	State/ Province	Postal Code	Country	Website
World Vegetable Center	60 Yi-Min liao	Shanhua	Tainan	74151	Taiwan	Link
Pusat Inovasi Agroteknologi Universitas Gadjah Mada (Agrotechnology Innovation Centre)	Kalitirto, Berbah, Sleman, Yogyakarta	Yogyakarta	Special Region of Yogyakarta	55573	Indonesia	Link
INTA	Ex Ruta 40 km 96	La Consulta	Mendoza	5567	Argentina	Link
Tropical Vegetable Research and Development Center (TVRC)	Tropical Vegetable Research and Development Center, Department of Horticulture, Faculty of Agriculture at Kamphaeng Saen, Kasetsart University	Kamphaeng Saen	Nakhon Pathom	73140	Thailand	Link
Embrapa Clima Temperado	Rodovia BR392, km 78	Pelotas	RS	96010-971	Brazil	Link
Department of Agriculture Genebank of Thailand	Sirindhorn Genebank Building,85 Rangsit-Nakhonnayok Rd.,Klong 6 Amphur Thanyaburi,Pathumthani Province,Thailand	Thanyaburi	Pathumthani Province	12110	Thailand	Link
Department of Genetics and Plant Breeding Ss. Cyril and Methodius University in Skopje/ Faculty of Agricultural Sciences and Food-Skopje	16-ta Makedonska brigada 3 1000 Skopje	Skopje		1000	North Macedonia	Link
Corporación Colombiana de Investigación Agropecuaria - Agrosavia	Km 7 Via Rionegro - Las palmas, Sector Llanogrande, CI La Selva Agrosavia	Rionegro	Antioquia	54048	Colombia	Link
International Center for Biosaline Agriculture	Dubai-Al Ain Road Rawayya	Dubai	Dubai	146600	United Arab Emirates	Link
Instituto de Investigaciones Agropecuarias	Av Santa Rosa 11610, La Pintana	Santiago	Metropolitana	8831314	CHILE	Link
Institute of Field and Vegetable Crops	Maksima Gorkog 30	Novi Sad	Vojvodina	21000	Serbia	Link
Crop Research Institute	Šlechtitelů 29	Olomouc		78371	Czech Republic	Link
Research Centre for Vegetable and Ornamental Crops	Via Cavalleggeri 25	Pontecagnano	Salerno	84098	Italy	Link
Centre de Ressources Biologiques Légumes	Domaine St Maurice	Montfavet		84143	France	Link
Agroscope	Route de Duillier 50	Nyon 1	Vaud	1260	Switzerland	Link
Seed Savers Exchange	3094 N Winn Road	Decorah	WI	52101	USA	Link
National Biodiversity Centre	Serbihang	Thimphu	Thimphu	11001	Bhutan	Link
Centre for Genetic Resources, The Netherlands	Droevendaalsesteeg 1	Wageningen	Gelderland	6708 PB	The Netherlands	Link
New Mexico State University Chile Breeding Program	PO Box 30003, MSC 3Q	Las Cruces	New Mexico	88003	United States of America	Link
National Agriculture and Food Research Organization Genebank	Kannon-dai 2-1-2	Tsukuba	Ibaraki	305-8602	Japan	Link

Name of Organization	Address	City/Town	State/ Province	Postal Code	Country	Website
United States Department of Agriculture – Agriculture Research Service: Plant Genetic Resources Conservation Unit	1109 Experiment St.	Griffin	Georgia	30223	USA	Link
Khon Kaen University	123 Moo 16 Mittraphap Rd., Nai-Muang	Muang	Khon Kaen	40002	Thailand	
Plant Resources Center (PRC)	An Khanh commune	Hoai Duc district	Hanoi	10000	Vietnam	Link
Division of Plant Germplasm, Taiwan Agricultural Research Institute	189, Chung-Cheng Road	Wufeng	Taichung	41362	Taiwan	Link
Fruit and Vegetable Research Institute (FAVRI)	Trau Qui – Gia Lam	Hanoi			Vietnam	Link
ICAR-Indian Institute of Vegetable Research	Post Box.01, Post Office-Jakhini, Varanasi (Uttar Pradesh), India	Varanasi	Uttar Pradesh	221305	India	Link
Plant Gene Resources of Canada	107 Science Place	Saskatoon	Saskatchewan	S7H 4M3	Canada	Link
National Gene Bank of Tunisia (NGBTUN)	Boulevard Leader Yasser Arafat	Charguia 1	Tunis	1080	Tunisia	
Southern Fruit Research Institute	Long Dinh village	Chau Thanh district	Tien Giang		Vietnam	
Universitat Politècnica de València	COMAV Institute. Camino de Vera s/n Edificio 8E, acceso J, 3er piso	Valencia	Valencia	46022	Spain	Link
ICAR- IIHR- Central Horticultural Experiment Station, Bhubaneswar	Aiginia, Dumduma	Bhubaneswar	Odisha	751019	India	Link
Indonesia Vegetable Research Institute (IVEGRI) under the IAARD (Indonesian Agency for Agricultural Research and Development), Ministry of Agriculture	Jl. Tangkuban Parahu No. 517 Lembang	Bandung Barat	West Java	40391	Indonesia	Link
Centro Nacional de Recursos Fitogenéticos (CRF) – INIA, CSIC	Autovía A-2, km. 36. Apdo 1045	Alcalá de Henares	Madrid	28805	Spain	Link
Embrapa Recursos Genéticos e Biotecnologia	PqEB Av W5 Norte (final)	Brasilia	Federal District	70770-917	Brazil	Link
National Plant Genetic Resources Centre (NPGRC)	Directorate: Genetic Resources, Private Bag X973	Pretoria	Gauteng	1	South Africa	Link
Australian Grains Genebank	110 Natimuk Road	Horsham	Victoria	3400	Australia	Link
Maritsa Vegetable Crops Research Institute	32, Brezovsko shose	Plovdiv	Plovdiv	4003	Bulgaria	Link
Institute of Plant Genetic Resources "K. Malkov"	2 Drouzba Str	Sadovo	Plovdiv	4122	Bulgaria	
Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA)	Avda. Montañana 930	Zaragoza	Zaragoza	50014	Spain	Link
Tropical Agronomic Research and High Education Center	CATIE Headquarters, Turrialba 30501, Cartago, Costa Rica	Turrialba	Cartago	30501	Costa Rica	Link

Annex III: *Capsicum* genetic resource stakeholder meetings agenda

Global strategy for the conservation and use of Capsicum genetic resources

Stakeholder meeting agenda

Dates/times:

Meeting 1: 11 January, 1400 pm UTC
Meeting 2: 13 January, 0300 am UTC
Total time: 3–3.5 hours

Introductions – 15 minutes

- Derek Barchenger and Colin Khoury
- Peter Giovannini (Crop Trust)
- Depending on size of group, make quick introductions of each participant (unlikely), or use a virtual app like padlet

Overview of *Capsicum* and its crops – 25 minutes

- Taxonomy – TBD – 10 minutes (recorded)
- Crops, current breeding and cultivation – global outlook – Paul Bosland – 10 minutes (recorded)
- Presentation of *Capsicum* collections survey results – Derek and Colin – 45 minutes
- Collections (including national, regional, and international)
- Size and composition of collections
- Structure and management (conservation methods, standards, core collections, etc.)
- Regeneration status
- Characterization and evaluation status
- Safety duplication status
- Collecting activities (past, current, planned)
- Priority conservation research, actions and targets
- Major constraints to operations (financial, staffing, facilities, research, policies, phytosanitary, etc.)
- In situ conservation activities

Break – 10 minutes

Discussion: Important steps to enhance the conservation and use of *Capsicum* genetic resources

***Capsicum* collections – status, gaps and vulnerability – 20–30 minutes**

- Identification of key/important collections and materials (uniqueness, etc.)
- Gaps
- Genetic and taxonomic gaps (including "diversity tree" approach)
- Ecogeographic gaps
- Major vulnerabilities and threats to the collections
- Safety duplication needs
- Other major threats
- *In situ* and on farm conservation needs
- Landraces (including community registries, on-farm trends and vulnerability)
- Wild relatives (including protected areas, habitat destruction and other threats)

Documentation and information sharing – 15 minutes

- Platforms (manual, electronic, both)
- Content (including passport, characterization, evaluation, regeneration, distribution)
- Completeness
- Access and availability of the information (nationally and internationally)

Access, distribution and use of genetic resources – 15 minutes

- Access status (e.g. party to ITPGRFA/MLS?, Annex 1?, Article 15?, CBD/Nagoya Protocol?)
- Distribution to a variety of users (e.g., breeders, researchers, farmers, NGOs)
- Constraints to distribution (e.g.,policy, phytosanitary/quarantine, availability, etc.)
- Breeding/user needs
- Repatriation/restoration (e.g., landraces to farmers, CWR to protected areas)

Networks and other collaborative initiatives – 10 minutes

- Global crop networks
- Regional crop and PGR networks
- National and inter-institutional collaborations
- Collaborations with the private sector, academia, NGOs, etc.

Moving forward – 30 minutes

- Priority activities and timeline
- Capacity building
- Implementation, governance, and opportunities for funding
- Conditions for success and indicators

Annex IV: Selected crop indicator metrics for *Capsicum*

This annex was written by Dr. Felix Frey, International Consultant, Global Crop Diversity Trust

Khoury et al. 2022 compiled a dataset as part of a project funded by the ITPGRFA, in collaboration with the Crop Trust, led by the International Center for Tropical Agriculture (CIAT), entitled "The Plants That Feed the World: baseline data and metrics to inform strategies for the conservation and use of plant genetic resources for food and agriculture". The aim was to develop standardized, reproducible indicators to serve as an evidence base for prioritizing actions on the conservation and use of plant genetic resources for food and agriculture. The indicators encompass metrics associated with the use of a crop (global importance), the interdependence among countries with respect to genetic resources, the demand for crop genetic resources, the supply of crop genetic resources, and the security of crop genetic resources. To generate the indicators, Khoury et al. collected a comprehensive dataset from multiple sources. We do not present those indicators here, but rather discuss the underlying raw data to shed light on the aspects represented by the indicators for peppers.

To put numbers into context, chillies and peppers were compared with tomatoes. Both crop groups are members of the *Solanaceae* family, and share characteristics such as type of growth, propagation, and use. Chillies and peppers are represented by the genus *Capsicum,* and by the species *C. annuum, C. baccatum, C. chinense, C. frutescens,* and *C. pubescens* (the spice pepper, *Piper* spp., is not included). Tomatoes are represented here by the genus *Solanum* and by the species *S. lycopersicum*. Results obtained at the genus level also include other *Solanum* species, foremost potato (*Solanum tuberosum*), and can thus be huge overestimations.

The metrics for "Global production," "Food supply" and "Quantity exported globally" under the indicator domain "Crop use" are annual average values drawn from FAOSTAT for the years 2015–2018. The percentage of countries producing and consuming (i.e., being supplied with) the crop is calculated as the number of countries where the respective crop is within the top 95% of most important crops divided by the number of countries that report respective numbers (can be different between metrics and crops). The global production of *Capsicum* is estimated at about 35. million tons annually, which is 22.4% of global tomato production (about 177.8 M t). The quantity of food supply by *Capsicum*, i.e. the average global consumption, is about 0.5 g/capita/day, 2.2% of global tomato supply as a food source (20.8 g/cap/day). That means that *Capsicum* food supply is relatively low, compared to its production. This is explained by its major use as a dried product, which is very different from tomatoes. Chillies and peppers are produced at considerable scale in 27% of the world's countries;tomatoes are produced in 56%.. This relatively high number indicates the importance of *Capsicum* across countries and cultures, though it is eaten in relatively smaller quantities by weight. Both crops are heavily internationally traded, at about 4.3 M t for *Capsicum* and 13.3 M t for tomato.

The crop use metrics with respect to research were assessed using a manual search on Google Scholar, searching for the respective genus or species in the titles of publications, including patents and citations, between the years 2009 and 2019. Search hits on Google Scholar indicate the level of scientific interest in a crop. The *Capsicum* genus is found in the titles of 11,900 publications, which is around 72% of the number of publication titles that include the tomato genus *Solanum* (16,500). The scientific names of the species (*C. annuum, C. baccatum, C. chinense, C. frutescens,* and *C. pubescens*) appear in 6,170 publication titles. The tomato species name *S. lycopersicum* appears in 4,740 publication titles. Assessing public interest in crops by counting public views of Wikipedia pages dedicated to the crops during the year 2019, 515,815 views were made for *Capsicum* crops, versus 8263 for tomatoes, based on taxonomic names.

Khoury et al. defined crop genetic resource interdependence as a measure for the degree of cultivation or use of a certain crop outside its origins and primary regions of diversity. These regions are not represented by countries, but rather by 23 world regions (Khoury et al. 2016). Estimated interdependence is high in crops that originate from a small area but are cultivated and used globally. For production, interdependence is calculated by dividing a crop's production outside the primary center of diversity by its global production. If all production is outside the primary center of diversity, estimated genetic resource interdependence would be 100%. For food supply, interdependence is calculated by dividing the food supply outside the origin region by the world average. Food supply outside can be higher than that inside the primary centers of diversity and thus also higher than the global mean. Therefore, interdependence with respect to food supply can be above 100%, but in such cases is set to 100%. The primary centers of diversity of *Capsicum* are located in Central America and Mexico, the Caribbean and tropical South America. Production of peppers and chilies is mainly taking place in China (FAOSTAT 2021), thus interdependence of global production is high (94.2%). The same is seen with tomatoes, where the primary regions of diversity are located in Central America and Mexico and Andean South America, while the main producers are located on the Asian continent (China, India and Turkey; FAOSTAT 2021), resulting in a high interdependence value of 97.5%. The interdependence values with respect to food supply of *Capsicum* as well as tomatoes are both extremely high at 100%.

Demand for germplasm is defined by various metrics including the number of distributions of samples under the SMTA as reported to the Data Store of the ITPGRFA, as an annual average between 2015 and 2019, numbers of accessions distributed by national genebanks as reported to the FAO WIEWS system as an annual average from 2014 to 2019, and the average annual number of new crop varieties released during the five years between 2014 and 2018, obtained from the International Union for the Protection of New Varieties of Plants (UPOV). There is relatively strong use of *Capsicum* germplasm. This is reflected by the 1076.5 samples of chillies and peppers distributed per year under the SMTA, which was higher than yearly distributions of tomato accessions (790.3) (note the neither crop is included in Annex 1 of the Plant Treaty). In the FAO WIEWS dataset, 6898 accessions of chillies and peppers were distributed per year, compared to 11,015 of tomatoes. We observe a similar picture with respect to the development of new cultivars. Some 438.5 varieties of chillies and peppers were released annually, compared to 1061.8 varieties of tomatoes.

Khoury et al. quantified the supply of germplasm by using the number of accessions available in *ex situ* collections around the world, with respect to the crop genus and the most important taxa of the respective crop. They also assessed the number and proportions of accessions (again with respect to genus and species) available under the multilateral system (MLS) of the ITPGRFA. This assessment was done first, directly, based on notation (in MLS / not in MLS) in the public online databases Genesys and FAO WIEWS. Secondly, the availability of accessions in the MLS was assessed by considering whether the country hosting the institution that held the respective germplasm collection was a Contracting Party to the ITPGRFA and whether the crop was listed in Annex 1 of the Plant Treaty, in which case the accession was regarded as available via the MLS. According to databases, global *ex situ* collections count a total of 42,939 accessions of chillies and peppers at the genus level. 36,528 of these accessions are counted to the species mentioned here. The number of accessions accounting for the tomato genus *Solanum* is 122,252, where 39,305 accessions are attributed to the species *Solanum lycopersicum*. It must be taken into account that the *Solanum* genus also includes other globally important crops, such as potatoes and eggplants, and that peppers and chilies encompass five species in contrast to one for tomato. The percentage of accessions available under the MLS stated directly in respective databases is 21.1% and 31.9%, for *Capsicum* amd *Solanum*, respectively, and 22% for the species of both crop groups. As neither chillies and peppers nor tomatoes are listed in Annex I of the Plant Treaty (FAO 2009), none of the accessions of both crop groups were considered available under the MLS when matching institute countries with party status.

Security of germplasm conservation is represented here by safety duplication at the Svalbard Global Seed Vault (SGSV). The numbers of accessions, by genus and species, safety duplicated were taken from the SGSV website and divided by the total number of accessions stored in global *ex situ* collections (see above), with the result giving the percentage of germplasm that is safety duplicated. At the genus level, 7.3% of *Capsicum* and 16.9% of *Solanum* accessions are safety duplicated at the SGSV. At the species level, 8.2% of the accessions of *Capsicum* are safety duplicated at the SGSV, compared to 18.2% of tomato.

Literature cited

FAO (2009) International Treaty on Plant Genetic Resources for Food and Agriculture. Food and Agriculture Organization of the United Nations. Annex I.

FAOSTAT (2021) Statistics for 2015-2019. Accessed 19 July 2021.

Khoury CK, Achicanoy HA, Bjorkman AD, Navarro-Racines C, Guarino L, Flores-Palacios X, Engels JMM, Wiersema JH, Dempewolf H, Ramírez-Villegas J, Castañeda-Álvarez NP, Fowler C, Jarvis A, Rieseberg LH, and Struik PC (2015) *Estimation of Countries' Interdependence in Plant Genetic Resources Provisioning National Food Supplies and Production Systems*. International Treaty on Plant Genetic Resources for Food and Agriculture, Research Study 8, FAO, Rome.

Khoury CK, Achicanoy HA, Bjorkman AD, Navarro-Racines C, Guarino L, Flores-Palacios X, Engels JMM, Wiersema JH, Dempewolf H, Sotelo S, Ramírez-Villegas J, Castañeda-Álvarez NP, Fowler C, Jarvis A, Rieseberg LH, Struik PC (2016) Origins of food crops connect countries worldwide. *Proceedings of the royal society B: biological sciences* 283(1832): 20160792.

Khoury CK, Sotelo S, Amariles D (2019) *The plants that feed the world: baseline information to underpin strategies for their conservation and use.* International Treaty on Plant Genetic Resources for Food and Agriculture (Rome) Project 2018 – 2019.

Khoury CK, Sotelo S, Hawtin G, Halewood M, Lopez Noriega I, and Lusty C (2022) Thematic Background Study on Germplasm Exchange for The Third Report on the State of the World's Plant Genetic Resources for Food and Agriculture. Rome: Food and Agricultural Organization of the United Nations.

Khoury CK, Sotelo S, Hawtin G, Wibisono J, Amariles D, Guarino L, Kiene T, and Toledo A (2022) The Plants That Feed the World: baseline data and metrics to inform strategies for the conservation and use of plant genetic resources for food and agriculture. International Treaty on Plant Genetic Resources for Food and Agriculture Background Study Paper X. Rome: Food and Agricultural Organization of the United Nations. https://www.fao.org/3/cc1988en/cc1988en.pdf

CROP TRUST

GENERAL CONTACT
+49 (0) 228 85427 122
info@croptrust.org

THE CROP TRUST
Platz Der Vereinten Nationen 7
53113 Bonn, Germany

MEDIA CONTACT
+49 (0) 228 85427 141
media@croptrust.org