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ON PLANT GENETIC RESOURCES FOR FOOD AND AGRICULTURE

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NINTH SESSION OF THE GOVERNING BODY

New Delhi, India, 19–24 September 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

Note by the Secretary

At its Eighth Session, the Governing Body welcomed "the collaboration between the Secretary, the Crop Trust and the International Center for Tropical Agriculture (CIAT) to identify and systematize baseline data of a wide range of crops and their genetic resources that is essential for decision-makers at global, regional and national levels in order to develop strategies to ensure the adequate conservation and use of these plant genetic resources for food and agriculture, including Crop Strategies, and recommend[ed] that the background study resulting from such collaboration and underlying baseline information be made available in a user-friendly manner as soon as possible, including for consideration by the Governing Body at its Ninth Session" (Resolution 10/2019, para.12).

As a follow-up to these earlier collaborations on the study on countries' interdependence in plant genetic resources for food and agriculture[1] *and the mapping of available information,*[2] *the Secretary, the Alliance of Bioversity International and CIAT, and the Crop Trust initiated the next phase during the biennium, aiming to add more data, finalize the methodology, and make both data and methodology available and accessible.*

This document presents the pre-publication version of the study, "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", which is a main output of this phase of the collaboration.

Important note: *This document serves as information document to the Ninth Session of the Governing Body of the International Treaty and will be replaced with the officially published study once available.*

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[1] Khoury, C.K., Achicanoy, H. A., Bjorkman, A. D. *et al*. 2015. *Estimation of countries' interdependence in plant genetic resources provisioning national food supplies and production systems*. The International Treaty Research Paper 8. Rome, ITPGRFA, FAO. www.fao.org/3/a-bq533e.pdf

[2] IT/GB-8/19/15.2, *Cooperation with the Global Crop Diversity Trust*, paras. 18–21.

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

[DRAFT – NOT FOR CITATION]

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*Bioversity International and the International Center for Tropical Agriculture (CIAT) are part of the Alliance of Bioversity International and the International Center for Tropical Agriculture (CIAT). https://alliancebioversityciat.org

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Executive summary

Information on the use of food and agricultural crops and on interdependence regarding, demand for, supply of, and security of their genetic resources is needed to prioritize conservation and utilization efforts. This information is increasingly available but is scattered through several information systems, databases, and scientific literature. The study "*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*" intends to bring together and make widely available pertinent information from these different sources. The aim is to develop a set of reproducible metrics that provide an evidence base for the international plant genetic resources community to prioritize conservation and utilization activities. Measured periodically, these metrics can also provide insights on change over time in the use of crops and issues regarding interdependence on, demand for, supply of, and security of their genetic resources.

The main global database sources for this study included: FAO's Food and Agricultural Statistics Database (FAOSTAT), the FAO World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture (FAO WIEWS), the Data Store of the International Treaty on Plant Genetic Resources for Food and Agriculture, the International Union for the Protection of New Varieties of Plants (UPOV)'s PLUTO Plant Variety Database, the Genesys Plant Genetic Resources portal (Genesys PGR), Botanic Garden Conservation International's PlantSearch database, the Global Biodiversity Information Facility (GBIF), the Svalbard Global Seed Vault's SeedPortal, Google Scholar, Wikipedia (pageviews), and the National Center for Biotechnology Information (NCBI)'s Entrez database. Metrics were generated for a total of 355 food and agricultural plants, a list which is inclusive of all those covered in FAOSTAT, in Annex 1 of the International Treaty, and of CGIAR mandate major crops, as well as other crops deemed internationally significant. A total of 98 global-level metrics were calculated, including 51 metrics on crop use and 22 metrics on interdependence regarding; 7 metrics on demand for; 16 metrics on supply of; and 2 metrics on security of crops' plant genetic resources.

The data on crop use show that hundreds of different crops are widely grown, traded, present in food supplies, and researched around the world. Crops that are valuable internationally are found in all the main crop use types examined in this study: ten food categories (cereal, fruit, herb and spice, nut, oil, pulse, root and tuber, stimulant, sugar, and vegetable crops) as well as fiber, forage, and industrial crops.

The data also show that crop use is not static and that a plant's utilization can vary widely both spatially and temporally. Crops that were not considered important on a global or regional scale a few decades ago have become widely utilized today. Likewise, plants that are currently grown only on a small scale could become major crops of the future, although it is impossible to predict with high accuracy which crops will flourish, and which will decline in use. The certainty is that the spectrum of globally and regionally important crops will change, possibly substantially, over time. Several boxes were included throughout the study on contemporary issues on PGRFA conservation and use, to further showcase how the management of plant genetic diversity is evolving at present.

The data further show that for almost all the most utilized crops, there is a high level of interdependence among countries with respect to their PGRFA. Many of the crops studied have high estimated interdependence values as well as large directly quantified germplasm distributions to recipients in many different countries and regions. This is true not only for the staple food crops but also for a large variety of other plants of various crop use types.

All metrics studied showed a wide variation among crops in terms of the amount of PGRFA held *ex situ* and hence that is available for use. For some crops, especially major, orthodox seed producing commodity crops, there are very large, readily available collections. However, for other crops, collections may be less available or much smaller, including for many of those that cannot be conserved as seed and must be maintained *in vivo* (in field collections) or *in vitro* (in specialized laboratory or cryopreservation facilities). Agricultural research institutions and botanic gardens appear to complement one another by focusing their conservation efforts on different crops.

The data also show that there are significant gaps in many *ex situ* collections, whether maintained by agricultural research institutions or botanic gardens. The availability of botanical research specimens and genetic sequence data (GSD) and other related data are likewise highly variable among crops, with abundant resources for many crops but substantial gaps for many others.

With respect to the security of PGRFA, while much has already been duplicated in the Svalbard Global Seed Vault, particularly for major cereals, pulses, and a few other crop types, the data show that many of the world's *ex situ* accessions are not documented as safety duplicated. Given the importance of safety duplication, special attention should be given to securing those accessions not currently safety duplicated, including those collections that must be maintained *in vivo* or *in vitro*.

The findings of the study have significant implications that could be applied to the future development of the Treaty's Multilateral System (MLS) of Access and Benefit Sharing and the crops listed in its Annex 1 as well as, potentially, Article 15 collections. As this study has shown, the contribution of crops to food security and interdependence, the two criteria used to design the Multilateral System, are dynamic, with many crops that are important for food security and sustainable agriculture today not currently included in Annex 1. Moreover, additional crops will almost certainly become more important than they are currently. Given the critical role that the use of PGRFA can play in helping ensure food security, sustainable agriculture, and climate adaptation and mitigation, and the value of facilitated access to PGRFA under the Plant Treaty to achieve these aims, it is hoped that the findings of this study will prove useful in helping to guide discussions on coverage of the MLS.

1. Introduction

1.1 The International Treaty on Plant Genetic Resources for Food and Agriculture and development of this study on "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 International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA, also called the Plant Treaty) is the FAO international agreement for the conservation and sustainable use of plant genetic resources for food and agriculture (PGRFA) and the fair and equitable sharing of benefits arising out of their use.

The Plant Treaty relates to PGRFA, so its scope includes the genetic diversity of all the plants used for food and agriculture. Conserving and using this diversity is essential to guarantee food security and sustainable agriculture today and in the future. The provision of baseline data, metrics, and indicators on this diversity is essential for decision-makers at global, regional, and national levels to develop strategies to ensure the adequate conservation and use of these plant genetic resources. The Plant Treaty, through its Article 5, calls for an integrated approach to the exploration, conservation and use of PGRFA.

The Secretariat of the Plant Treaty has established partnerships with the CGIAR Centers, the Global Crop Diversity Trust (Crop Trust), and the botanic garden community around a common interest in strengthening the provision of data and science to inform policymaking regarding PGRFA. The Governing Body of the Plant Treaty recommended the Secretariat and the Crop Trust to further enhance its collaboration and complementarity on scientific and technical matters, including through improved linkages in the updating and implementation of Global Crop Conservation Strategies. The Secretariat previously worked closely together with CIAT and the Crop Trust in the preparation of the study "*Estimation of countries' interdependence in plant genetic resources provisioning national food supplies and production systems*" (Research Study 8) (Khoury *et al.* 2015). The present analysis is a follow-up to the previous partnership, under a plan to be published jointly as a flagship background study for the global PGRFA community. This analysis furthers these longstanding partnerships as well as forms new ones, particularly with the botanic garden community and especially the San Diego Botanic Garden.

An update on the on-going collaboration was provided to the Governing Body in November 2019, at its Eighth Regular Session. Through Resolution 10/2019, para.12, the Governing Body welcomed "the collaboration between the Secretary, the Crop Trust and the International Center for Tropical Agriculture (CIAT) to identify and systematize baseline data of a wide range of crops and their genetic resources that is essential for decision-makers at global, regional and national levels in order to develop strategies to ensure the adequate conservation and use of these plant genetic resources for food and agriculture, including Crop Strategies, and recommend[ed] that the background study resulting from such collaboration and underlying baseline information be made available in a user-friendly manner as soon as possible, including for consideration by the Governing Body at its Ninth Session." (FAO 2019b).

Information on food and agricultural plants is increasingly available but scattered through several information systems, databases, and scientific literature. Data on the status of cultivation, trade, and contribution to food supply of the most important crops worldwide is provided by FAO's Food and Agricultural Statistics Database (FAOSTAT), while FAO's World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture (FAO WIEWS) provides information about the PGRFA conserved and distributed by national and international genebanks around the world. Several other information systems, including the Genesys Plant Genetic Resources portal (Genesys

PGR), Botanic Garden Conservation International's PlantSearch, the Global Biodiversity Information Facility (GBIF), and the Svalbard Global Seed Vault's SeedPortal also provide data on the supply and/or security backup of PGRFA. The Data Store of the Plant Treaty and FAO WIEWS, meanwhile, provide information on the exchange of PGRFA, while FAO WIEWS and the International Union for the Protection of New Varieties of Plants (UPOV)'s PLUTO Plant Variety Database offer information on varietal registrations and/or releases. Various other information systems provide data on these and other metrics related to PGRFA at regional, national, and local levels. The scientific literature supplements these information sources with data and analyses at different scales and timeframes.

The study "*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*" intends to bring together and make widely available, for the first time, pertinent information from these different sources to provide baseline metrics and indicators of the use of food and agricultural crop plants worldwide, as well as information regarding interdependence regarding, demand for, supply of, and security of their genetic resources. The aim is to develop a set of metrics and indicators that provide an evidence base for the international PGRFA community to prioritize conservation and availability for use among crops and PGRFA activities. The methodologies allow these metrics and indicators to be reproducible to enable identification of change over time in status and trends for PGRFA. In addition, the methodologies have been developed to enable future use of data and tools for national-level decision-makers on Treaty implementation, leveraging the knowledge gained at global level for use at the national scale.

The study is one of the main products of this collaborative initiative. The full list of products of this partnership include:

1. This background study paper summarizing and analysing the baseline information gathered
2. A full description of the methodologies and materials used for this study and all metrics calculated (provided in Annex 1 of this study)
3. The full data, code, and results, which will be made available through the Treaty website and other means to enable future use by the PGRFA community and partner organizations. The full data contains more metrics than the ones highlighted in this study, as described in the methodology section
4. An interactive website of the results, including visualizations of the metrics and infographics arising from the study, which will be available through FAO
5. Use of PGRFA metrics for individual crops in the development of Global Crop Conservation Strategies, which are facilitated by the Global Crop Diversity Trust

The information being made available is intended to be used by a wide range of experts and researchers in plant genetic resources. By pooling together, from a wide range of sources, information on plant genetic resources, and making these data available in a user-friendly manner, the initiative enables researchers access to a wide variety of pertinent metrics in one combined resource. It is important to highlight that the present work does not create new information systems but gathers and processes in a standardized manner data from various relevant systems. It does not substitute PGRFA indicators (i.e., SDGs 2.5 or 15.6) gathered through country-driven efforts or the Global Crop Conservation Strategies facilitated by the Crop Trust that provide a comprehensive overview for specific crops. Moreover, while these data will be critical for developing future strategies for conservation and use of plant genetic resources, they are most appropriately complemented by other sources of information and analysis that cannot be made available in the form of reproducible metrics, as evident in the development of the Global Crop Conservation Strategies.

This initiative has created an initial methodology and set of metrics with the intention to create a benchmark that can be replicated periodically (i.e., every 5-10 years). Such an iterative process would provide valuable insights in how metrics change for individual crops. While changes for some crops (in particular major staples) and some metrics are likely to remain relatively consistent, it is probable that metrics for various other crops will evolve considerably, demonstrating the dynamism in the conservation, use and availability of plant genetic resources.

1.2 Relevant background on plant genetic resources for food and agriculture

1.2.1 The diversity of crop plants

There are more than 350,000 currently described plant species (Antonelli *et al.* 2020), with thousands of newly identified species still being added to the global list every year (Cheek *et al.* 2020). Of these known plants, more than 7000 documented species (Antonelli *et al.* 2020) and perhaps up to 30,000 plants in total (Wilson 1992) may be considered edible by humans, with at least 7000 having been cultivated to some degree for food and agricultural purposes (Khoshbakht and Hammer 2008; Leibniz Institute of Plant Genetics and Crop Plant Research 2022).

Yet only a small fraction of these plants feed humanity in the present. Statistical information published by the FAO both for individually measured crops as well as those included within generalized commodity categories – in combination assumedly representing much of the human diet worldwide – is recorded for approximately 255 plants – including around 26 cereals, 17 roots and tubers, 26 pulses, 44 vegetables, 69 fruits, 14 nuts, 28 oils, 24 herbs and spices, 3 sugars, and 4 stimulant crops (this analysis; see https://docs.google.com/spreadsheets/d/1GHH4lp199BhrVOIr4E61C4DxHgD23KNHKNliuhfzNPk/edit?usp=sharing for the full crop list). More extreme calculations of the same data, generally focused on contribution to calories, lead to assertions that as few as a handful of staple crops provide the bulk of the world's food (FAO 2019).

Regardless of the precise number, this relatively small list of highly globalized crops has clearly come to dominate food supplies worldwide, leading to increasing homogeneity in the global diet (Khoury *et al.* 2014, 2016). Diversity within these crops - both in terms of their varieties and the genetic and phenotypic variation within and among them - is widely considered to have declined in farmers' fields over the past 100 years (FAO 2019; Khoury *et al.* 2021). Both trends are commonly cited as central reasons why the conservation and sustainable use of PGRFA is essential to humanity's future.

To arrive at a more comprehensive account of contemporary food and agricultural plants, additional information is required. FAO statistics also report (production and/or trade) information for 20 fiber crops, 3 forages, and 9 industrial crops. A survey of the Plant Treaty's Annex 1 and CGIAR mandate crops adds dozens of additional forages and a few more food crops, while accounts of other globally significant fruits, vegetables, roots and tubers, and herbs and spices easily add another 30 crops. By our calculations, this more inclusive scope of food and agricultural plants totals around 350 crops (including forages); these are the focus of investigation within this Study (see https://docs.google.com/spreadsheets/d/1GHH4lp199BhrVOIr4E61C4DxHgD23KNHKNliuhfzNPk/edit?usp=sharing for the full crop list).

The crops studied here represent those for which considerable amounts of information regarding their use as well as important metrics around demand for, supply of, and security of their PGRFA exists and is relatively readily available (see the extended Methodology and data sources Annex for a full description). This said, two observations must noted.

First, these cultivated plant species have "wild cousins" that are referred scientifically as crop wild relatives (CWR). As sources of new genetic diversity, crop wild relatives have been used for many decades for plant breeding, contributing a wide range of beneficial agronomical and beneficial traits. Their utilization is expected to increase because of ongoing improvements in information on species and their diversity and advances in breeding tools (Castañeda-Álvarez *et al*. 2016). A curated database on the taxonomy, distributions, and genetic relationships regarding crop wild relatives of many of the world's food and agricultural crops is available through GRIN Global Taxonomy (USDA NPGS 2022), building on efforts made by national and international partners over the previous decade.

Second, it must be noted that many hundreds or even thousands of food and agricultural plants significant to specific regions and localities around the world are outside the scope of this Study. The Mansfeld's World Database of Agriculture and Horticultural Crops contains information on 6,100 crop plant species, including forages but excluding forestry and ornamental plants (IPK Gatersleben 2022). Such crops are often called "Neglected and Underutilized Species" (NUS), among other terms, although they are important and thus hardly neglected by the communities they are native to; it should also be noted that various crops within the 355 studied here may be considered by some as NUS. Beyond what is traditionally recognized as food and agriculture, a wide diversity of other plants is also cultivated for ornamental, medicinal, forestry, restoration, and other purposes. These are also beyond the scope of this present Study.

1.2.2 A brief history of global efforts on PGRFA conservation and use

PGRFA, including seeds and other reproductive propagules of food and agricultural crop plants and their wild relatives, are critically important resources underpinning the productivity, quality, sustainability, resilience, and adaptive capacity of food and agricultural systems (Hoisington et al. 1999; Esquinas-Alcázar 2005; Gepts 2006). Farmer varieties (landraces) and their wild relatives have been the basis of agricultural production for over 10,000 years (Larson *et al.* 2014). These plants began to be recognized by scientists as valuable resources in the late 19th and early 20th centuries (Baur 1914; Zeven 1998), in parallel with the rediscovery of Mendel's laws of inheritance and the subsequent development of modern genetics (Harwood 2016; Khoury *et al.* 2021). *Ex situ* repositories (genebanks) were subsequently established to maintain genetic resource (germplasm) collections to support the breeding of new crop varieties (Vavilov 1926; Lehmann 1981; Saraiva 2013).

In parallel, concerns began to be raised over the loss of crop diversity from farmers' fields and from wild habitats due to rapid agricultural, environmental, socioeconomic, and other changes (Baur 1914; Harlan and Martini 1936). These concerns were voiced at the Food and Agricultural Organization (FAO) of the United Nations and elsewhere in light of the large-scale replacement of traditional crop varieties by modern cultivars worldwide during the "Green Revolution" (Bennett 1964, 1968; Frankel and Bennett 1970; Frankel 1974; Pistorius 1997; Fenzi and Bonneuil 2016) and because of increasing awareness of the susceptibility of modern crop cultivars to pests and diseases as a consequence of their genetic uniformity (Tatum 1971; National Research Council 1972; U.S. Senate 1980).

These concerns resulted in the expansion of efforts around the world to collect and maintain plant genetic resources *ex situ* (Plucknett et al. 1987). At the international level, the International Board for Plant Genetic Resources (IBPGR) was established in 1974 to coordinate a global initiative to conserve threatened genetic resources. Collaborating with national and other partners, IBPGR supported the collecting of over 200,000 samples of landraces, crop wild relatives, and other materials in 136 countries between 1975 and 1995, and helped to establish international genebank collections to maintain these samples (Thormann *et al.* 2019).

Over the course of the 1980s and 1990s, while national, regional, and international *ex situ* collections were amassed, there was growing concern about the vulnerability of these collections, due largely to insufficient funding and infrastructure. Genebanks were encouraged to duplicate their holdings to mitigate these challenges as well as to protect them from natural disasters, war, and civil strife (Holden 1984; Lyman 1984; Peeters and Williams 1984).

At the same time, PGRFA were increasingly recognized by the international community as important not only for breeding but also in underpinning the resilience and adaptive capacity of agrarian communities and their agroecosystems (Mijatović *et al.* 2013; Fenzi and Bonneuil 2016; Sirami *et al.* 2019). *In situ*/on-farm conservation support increased (Brush 1991; Wood and Lenne 1997; Bellon

2004), though some questioned its efficacy in the face of widespread environmental and societal change (Frankel and Soule 1981; Zeven 1996; Peres 2016).

In the 1990s concern about the loss of biodiversity, in all its forms, became a global priority and resulted in the adoption of the Convention on Biological Diversity (CBD), which mandated its conservation, sustainable use, and the fair and equitable sharing of the benefits arising from such use (CBD 1992). With the coming into force of the CBD, earlier international agreements on plant genetic resources (e.g., FAO 1983) were renegotiated, resulting in the adoption in 2001 of the legally binding International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA, also known as the Plant Treaty) (FAO 2002). In 2004, the Global Crop Diversity Trust was established by FAO and the Consultative Group on International Agricultural Research (CGIAR) to help provide long-term funding for the *ex situ* conservation of PGRFA (Esquinas-Alcázar 2005).

There are now approximately 1750 germplasm collections worldwide (FAO 2010), around half of which are international, national, and regional base/long-term collections (FAO 2022); as a whole these maintain over seven million samples (FAO 2010). Safety duplication of a substantial proportion of this diversity is accomplished among genebanks and at the global backup in the Svalbard Global Seed Vault (Westengen et al. 2013), where over 1.1 million samples are now duplicated (Norwegian Ministry of Agriculture and Food 2022; NordGen 2022). Genetic resources are also conserved by botanic gardens, universities, nonprofits, community seedbanks, local conservation networks, and private companies, while plant breeding and other research programs also store genetic resources, at least for short periods, (Miller *et al.* 2015; Vernooy *et al.* 2017). Various initiatives continue to focus on *in situ* and/or on-farm conservation (e.g., FAO 2022, Stenner *et al.* 2016; AGUAPAN 2021; Global Environmental Facility 2021). Many hundreds of thousands of plant genetic resource samples are distributed annually by national and international institutions (Halewood *et al.* 2020; Lusty *et al*. 2021; Khoury *et al.* 2022).

These efforts around PGRFA conservation and use have been both substantial and global, but gaps continue to persist (FAO 2010; Castañeda-Álvarez *et al.* 2016; Khoury *et al.* 2021, 2022; Ramirez-Villegas *et al.* 2022). Two Global Plans of Action for Plant Genetic Resources for Food and Agriculture have been adopted by FAO councils to address these gaps (FAO 1996; FAO 2011). In recent decades, the CBD and the United Nations Sustainable Development Goals have also set targets for enhanced conservation of plant genetic resources (CBD 2002, 2010; United Nations 2015). Current negotiations aim to renew these targets, which were not met by the original (2020) deadline (Díaz *et al.* 2020).

2. Methodology and data sources summary

Crop-level metrics on the use of food and agricultural plants worldwide and interdependence regarding, demand for, supply of, and security of their genetic resources were created through the compilation, processing, and standardization of data from a wide number of pertinent global information databases and data sources, supplemented by information from regional, national, and local datasets and published literature. Emphasis was placed on curated, openly accessible, comprehensive data sources likely to be available in updated forms in the future, so that these methodologies can be reproduced to discern change over time.

The main global database sources for this study included: FAO's Food and Agricultural Statistics Database (FAOSTAT), the FAO World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture (FAO WIEWS), the Data Store of the International Treaty on Plant Genetic Resources for Food and Agriculture, the International Union for the Protection of New Varieties of Plants (UPOV)'s PLUTO Plant Variety Database, the Genesys Plant Genetic Resources portal (Genesys PGR), Botanic Garden Conservation International's PlantSearch database, the Global Biodiversity Information Facility (GBIF), the Svalbard Global Seed Vault's SeedPortal, Google

Scholar, Wikipedia (pageviews), and the National Center for Biotechnology Information (NCBI)'s Entrez database.

These metrics were organized into five domains - crop use, interdependence (regarding genetic resources), demand (for genetic resources), supply (of genetic resources), and security (of genetic resources). Within these domains, individual metrics were further categorized within related groups and thematic components.

Crop-level results are available for each metric and as average values across groups, components, and domains. These results were produced in real value, indicator value (i.e., values generally between 0 and 1, often in proportion to all other crops), and normalized indicator value forms (normalized across pertinent crops for each metric, with the bottom crop at 0 and the top crop at 1). All indicator and normalized indicator values were calculated with low numbers (close to 0) representing a low or poor status, and high numbers (close to 1) representing a high or good status.

Metrics were generated for a total of 355 food and agricultural plants (see https://docs.google.com/spreadsheets/d/1GHH4lp199BhrVOIr4E61C4DxHgD23KNHKNliuhfzNPk/edit?usp=sharing), a list which is inclusive of all those covered in FAOSTAT, in Annex 1 of the International Treaty, and of CGIAR mandate crops, as well as other crops deemed internationally significant per our methodologies and for which sufficient data was available. These crops were categorized into 13 crop use types, including 10 food uses (cereal, fruit, herb and spice, nut, oil, pulse, root and tuber, stimulant, sugar, and vegetable), as well as fiber, forage, and industrial crops. Indicator values and normalized indicator values were calculated both across all crops, as well as across each of the crops within each crop use type. Figures in the results section of this study show metrics per crop use type, for eight crop use types of particular interest to each metric.

A total of 98 global-level metrics were calculated, including 51 metrics on crop use (within 6 components and 15 groups); 22 metrics on interdependence (within 2 components and 6 groups); 7 metrics on demand (within 4 components and 4 groups); 16 metrics on supply (within 6 components and 7 groups); and 2 metrics on security (within 1 component and 1 group).

Not all possible metrics where systematic information potentially exists were explored. Metrics on demand for PGRFA as measured by patent applications remains to be investigated and possibly developed, for example. Many other sources of information were explored during this study but were not integrated into the analysis at the present time due to insufficiency or inaccessibility of the data. Other potential sources of data were noted but not explored in depth for this present analysis. A process of production of results at a national rather than global scale was also investigated for pertinent metrics but are not reported here. A full description of methods and materials for this study, as well as other sources of information explored or noted as potentially useful, is available in **Annex 1** of this study. The full data, code, and results will be made available at FAO; at this time the code is available at https://github.com/CIAT-DAPA/itpgrfa_crop_indicator_code and main results at https://drive.google.com/drive/folders/19Omcz-KuKrMxaUHfX4duRVjzitcKKmgp?usp=sharing. An interactive website of the results will be made available at FAO.

3. Results

3.1 Use of food and agricultural crop plants

3.1.1 Use of food and agricultural crop plants in terms of global production, trade, and contribution to food supply

A total of 280 crops assessed in this study are reported in FAOSTAT production metrics (277 in the value of production metric), either specifically or within general crop commodities. Likewise, 239 of the crops are reported in FAOSTAT trade metrics, and 252 crops are reported in FAOSTAT food supply metrics, again either directly or within general commodities. After disaggregating values for general commodities (such as “Vegetables, fresh nes” in production metrics and “Vegetables, Other” in food supply metrics) into their specific crop components, the contribution of each assessed crop to global agricultural production (in terms of harvested area (Ha), production quantity (tonnes), and production value (current thousand US$); to global trade (in terms of export quantity (tonnes), export value (1000 US$), import quantity (tonnes), and import value (1000 US$)); and to the global food supply (in terms of calories (kcal/capita/day), protein (g/capita/day), fat (g/capita/day), and food weight (g/capita/day)) was calculated as an annual average value between years 2015 to 2018.

The most utilized crops in terms of global production (tonnes) for eight different crop use types of interest are presented in **Figure 1.** The results are presented as the proportion of the value of the crop, compared to all crops per crop use type.

In terms of the most utilized crops across all metrics and all crop use types, the range of metrics generally provide a consistent picture of the primary reliance in global production systems, trade, and food supplies on major cereal, oil, and root and tuber crops such as wheat, rice, maize, soybeans, oil palm, potatoes, and cassava. Specific metrics further provide insights into the importance of other crops for those particular uses. For example, metrics based on weight, including global production (tonnes) and food supply quantity (g/capita/day), also document the global use of (heavy) fruits such as tomatoes, citrus, onions, and apples, while the protein metric in global food supplies further documents the importance of pulse crops. Production value and trade value metrics, meanwhile, also document the global use of sugar, fruit, herb and spice, and stimulant crops (such as tobacco, cocoa, and coffee). As a whole, significant crops in terms of global agricultural production, trade, and food supplies evidently included a broad range of plants from a variety of crop types.

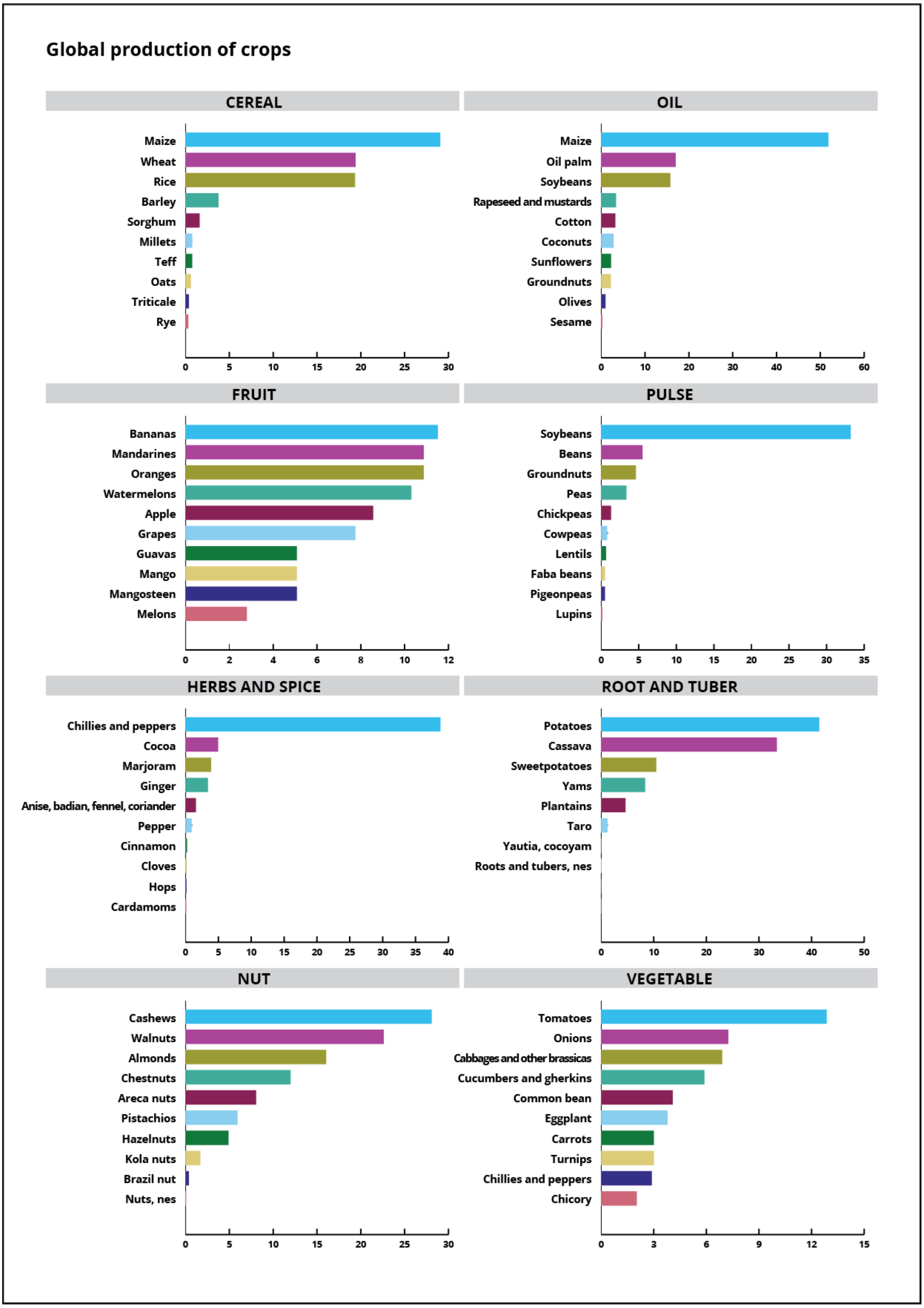

Figure 1: Use of crops in global agricultural production as measured in terms of production quantity. Metrics are presented per crop as a proportion of total production across all crops within each crop use type. The subfigures

display the ten crops with largest use values per crop use type. For crops such as maize or soybeans with multiple uses, these are included in all relevant use type categories; values for these crops are total global, not separated by specific use. Values for general crop commodities such as ‘Roots and tubers, nes’ are presented as the value of each specific crop included within the commodities (each of these crops has the same value), not as a sum across all crops; due to space limitations each individual crop within these commodities could not be listed within the figure. ‘Roots and tubers, nes’ includes arracacha, arrowroot, chufa, Jerusalem artichoke, maca, mashua, mauka, oca, sago palm, and ulluco; ‘Nuts, nes’ includes butter-nut, macadamia nut, pecan, pili nut, and pine nut.

Global summary agricultural production, trade, and food supply statistics are useful to identify the most utilized crops globally, but do not provide clear information on the geographic extent or evenness of the use of crops worldwide. To understand the current extent of geographic spread of these assessed crops, for each crop we calculated the number of countries for each production, trade, and food supply metric in which the crop is produced, traded, or used in the food supply at a significant scale, using national-scale data from FAOSTAT. For our purposes, significance meant being within the top 95% of crops reported used in the country for the production, trade, or food supply purpose.

The most geographically spread crops in terms of global production (tonnes) for eight different crop use types of interest are presented in **Figure 2**. The results are presented as the proportion of countries in which the crop is significant compared to the total number of countries reported in FAOSTAT (a total of 205 countries were reported in the production data, 198 countries in the trade data, and 173 countries in the food supply data).

In terms of the most geographically spread crops across all metrics and all crop use types, the range of metrics again provide a fairly consistent picture of the primary reliance in global production systems, trade, and food supplies on major cereal, oil, pulse, and root and tuber crops. Additional crops, not as visible in global summary statistical data, are also evidently widespread for certain metrics such as production quantity as well as for fat, calories, and food weight metrics.

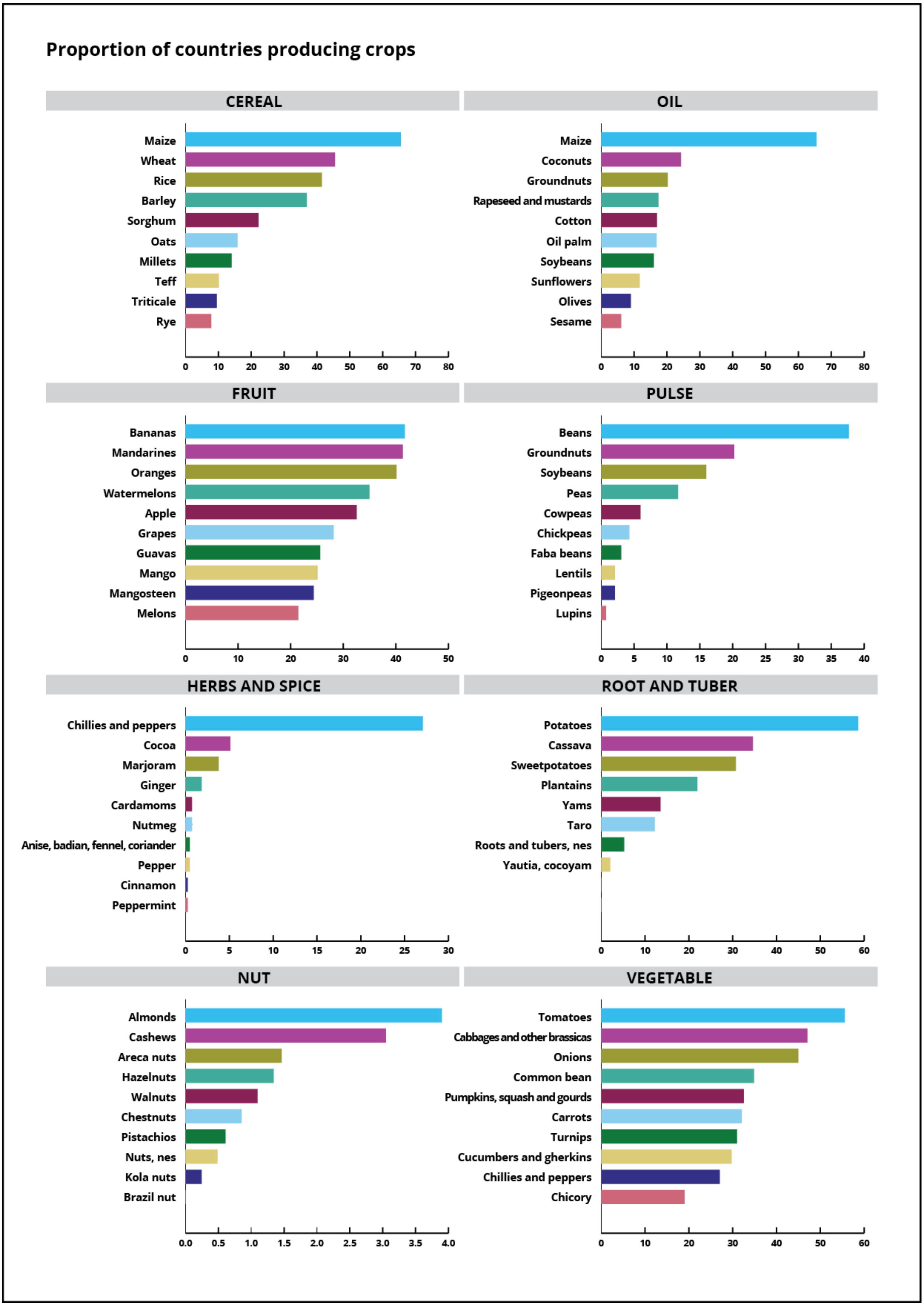

Figure 2: Geographic spread of crops in global agricultural production as measured in terms of the proportion of countries in which the crop is significant compared to the total number of countries reported in FAOSTAT (a

total of 205 countries were reported in the production data). The figures display the ten crops with largest geographic spread values per crop use type. For crops such as maize or soybeans with multiple uses, these are included in all relevant use type categories; values for these crops are total global, not separated by specific use. Values for general crop commodities such as 'Nuts, nes' represent the value of each specific crop included within the commodities (each of these crops has the same value), not as a sum across all crops; due to space limitations each individual crop within these commodities could not be listed within the figure. 'Nuts, nes' includes butter-nut, macadamia nut, pecan, pili nut, and pine nut; 'Roots and tubers, nes' includes arracacha, arrowroot, chufa, Jerusalem artichoke, maca, mashua, mauka, oca, sago palm, and ulluco.

To understand the current evenness or balance worldwide of production, trade, and food supply uses for each crop, we compared each crop's production, trade, and contribution to food supply across world regions. The most geographically even/balanced crops in terms of global production (tonnes) for eight different crop use types of interest, are presented in **Figure 3**. The results are presented based on a mathematical metric of evenness called the Gini coefficient, in this case with values close to 100 representing high evenness in use across regions, and those close to 0 representing unevenness.

In terms of the most geographically even/balanced crops across all metrics and all crop use types, the range of metrics provide somewhat different insights than those offered by the global summary and geographic spread analyses. Note that those crops with the highest evenness values are not necessarily the most utilized around the world, but simply those with the greatest balance in use across world regions.

For production metrics, many fruit, vegetable, and pulse crops, as well as cereals such as wheat, maize, oats, sorghum, and barley, are produced quite evenly across world regions. For trade, various fruit and nut crops, as well as tobacco, are quite evenly exported, while assorted fruit, vegetable, and herb and spice crops, as well as wheat, tobacco, and oil palm, are among those most evenly imported. In contribution to regional food supplies, the most balanced crops across world regions appear mainly to be fruits and vegetables.

These geographic spread and evenness assessments complement the global value metrics by providing additional insights on extent and balance of use worldwide. This may be particularly useful as a means by which to highlight crops that are produced, traded, and/or consumed extensively worldwide, yet in relatively small quantities. For crops with significant use in many countries, and/or with considerable evenness in use across world regions, perhaps particularly regarding production, these metrics may indirectly indicate a strong degree of interdependence among countries and regions regarding PGRFA.

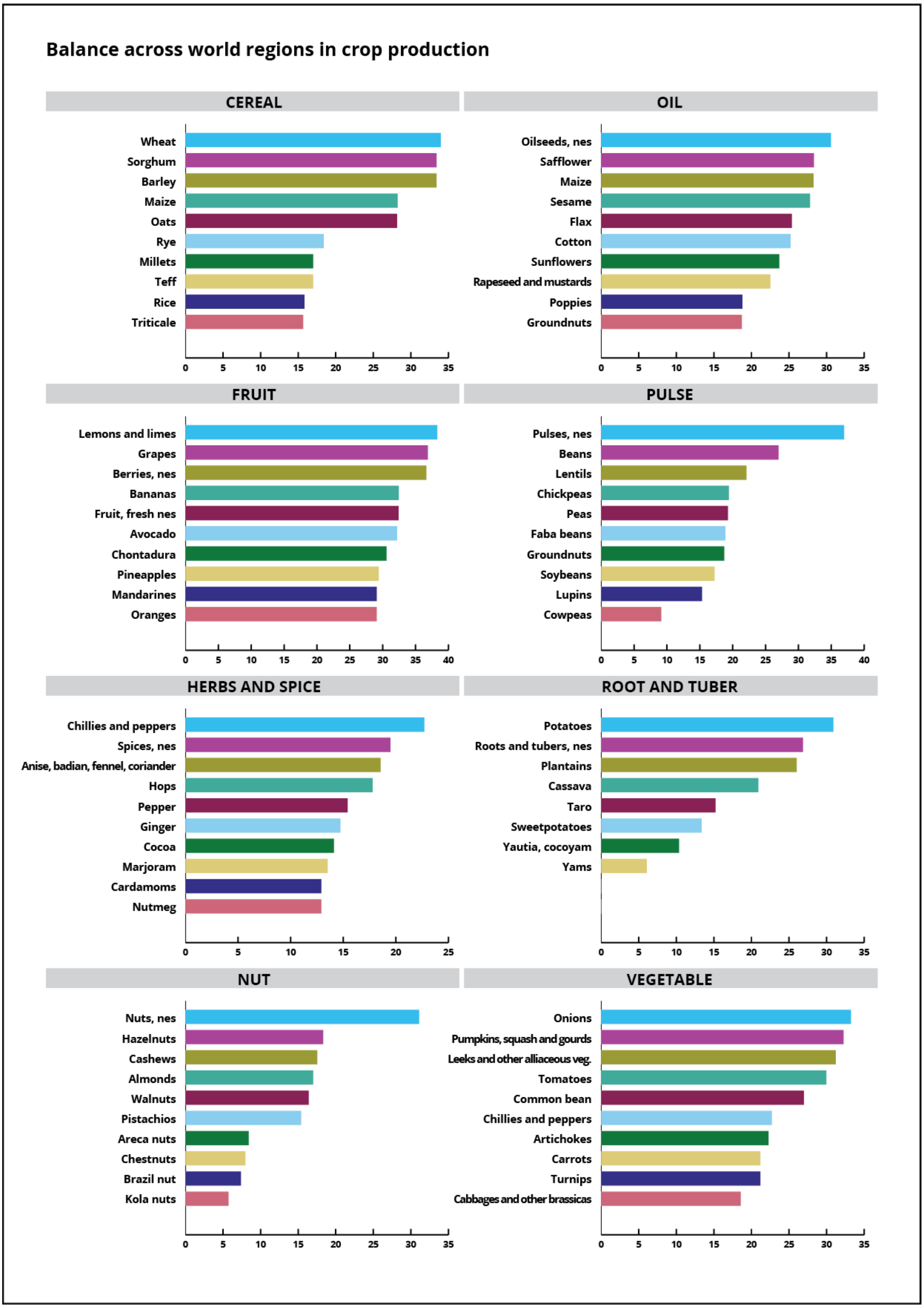

Figure 3: Geographic evenness of crops in terms of agricultural production in different world regions. The results are presented based on a mathematical metric of evenness called the Gini coefficient, in this case with

values close to 100 representing high evenness in production across regions, and those close to 0 representing unevenness. The figures display the ten crops with highest evenness values per crop use type. For crops such as maize or soybeans with multiple uses, these are included in all relevant use type categories; values for these crops are total global, not separated by specific use. Values for general crop commodities such as ‘Berries, nes’ represent the value of each specific crop included within the commodities (each of these crops has the same value), not as a sum across all crops; due to space limitations each individual crop within these commodities could not be listed within the figure. ‘Berries, nes’ includes huckleberry, mulberry, and myrtle; ‘Fruit, fresh nes’ includes azarole, babaco, elderberry, jujube, litchi, loquat, medlar, pawpaw, pomegranate, prickly pear, service tree, strawberry tree, and tamarind; ‘Spices, nes’ includes bay leaf, dill, fenugreek, saffron, thyme, and turmeric; ‘Nuts, nes’ includes butter-nut, macadamia nut, pecan, pili nut, and pine nut; ‘Oilseeds, nes’ includes beech nut, candlenut, carapa, chontadura, mahuwa, noog, oiticica, perilla, physic nut, pongamia oil, purging croton, and shala tree; ‘Pulses, nes’ includes grasspea, jack bean, jicama, lablab, sword bean, velvet bean, and winged bean; ‘Roots and tubers, nes’ includes arracacha, arrowroot, chufa, Jerusalem artichoke, maca, mashua, mauka, oca, sago palm, and ulluco.

Information on crops’ contributions to national food supplies over the ca. 50 years from 1961 to 2009, based on FAOSTAT data, indicates that considerable change has occurred in terms of the diversity and abundance of crops globally. Khoury *et al.* (2014) documented an increasing richness of internationally traded crop commodities in national food supplies, and greater evenness in the contribution of the individual commodities to these supplies. While major cereals and sugar continued to be dominant, oil crops in particular increased enormously in their availability in food supplies, while regionally important staple cereals and starchy root and tuber species became further marginalized. These shifts have led to significantly greater similarities (i.e., homogeneity) among national food supplies around the world.

This current assessment demonstrates that further change in the use of crops worldwide, not only in terms of contribution to food supplies but also regarding agricultural production and trade, is visible even within the four years analyzed (2015 to 2018). The results are presented as the relative change in the value of each crop from 2015 to 2018. Note that those crops with the greatest relative change are not necessarily the most utilized around the world, but simply those with the greatest growth (or decline) in use over the period.

In terms of the crops that have changed the most in the period, each of the metrics provides different insights, including not only for those crops with the greatest positive change, but also those with the most marked declines (although for all metrics, there were many more crops that increased in use in the time period than there were crops that declined). Increases in production systems were especially visible for many herb and spice, nut, fruit, and pulse crops, while decreases were evident in an assortment of crops and crop use types. Increases in food supply metrics were particularly visible in crops such as coffee, cocoa, sunflower, dates, and various herbs and spices, while declines were seen in various root and tuber crops such as sweetpotatoes, cassava, and potatoes, as well as for sorghum, among others. Declines in trade were also visible for crops such as sorghum and cassava.

3.1.2 Research significance of food and agricultural crop plants

Global tracking systems of research publications provide insights into the degree of research activity for the assessed crops. We calculated the number of research publications for each crop found in the Google Scholar online system, published between 2009 and 2019, by querying the titles of research articles based on each crop’s common name(s), genus, and taxon (scientific) name (separately). Likewise, we queried the PubMed Central online archive of biomedical and life sciences journal literature for full-text results for each crop, based on its scientific name.

The most researched crops in terms of publications in Google Scholar based on appearance of the common name of the crop in the article title, for eight different crop use types of interest, are presented in **Figure 4**. The results are presented as the proportion of the number of publications of the crop, compared to all crops per crop use type.

All 355 assessed crops were found to have research publications. Across the crops, these totaled a sum of 1,162,595 publications if queried by crop common name(s), 1,440, 652 publications if by genus, and 387,407 publications if queried by taxonomic name in Google Scholar. In PubMed Central, a total of 2,401,453 publications were found across all crops.

Assessing research activity results across all crops, crop use types, and search criteria, publication focus on crops appears to parallel statistics on use of crops in global production systems, trade, and food supplies. This said, other areas of focus were also evident. These include on industrial, fiber, and multi-use crops such as rubber, hemp, and sugar beets, on model crops in science such as tobacco, on traditional crops with increasing research interest for alternative applications such as kola nuts and physic nut, and on an assortment of fruits such as citrus (various), mango, and papaya. These research trends may be associated with a wide variety of factors including the development of new industries, scientific innovations, public research funding priorities, and more. As a whole, significant crops in terms of research publications evidently include a very broad range of plants from a variety of crop use types.

Research citations for crops

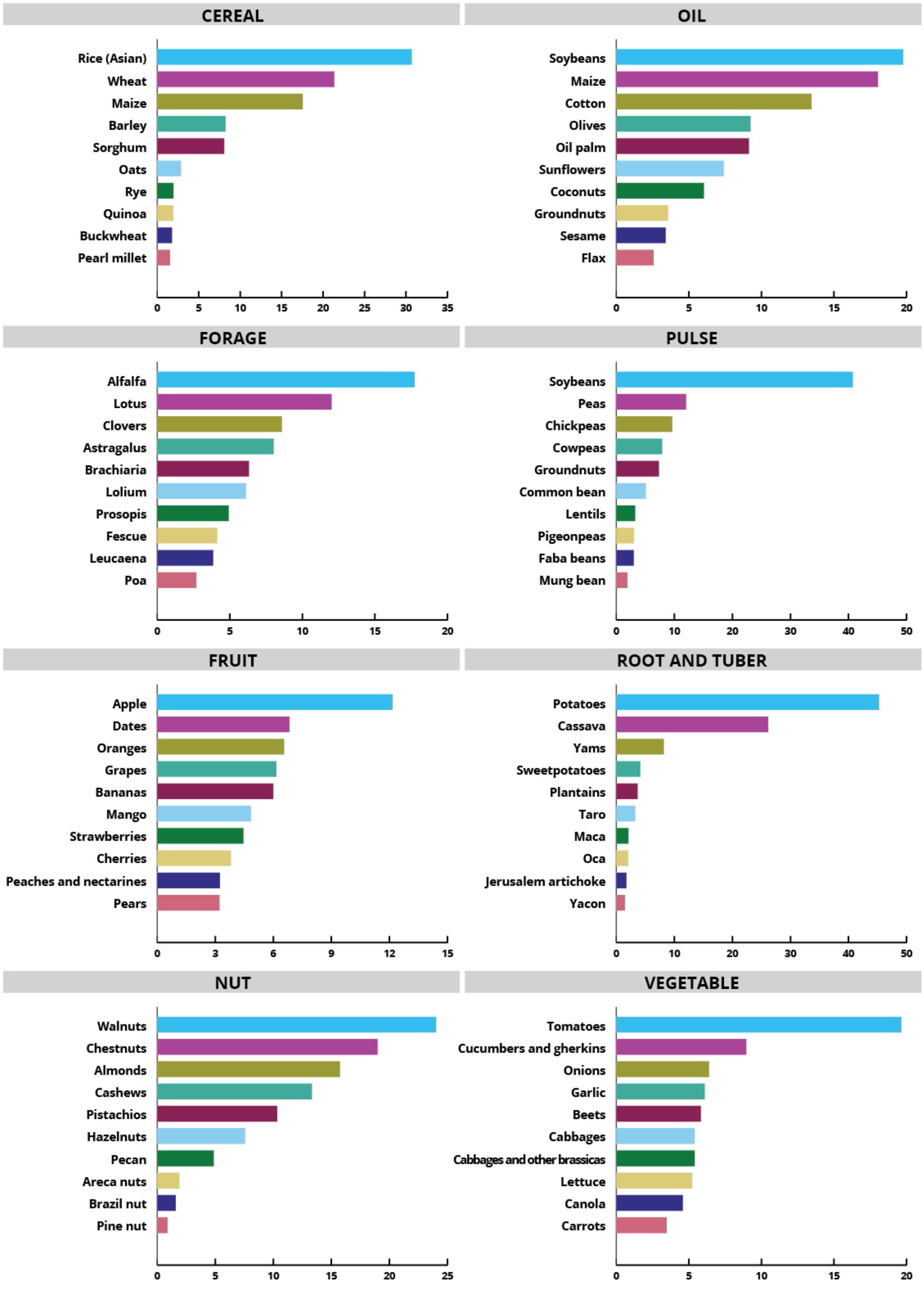

Figure 4: Research significance of crops as measured in terms of Google Scholar citations based on appearance of the common name of the crop in the article title. Metrics are presented per crop as a proportion of total citations across all crops within each crop use type. The subfigures display the ten crops with the highest proportions of citations per crop use type. For crops such as maize or soybeans with multiple uses, these are included in all relevant use type categories; values for these crops are total global, not separated by specific use.

3.1.3 Public interest in food and agricultural crop plants

Internet search and engagement activity may serve as useful information regarding public interest in food and agricultural crop plants. We calculated the degree of public interest in learning about assessed crops based on the number of pageviews of the Wikipedia website for the entirety of the year 2019, querying Wikipedia by each crop's common name(s), genus, and taxon (scientific) name (separately). The results are presented as the proportion of the number of pageviews of the crop, compared to those for all crops.

All 355 assessed crops were found to have pages on Wikipedia viewed by the public. Across the crops, these totaled a sum of 120,743,389 pageviews if queried by crop common name(s), 30,621,492 pageviews if by genus, and 24,758,059 if queried by taxonomic name.

Assessing pageview results across all crops, crop use types, and search criteria, public interest in crops is clearly not solely focused on global staple cereals and other dominant crops in global production systems, trade, and food supplies. Instead, views of Wikipedia pages on fruits and vegetables (e.g. artichokes, avocado, bitter gourd, cabbages, citrus (various crops), durian, jackfruit, passionfruit, pawpaw, persimmons, strawberries, and tomatillo) were among the most common, as well as those for herbs and spices (e.g. cardamoms, coriander, lavender, peppermint, saffron, thyme, turmeric, and vanilla), plants used to make alcoholic beverages or for stimulant or narcotic uses (agave, coffee, cocoa, elderberry, maca, and poppies), and a variety of other plants (e.g. citronella, faba beans, hemp, quinoa, pyrethrum, snake plant, and tallowtree). These public interest trends may be associated with a wide variety of factors including world events, media articles, interest in cultivation or nutritional values, social influencer activity, and more. As a whole, significant crops in terms of public interest evidently include a very broad range of plants from a variety of crop use types.

Box 1: The oil crop revolution

While changes over time in the crops contributing to the human diet are not comprehensively documented, evidence suggests both that enormous change has occurred historically, and that this trend continues in the present. Assessing the crops contributing to national food supplies worldwide from 1961 to 2009, Khoury *et al.* (2014) documented an increasing richness of internationally traded crop commodities in national food supplies, and greater evenness in the contribution of the individual commodities to supplies, including a diminished dominance of the formerly most important staple, as a result of economic development, demographic change, and globalization.

Oil crops in particular increased in their availability in food supplies during this time, while regionally important staple cereals and starchy root and tuber species became further marginalized. These shifts have led to greater similarities (i.e., homogeneity) among national food supplies around the world, likely accompanied by losses of locally unique crop species diversity (Khoury *et al.* 2021). Greater numbers of commodity crops in national food supplies have been attributed primarily to increased international trade (Aguiar *et al.* 2020), even as diversity in import partners may have narrowed (Kummu *et al.* 2020), potentially indicating both increasing interconnectedness among, and vulnerabilities within, national food systems.

Among the changes in global crop diversity evident in the past half century, the expansion of oil crops stands out as the most significant. In just two decades (1990 to 2010), the world's production of the two most dominant oil crops — soybeans and oil palm — more than doubled (Byerlee *et al.* 2016). The palm oil trade is the third biggest of all crop commodities, with products from this tropical crop now distributed in almost all the world's countries. Soybeans, meanwhile, have risen to the top of this list due to increase in demand both as a consumable oil as well as for animal feed and other purposes (Byerlee *et al*. 2016).

This rapid expansion in oil crops has led to human health and social concerns due to widespread overconsumption (Popkin 2006; Pingali 2007; Kearney 2010; Byerlee *et al*. 2016). Major environmental challenges have also been created, including extensive deforestation (Vijay 2016), and significant greenhouse gas emissions (Alcock *et al.* 2022). Further, and unlike the Green Revolution, where production changed worldwide (Pingali *et al.* 2012), cultivation of these "oil crop revolution" crops has thus far been more restricted geographically, with a handful of countries including Brazil, Argentina, Malaysia, and Indonesia currently providing most of the supply (Byerlee *et al.* 2016).

Current projections indicate that soybeans, oil palm, and other major oil crops including sunflowers, groundnuts, and rapeseeds and mustards are likely to continue to expand in global food supplies (Pacheco *et al.* 2017) and in terms of the geography of their production, for example with strong growth projected in Africa (Byerlee *et al.* 2016). A major challenge will be managing this growth while necessarily moving toward greater product quality and environmental sustainability (Byerlee *et al*. 2016; Voora *et al*. 2020). Expanding the use of diverse PGRFA in these crops is important to this future growth, including in combating emerging pests and diseases, increasing resource use efficiency, raising yields and creating faster production, adapting to new production areas, and deriving healthier oil products (Byerlee *et al*. 2016; Alcock *et al*. 2022).

The use of oil crop PGRFA will also be essential to further diversification in the number of important crops in the sector. Though different regions have their preferred consumable oils, vegetable oils are typically comparable substitutes for one another (Byerlee *et al*. 2016). Rapid recent growth in the supply of avocado oil (Flores *et al.* 2019) and various tree nut oils (Jinadasa *et al.* 2022) provides evidence for further opportunities for new oil crops, while also highlighting the need for emphasis on product quality and minimization of environmental impacts (Green and Wang 2020; Maestri *et al.* 2020; Cervantes-Paz and Yahia 2021).

Box 2: Plant based protein and meat substitutes and analogs

While legume and other high protein crops have played a primary role in human nutrition since the dawn of agriculture, they have been given a new boost through the development of plant-based meat substitutes and analogs (Lemken *et al.* 2019; Tziva *et al.* 2020; Cusworth *et al.* 2021; Ferreira *et al.* 2021). This trend, and the underpinning momentum toward healthier food as well as environmental sustainability that have motivated it, have opened new opportunities for the cultivation of these plants, which were for some time considered mainly foods for those that could not afford meat (Castro-Guerrero *et al.* 2016).

Modern meat analogs are plant-based replacements of animal meat, developed to mimic the taste and texture of ground beef, sausage, chicken, and other meat products (Kyriakopoulou *et al.* 2019). These analogs typically have high water concentrations, consist of 10-25% vegetable protein, and have small proportions of flavors, fats/oils, and binding and coloring agents (Egbert and Borders 2016). Modern meat analogs may represent an easier opportunity for meat consumers to decrease their meat consumption than to transition directly to traditional plant-based protein crops and products (Kumar *et al.* 2017; Hoek *et al.* 2011), although they present some deficiencies in terms of protein balance and quality compared to their animal protein equivalents (Gorissen *et al.* 2018; Hertzler *et al.* 2020).

For meat analog purposes, pea protein is a current frontrunner in terms of functional properties and wide range of potential product applications (Krefting 2017; Kyriakopoulou *et al.* 2019; Boukid *et al.* 2021). Peas have several favorable attributes as a plant-based protein source: the crop has a high protein digestibility-corrected amino acid score (PDCAAS), it is easily broken down into its functional components of protein, starch and fiber, and its cultivation is considered environmentally friendly. Current pea production occurs in over 100 countries, and the global pea protein market was worth $1.8 billion in 2021; this is projected to reach $4.5 billion by 2027 (IMARC 2022).

While peas have recently risen in research focus and consumer popularity due to the burgeoning meat substitute and analog markets, their further potential depends, in part, on the conservation, access to, and use of the crop's PGRFA, all of which have current gaps (Coyne *et al*. 2020). The same is often true for other major pulses (Ferreira *et al*. 2021; Bauchet *et al*. 2019; Considine *et al*. 2017) and certainly so for the many dozens of lesser-known leguminous crops that could play a larger role in human protein provision given further research and action, both in terms of supply and demand (Cheng *et al*. 2019; Popoola *et al.* 2022).

Beyond legumes, there continues to be significant interest in the further development of alternative plant-based protein sources within the larger transition toward healthier and more sustainable food. Algal proteins have high protein content and a wide range of useful functional properties such as gelation, water and fat absorption, emulsification, and foaming capacity (Chronakis and Madsen 2011), as well as extremely fast production cycles (Bleakley and Hayes 2017). Intriguingly, algal proteins can balance those amino acids present in pulses and other plants, as the limiting amino acids in many legumes include methionine, cysteine, and tryptophan, while those in algal protein species are mainly histidine and isoleucine (Wang *et al.* 2021). The future of plant-based protein in the human diet appears to be bright, with extensive research needed to bring this potential to fruition.

Box 3: What are the crops of the future?

What people will eat in the future is a topic that has captured the imagination of both the scientific community (Manners and van Etten 2018; Gregory *et al.* 2019; Yu and Li 2022) and the public (Gertzman 2015; Beggs 2022; Briggs 2022). The assumption - well founded, if historical and current trends continue (Popkin 2006; Kearney 2010; Khoury *et al.* 2014; Vermeulen *et al.* 2020) - is that the foods that humans eat are likely to further change considerably in the coming decades.

From the human health perspective, crops with greater nutritional quality or density than current staples are often listed as candidates for becoming the crops of the future. Emphasis has mainly been placed on greater consumption of vegetables, fruits, nuts, and seeds (Alae-Carew *et al.* 2020). Alternatives to major cereals with high nutrient density are also commonly proposed, for example other traditional cereals such as millets and sorghum (Saleh *et al.* 2013; Anitha *et al.* 2019), and pseudocereals such as quinoa (Bazile *et al.* 2016) and amaranth (Baraniak and Kania-Dobrowolska 2022). Less-globalized foods with high nutritional quality, including crops such as bambara groundnut (*Vigna subterranea* (L.) Verdc.) and other legumes, African eggplant (*Solanum aethiopicum* L.), and minor millets are also often listed (Gregory *et al.* 2019) even if they are not yet widely available outside of their regions of origin. Varietal diversity has also been proposed as a path toward increasing nutritional quality, as micronutrient levels can vary widely between crop varieties (Marles 2017; de Haan *et al.* 2019). Micronutrient density can be increased significantly through breeding "biofortified" varieties (Bouis and Saltzman 2017).

As overconsumption of calories, fat, and salt are increasingly understood to lead to diet-related noncommunicable diseases including heart disease, Type-2 diabetes, and some forms of cancer (Popkin 2006), foods that are low in macronutrients relative to other nutritional factors have also come to be proposed as candidate crops of the future. While vegetables and fruits have again been the major area of focus, many other crops may contribute importantly to satisfying hunger without contributing excessive calories. Two root and tuber crops in the sunflower family (Asteraceae) with high levels of sweet, non-digestible oligosaccharides and inulin - yacon (*Smallanthus sonchifolius* (Poepp.) H. Rob.) and Jerusalem artichoke (*Helianthus tuberosus* L.) - serve as examples (Choque Delgado *et al.* 2013; Judprasong *et al.* 2018). Foods without gluten or other ingredients considered by some consumers - and often proposed by their influencers - as detrimental to their health are also gaining in popularity (Jones 2017; Niland and Cash 2018), leading to new opportunities for alternative cereal crops and other plants.

Environmental, climate change, and various labor and other social factors also combine with health concerns to motivate proposals for the crops of the future. While new ways to produce animal products are being innovated (Stephens *et al.* 2018), plant-based alternatives to meat and dairy are continuously rising in variety and availability (Haas *et al.* 2019; Clay *et al.* 2020) (also see **Box 2**). High sustainability and "climate smart" crops are also often discussed in comparison to current staple commodities (e.g., Jarvis *et al.* 2012).

The specific crops and varieties that will emerge as the "crops of the future" are not straightforward to predict. While a general move toward greater consumption of minimally refined plant-based foods, and especially more vegetables and fruits, is widely advisable (Katz and Meller 2014), the true human health, sustainability, and other impacts of different crops and the foods made from them depend on a wide variety of factors (Katz and Meller 2014), with many likely tradeoffs between health, environment, and social goals (Chalupa-Krebzdak *et al.* 2018; Béné *et al.* 2019; Scheelbeek *et al.* 2020). What is certain is that both supply and demand changes can lead to significant shifts in consumption (Vermeulen *et al.* 2020). Equally certain is that the conservation, availability, and use of PGRFA will critically determine the potential of different crops to sustainably nourish humanity (Sellitti *et al*. 2020) as well as to adapt to changing environmental conditions (Alae-Carew *et al.* 2020).

3.2 Interdependence regarding food and agricultural crop plant genetic resources

3.2.1 Significance of each crop in terms of agricultural production, trade, and contribution to food supplies, outside of its geographic origins and primary region(s) of diversity

Information on national agricultural production, trade, and contribution of crops to food supplies may be used to indicate potential interdependence among countries and regions regarding PGRFA. Khoury *et al*. (2015, 2016) linked the origins and primary regions of diversity of food and agricultural crops, defined as "areas typically including the locations of the initial domestication of crops, encompassing the primary geographical zones of crop variation generated since that time, and containing relatively high species richness in crop wild relatives" with their current (years 2009 to 2011) use around the world in national agricultural production and food supplies. Production systems and food supplies were found to comprise a wide range of crops deriving from many different primary regions of diversity, indicating a thoroughly interconnected global food system regarding the geographic origins of food plants. As a global average across countries, 71.0% of total production quantity, 64.0% of harvested area, and 72.9% of production value were of crops whose origins and primary regions of diversity were not in the same region as where currently produced; likewise 65.8% of plant-based calories, 66.6% of protein, 73.7% of fat, and 68.7% food weight derived from crops whose origins and primary regions of diversity were in other regions on the planet from where currently available for consumption.

Building on this previous work, this current assessment calculates the significance of each crop in terms of agricultural production, trade, and contribution to food supplies, outside of its geographic origins and primary region(s) of diversity. The underlying assumption is that if a crop has considerable use outside of its origins and primary region(s) of diversity, then that use is likely dependent on PGRFA acquisition from elsewhere, including origin regions. Thus, a crop with a high use outside of its origins and primary region(s) of diversity is likely to be one where there is considerable interdependence globally for its PGRFA.

Using the same 2015 to 2018 FAOSTAT data described in the crop use domain, the highest interdependence crops in terms of global production for eight different crop use types of interest are presented in **Figure 5**. The results are presented as the proportion of the production of each crop outside its origins and primary region(s) of diversity, compared to total production of the crop worldwide.

Across all metrics and all crop use types, the foremost insight from the analysis on estimated interdependence regarding PGRFA in terms of global production, trade, and contribution to food supply is that the great majority of crops have high estimated interdependence values. Note that these values do not directly indicate extent of crop utilization around the world, but, rather, simply the high degree of use outside of crops’ origins in the context of crops’ total use worldwide.

In terms of the crops with the highest interdependence values, these include plants from all the crop use types, and also differ across metrics - essentially the high interdependence crops are a global cornucopia of plants. On the other hand, those with the lowest interdependence values are more clearly discerned, as the crops that are primarily still cultivated in their primary region(s) of diversity (such as mate, karite nut, gooseberries and currants, cinnamon, and yautia/cocoyam) and/or are significant in food supplies mainly within their primary region(s) of diversity (such as yams, various millets, dates, and olives). We note that the aggregation of FAOSTAT values in general crop commodities makes calculation of accurate interdependence values for those crops listed within these general commodities particularly challenging.

Significance of crops in terms of agricultural production outside of their geographic origins and primary region(s) of diversity

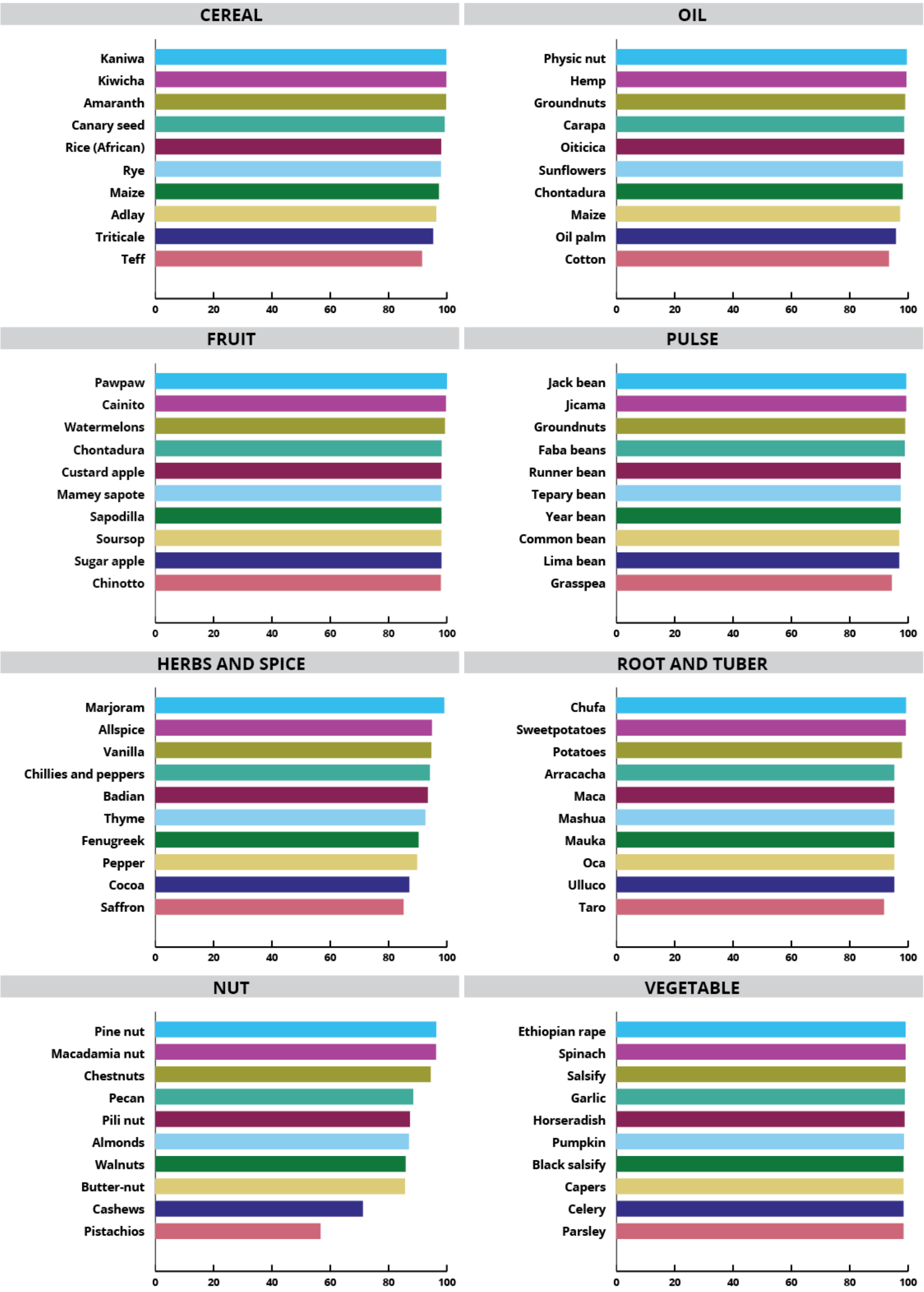

Figure 5: Significance of each crop in terms of agricultural production outside of its geographic origins and primary region(s) of diversity. The results are presented as the proportion of the production of each crop outside its origins and primary region(s) of diversity, compared to total production of the crop worldwide. The subfigures display the ten crops with largest values per crop use type. For crops such as maize with multiple uses, these are included in all relevant use type categories; values for these crops are total global, not separated by specific use.

3.2.2 Change in significance of each crop in terms of agricultural production, trade, and contribution to food supplies, outside of its geographic origins and primary region(s) of diversity

Information on change in the degree of estimated interdependence among countries regarding PGRFA over the ca. 50 years from 1961 to 2009, based on FAOSTAT data, has indicated that use of crops outside their origins and primary region(s) of diversity increased in concert with economic and agricultural development and the globalization of food systems, with estimated interdependence regarding production value and production quantity, as well as fat and food weight in food supplies, increasing the most among measurable metrics (Khoury *et al.* 2015, 2016).

This current assessment demonstrates that further change in the significance of crops outside their origins and primary region(s) of diversity is visible even within the four years analyzed (2015 to 2018). The results are presented as the relative change in the proportion of the use of each crop outside its origins and primary region(s) of diversity, compared to total use of the crop worldwide, over this period.

Box 4: The many crops that feed the world

The list of plants produced within many countries and regions, and consumed by the majority of humanity, is much longer than just wheat, rice, maize, and a few other staple cereal, pulse, and root and tuber crops. Oil crops such as soybeans, oil palm, sunflowers, and groundnuts, for example, represent not only the most important contributors to fat from plants in global food supplies, but now are among the top ten crops in contribution to total calories (see **Box 1**).

The list of crops upon which the world fundamentally depends for its food also extends to many vegetable, fruit, nut and seed, herb and spice, and stimulant crops. Onions, for example, are important production crops (tonnes produced) in 92 countries (45% of total countries), behind only maize, potatoes, tomatoes, cabbages, canola, and wheat in terms of number of important producing countries and are significant contributors to the food supplies (quantity in g) of 150 countries (86.9%), including being important crops in terms of import value in 116 countries (58.3%). Tomatoes are important production crops in 114 countries (55.6% of countries) and are significant contributors to the national food supply (weight in g) of 155 countries (89.6%), including being important crops in terms of import value in 140 countries (70.8%). Chillies and peppers (*Capsicum* crops), meanwhile, are important production crops in 56 countries (27.1%). Consumed daily by approximately a quarter of the world's population (Halikowksi Smith 2015), chillies and peppers are significant contributors to the national food supply (quantity in g) of 17 countries (10%) and are important crops in terms of import quantity in 82 countries (41.5%). All three of these essential gifts to the world's cuisines in terms of flavor, acidity, micronutrients, and other nutritional and cultural aspects have very high interdependence values as measured by the substantial degree of production, trade, and contribution to food supplies outside of their regions of origin.

Other crops consumed widely around the world are very rarely considered in discussions around genetic resource interdependence and, further, are essentially absent from reported food and agricultural statistics. These include crops consumed in relatively small quantities but present in an enormous diversity of processed products as thickeners or stabilizers, such as gum arabic (various wild-harvested species of *Acacia* Mill. and occasionally *Combretum* Loefl., *Albizia* Durazz., and other leguminous tree genera) and guar gum (cultivated cluster bean [*Cyamopsis tetragonoloba* (L.) Taub.]) (Mudgil *et al.* 2014), among others.

Finally, while most of the long list of crops that interconnect the world have contributed to global production, trade, and food supplies for centuries, various other crops are rapidly expanding in terms of the numbers of countries producing the plants and the consumers eating them. Quinoa (*Chenopodium quinoa* Willd.), which has grown from a regionally important crop to one cultivated in over 100 countries within the past half-century (Bazile *et al.* 2016), is a well-known example. Other examples of crops that appear to be spreading include chia (*Salvia hispanica* L.) (Bochicchio *et al.* 2015) and rocket (various *Eruca* Mill. and *Diplotaxis* DC. spp.) (Yaniv *et al.* 1998). As indicated in FAOSTAT in terms of growth in global production quantity (tonnes) solely within recent years (2015 to 2018), hemp, chickpeas, cowpeas, avocados, hops, raspberries, many herbs and spices, and various other crops may also be on a steep upward trajectory currently.

While most of the global food and agricultural crop production, trade, and contribution to food supplies, as measured by those metrics reported in FAOSTAT, is of crops currently listed in Annex 1 of the International Treaty on Plant Genetic Resources for Food and Agriculture and thus included in its Multilateral System of Access and Benefit Sharing, the remaining proportion is not. This proportion is substantial, for example approximately 41.0% of total global production quantity and 28.7% of calories in global aggregate food supplies are of crops not listed in Annex 1 (Khoury *et al.* 2015). The most obvious gaps include oils (groundnuts, oil palm, rapeseeds and mustards, and soybeans) and sugars (sugar beets and sugarcane).

If, instead, a comparison was made of the crops listed in Annex 1 versus all crops contributing importantly to global production, trade, and food supplies (even if only those crops for which global statistical information is available), current Annex 1 crops would appear to reflect global food and agriculture much more poorly. Among those on the long list of globally important crops not currently on Annex 1 are almonds, amaranth, apricots, avocados, blueberries, buckwheat, cashews, cherries, chillies and peppers, coconuts, coffee, cotton, cranberries, cucumbers, dates, figs, garlic, ginger, grapes, guavas, hazelnuts, kiwi fruit, lettuce, mangoes, melons, millets (various), olives, onions, papayas, passionfruit, peaches and nectarines, pepper (*Piper* L.), pineapples, plums, pistachios, pumpkins, quinoa, raspberries, sesame, spinach, tea, tomatoes, walnuts, watermelons, and zucchini.

Box 5: PGRFA and climate change adaptation

That the world is warming rapidly is no longer in doubt. According to the Annual Report of the National Centers for Environmental Information for 2021, the years 2013–2021 all rank among the ten hottest years on record (NOAA 2022). Not only are temperatures increasing but weather patterns are shifting, and the frequency of extreme weather events is on the rise. The effect of changing climates on the environments in which crops grow are many and varied. While some higher latitude regions might benefit from longer growing seasons (King *et al.* 2018) and possibly increased CO_2 fertilization (Degener 2015), overall, climate change is expected to impact negatively on global agricultural production (IPCC 2019). A greater frequency of early-, mid- or late-season droughts, more intense rainstorms leading to waterlogging or flooding, higher or lower than ‘normal’ temperatures at different plant growth stages, and a greater occurrence of high winds, will all take their toll.

In addition to the direct effects of climate change, agriculture will increasingly have to contend with other related effects such as a shifting spectrum of economically damaging pests (Skendžić *et al.* 2021), diseases (Luck *et al.* 2011; Velásquez 2018) and weeds (Vilà *et al.* 2021), as well as rising water tables, soil erosion, salt intrusion, and damage to infrastructure (IPCC 2019). For most farmers, the coming decades will require having to continually adapt to evolving conditions.

Although increasingly reliable climate modeling will facilitate the development of coping strategies (Joshi *et al.* 2015), given the inherently uncertain nature of future climates, a broad range of strategies will be needed in the transition to climate smart agriculture. These will involve technological, socio-economic and policy changes. Practices such as planting dates, irrigation regimes, and pest and disease management will all have to be adapted, updated, and adjusted (Rosenstock *et al.* 2016).

Whatever the agricultural strategy, almost all will depend, to a greater or lesser extent, on the availability of appropriate PGRFA. This will be the case whether efforts are made to increase resilience through the deployment of greater spatial or temporal diversity (Lin 2011), or through introducing and/or breeding new crops or varieties that are better able to cope with changing environmental and agronomic conditions (Joshi *et al*. 2017). Crops that have an enhanced ability to withstand high temperatures, drought, waterlogging, or high levels of soil salinity, or that can resist or tolerate new pests and diseases, will all be critical (Galluzzi *et al.* 2020).

There are many ways in which PGRFA can contribute to ensuring agriculture will be able to meet future food demands, for example:

- Introducing new varieties of currently grown crops that are better adapted to new climatic regimes from areas that have, or had in the recent past, an analogous climate and similar agro-ecological conditions (Bos *et al.* 2015; Joshi *et al.* 2017). However, these new varieties must meet local cultural preferences.

- Breeding new varieties of locally important crops to be better adapted to new abiotic and biotic conditions, while at the same time maintaining or enhancing their productivity and preferred food and agronomic characteristics (Mickelbart *et al.* 2015; Rane *et al.* 2021). In recent years there has been a growing interest in looking for genes that contribute to climate resilience, not only in cultivated germplasm of crop species but also in related cultivated species and in wild relatives (Redden *et al.* 2015; Cortés and López-Hernández 2021). Genes for heat and drought tolerance, for example, have been successfully transferred from the tepary bean (*Phaseolus acutifolius*) to the more widespread common bean (*Phaseolus vulgaris*) (Burbano-Erazo *et al.* 2021). Given the on-going and rapid nature of climate change, it is important to make every effort to speed up these breeding processes and ensure there is a continuous pipeline of new varieties (Atlin *et al.* 2017).

- Introducing new crops from regions with analogous climates. Growing new and different crops presents an opportunity to adapt agriculture to changing conditions. As temperatures rise, it will become increasingly possible, even necessary, to grow crops that were previously only to be found in warmer climes. The following crops, for example, have been proposed to be produced on a large scale in UK in the future: almonds, avocados, butternut squash, durum wheat, grapes, kiwi, navy beans, nectarines, olives, peaches, sunflower, soybeans, tea and wasabi (Pole and Mills 2008). However, while switching to new crops as temperatures rise may be a viable option for many temperate areas of the world, it may be less appropriate for those mainly tropical regions that are already only able to grow the most heat-tolerant of crops.

- Domesticating and introducing new crop species from the wild. *De novo* domestication could, in certain circumstances, help agriculture adapt, despite the complexity of having to overcome many biological, physical, economic, and cultural barriers. Increasingly, scientists are looking for plant species that could become new crops (von Wettberg *et al.* 2020). *Vigna stipulacea*, for example, has fast growth and broad resistance to pests and diseases (Takahashi *et al.* 2019), and several species of *Salicornia* L., a potential vegetable crop*,* can be grown in hot regions with saline soils, where little else will survive (Patel 2016).

The examples listed above represent a progression in terms of their ease of development and likelihood of adoption by farmers and consumers. Changes that cause the least disruption to existing practices and preferences are the most likely to be adopted (Rickards and Howden 2012), actualizing the transformational changes required for agriculture to adapt to the new and evolving climates in the coming decades. These processes may also differ with reference to the existing Multilateral System of the Plant Treaty, with accessing PGRFA of major staple cereals, pulses, and some other crops already well incorporated, while PGRFA of many proposed ‘crops of the future’ (see **Box 3**) are currently outside the scope of the Multilateral System.

3.3 Demand for food and agricultural crop plant genetic resources

3.3.1 Demand for food and agricultural crop plant genetic resources in terms of germplasm distributions

Global tracking of germplasm distributions provides insights into demand for PGRFA worldwide. The Data Store of the International Treaty on Plant Genetic Resources for Food and Agriculture provides information on germplasm distributions made under the Standard Material Transfer Agreement (SMTA) that have been reported to the Governing Body. This dataset records numbers of samples distributed by any provider, including genebanks as well as breeding programs and other organizational types, as reported to the Data Store; it is primarily composed of distributions made by CGIAR genebanks and breeding programs. We calculated an average annual number of germplasm distributions for each crop worldwide from 2015 to 2019.

The most distributed crops, for eight different crop use types of interest, are presented in **Figure 6**. The results are presented as the proportion of distributions of the crop, compared to total distributions of all crops per crop use type.

The PGRFA of a total of 142 different crops assessed in this study was reported distributed in the Plant Treaty Data Store dataset, with a total of 505,786 samples distributed across all these crops, as an annual average across 2015 to 2019. Across all crop use types, cereals such as wheat, maize, rice, barley, pearl millet, sorghum, oats, and triticale were among the most distributed, followed by a broad range of crops in different crop use type categories, including pulses (e.g. chickpeas, lentils, common bean, faba beans, cowpeas, pigeonpeas, groundnuts, grasspea, and soybeans), vegetables (e.g. cabbages, lettuce, chillies and peppers, eggplants, and tomatoes), and roots and tubers (e.g. potatoes and cassava). While seed propagated crops dominate the list, among the crops with considerable distributions are also vegetatively propagated crops. Also evident in this dataset was wide variation in numbers of distributions across the entire set of crops. As a whole, significant crops in terms of global germplasm distribution evidently include a broad range of plants from a variety of crop types.

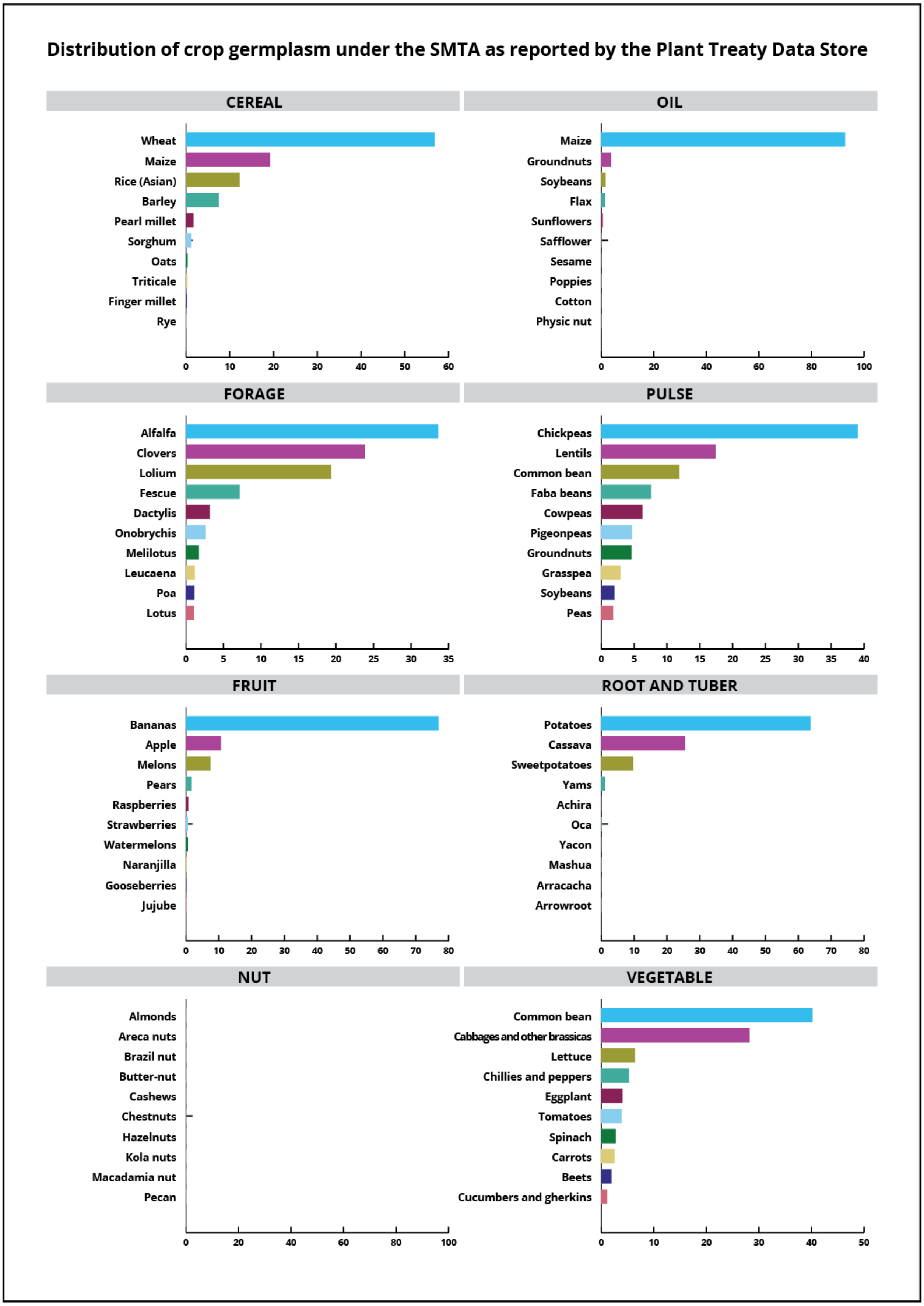

Figure 6: Demand for crop genetic resources as measured in terms of germplasm distributions under the SMTA of the Plant Treaty. Metrics are presented per crop as a proportion of total distributions across all crops within

each crop use type. The subfigures display the ten crops with highest distributions per crop use type. For crops such as maize with multiple uses, these are included in all relevant use type categories; values for these crops are total global, not separated by specific use. No distributions of germplasm of nut crops were recorded in the dataset.

Global summary germplasm distribution statistics are useful to identify the most distributed crops globally, but do not provide information on the geographic extent or evenness of demand for PGRFA worldwide. To understand the current extent of geographic spread of demand for PGRFA of assessed crops, for each crop we calculated the average annual number of countries to which the crop was distributed, using the same 2015 to 2019 distributions data from the Data Store of the of the International Treaty on Plant Genetic Resources for Food and Agriculture. The results are presented as the proportion of countries receiving the crop compared to the total number of countries reported in the Data Store during the period (a total of 179 recipient countries were reported in the dataset).

In terms of the crops with the greatest geographic spread regarding country recipients of germplasm, across all crop use types, the most widely distributed crops generally paralleled the results for total samples distributed. Global staple cereals such as wheat, rice, maize, and barley were distributed to an average of 100.3, 68.8, 65.3, and 58.8 countries per year, respectively, with pulses such as chickpeas, faba beans, lentils, and common beans also distributed to many countries. Also evident in this dataset was wide variation in numbers of recipient countries across the entire set of crops. As a whole, significant crops in terms of geographic extent of germplasm distributions include a broad range of plants from a variety of crop types.

To understand the current evenness or balance worldwide of PGRFA distribution for each crop, we compared its quantities of germplasm received across world regions, using the same 2015 to 2019 distribution data from the Data Store of the of the International Treaty on Plant Genetic Resources for Food and Agriculture. The most geographically even/balanced crops in terms of germplasm distribution, for eight different crop use types of interest, are presented in **Figure 7**. The results are presented based on a mathematical metric of evenness called the Gini coefficient, in this case with values close to 100 representing high evenness in receipt of quantities of germplasm samples across regions, and those close to 0 representing unevenness. Note that those crops with the highest evenness values are not necessarily the most distributed around the world, but simply those with the greatest balance in quantities of distributions received by all world regions.

In terms of the crops with the greatest regional balance regarding receipt of germplasm, across all crop use types, the most evenly distributed crops also paralleled fairly well those most distributed in terms of quantities of samples and geographic spread. Examples of additional crops with relatively high evenness included bananas, eggplants, alfalfa, and sweetpotatoes. Also evident in this dataset was wide variation in evenness of distributions across the entire set of crops. These geographic spread and evenness assessments complement the global value metrics by providing additional insights on extent and balance of demand for germplasm worldwide. For crops with significant distributions to many countries, and/or with considerable evenness in receipt of germplasm samples across world regions, these metrics directly indicate a strong degree of interdependence among countries and regions regarding these PGRFA.

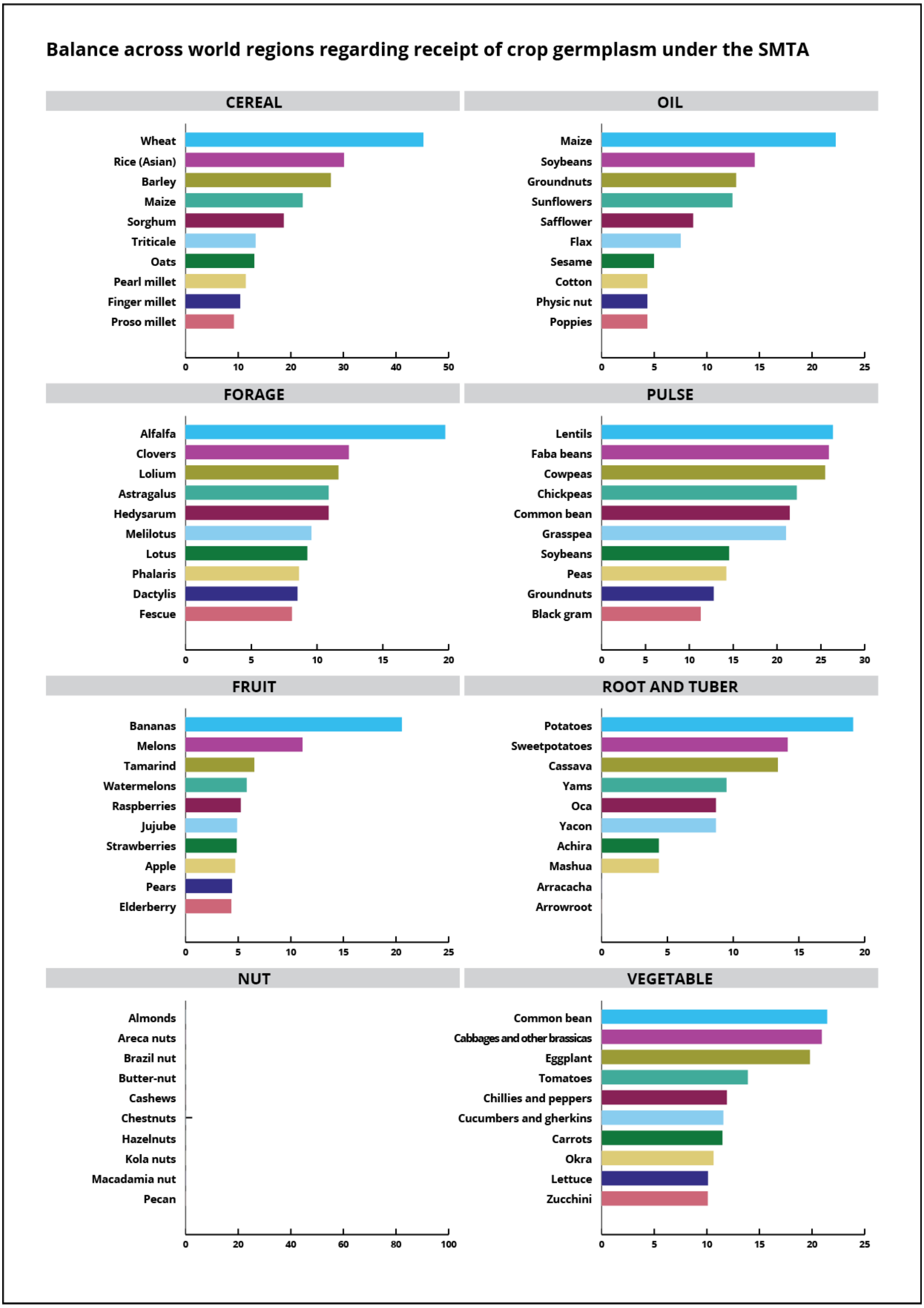

Figure 7: Geographic evenness in demand for crop genetic resources as measured in terms of regional balance in receipt of germplasm distributions under the SMTA of the Plant Treaty. Metrics are presented per crop as based

on a mathematical metric of evenness called the Gini coefficient, in this case with values close to 100 representing high evenness in receipt of quantities of germplasm samples across regions, and those close to 0 representing unevenness. The subfigures display the ten crops with highest evenness in distributions per crop use type. For crops such as maize with multiple uses, these are included in all relevant use type categories; values for these crops are total global, not separated by specific use. No distributions of germplasm of nut crops were recorded in the dataset.

As a complementary metric on global germplasm distributions, we calculated an average annual number of germplasm distributions for each crop worldwide from 2014 to 2019 using data from the FAO World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture (FAO WIEWS), both in terms of numbers of accessions (unique populations/collecting events conserved *ex situ*) and of samples (individual packets of seeds or other propagules). This dataset primarily records distributions of germplasm from national genebanks, as reported by national focal points to the FAO.

The most distributed crops in terms of accessions, for eight different crop use types of interest, are presented in **Figure 8**. The results are presented as the proportion of distributions of the crop, compared to total distributions of all crops per crop use type.

The PGRFA of a total of 256 different crops assessed in this study was reported distributed in the FAO WIEWS dataset, with a total of 865,479 accessions distributed across all crops and all years. Across all crop use types, major cereals such as wheat, rice, barley, maize, oats, and sorghum were among the most distributed of accessions, followed by a broad range of crops in different crop use types, including pulses (e.g. common beans, chickpeas, peas, cowpeas, faba beans, and lentils), vegetables (e.g. cabbages, tomatoes, and chillies and peppers), fruits (e.g. oranges, pears, and apples) and roots and tubers (e.g. potatoes). While seed propagated crops dominate the list, among the crops with considerable distributions are also likely vegetatively propagated crops. Also evident in this dataset was wide variation in numbers of distributions across the entire set of crops. As a whole, significant crops in terms of global germplasm distribution evidently include a broad range of plants from a variety of crop types.

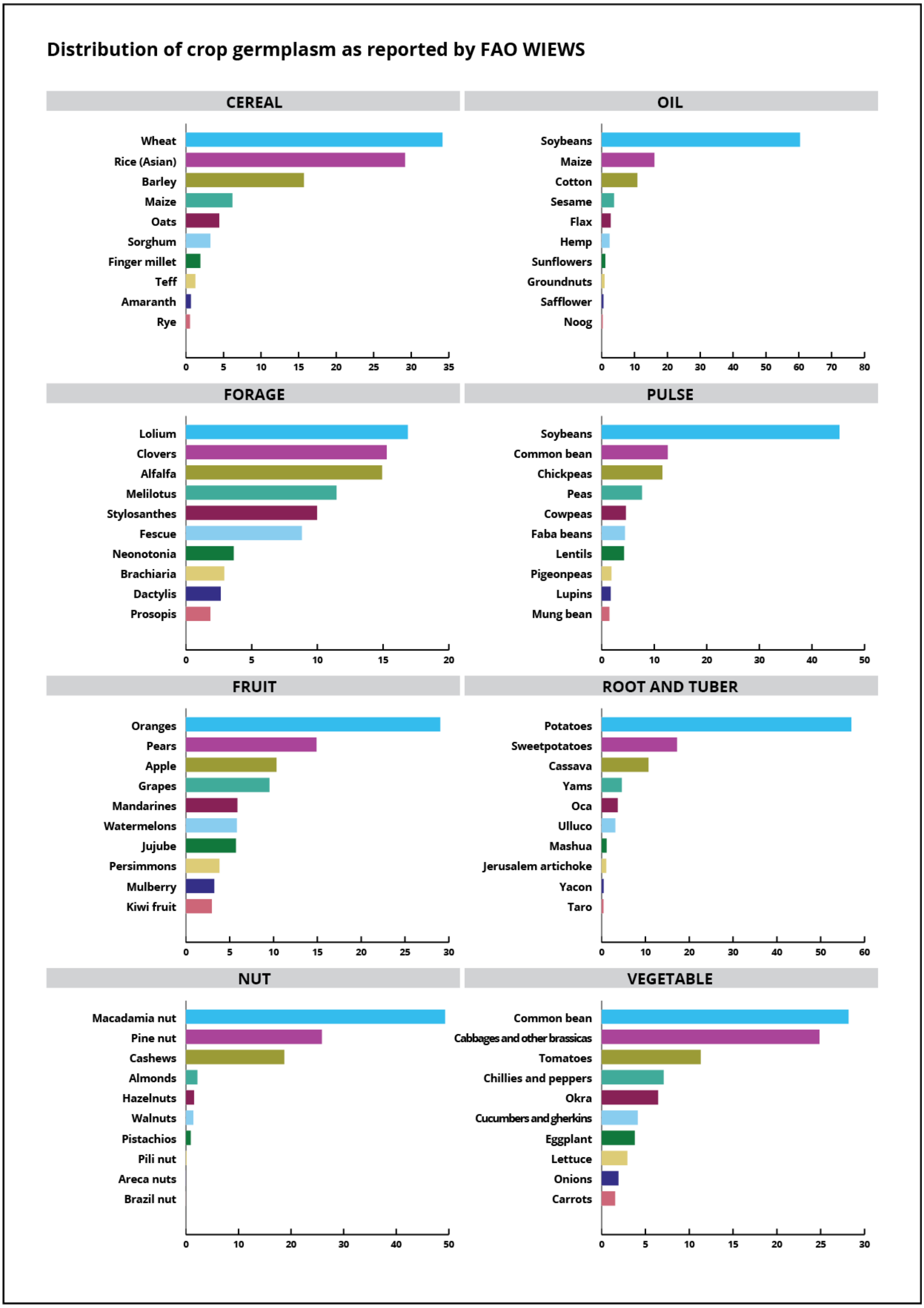

Figure 8: Demand for crop genetic resources as measured in terms of germplasm distributions of accessions reported by FAO WIEWS. Metrics are presented per crop as a proportion of total distributions of accessions

across all crops within each crop use type. The subfigures display the ten crops with highest distributions per crop use type. For crops such as maize with multiple uses, these are included in all relevant use type categories; values for these crops are total global, not separated by specific use.

3.3.2 Demand for food and agricultural crop plant genetic resources in terms of varietal registrations and releases

Global tracking of crop varietal registrations and releases provides further insights into global demand for PGRFA. We calculated an average annual number of varietal registrations for each crop worldwide from 2014 to 2018 using data from the International Union for the Protection of New Varieties of Plants (UPOV). Crops with the greatest number of varietal registrations, for eight different crop use types of interest, are presented in **Figure 9**. The results are presented as the proportion of registrations of the crop, compared to total registrations of all crops per crop use type.

Varietal registrations of a total of 194 different crops assessed in this study were reported in the UPOV dataset, with a total of 21,169.8 registrations made on average annually for the crops as a whole. Across all crop use types, in terms of crops with large numbers of varietal registrations, a variety of crops and crop use types were among the most significant. These included various cereals (maize, wheat, and barley), vegetables (cabbages, tomatoes, beets, lettuce, chillies and peppers, and cucumbers), sugar crops (sugar beets), oil crops (rapeseed and mustards, sunflowers, and soybeans), pulses (peas, soybeans, and common beans), roots and tubers (potatoes), and forages (*Lolium*, fescue, and clovers). Also evident in this dataset was wide variation in numbers of varietal registrations across the entire set of crops. As a whole, significant crops in terms of global varietal registrations evidently include a broad range of plants from a variety of crop types.

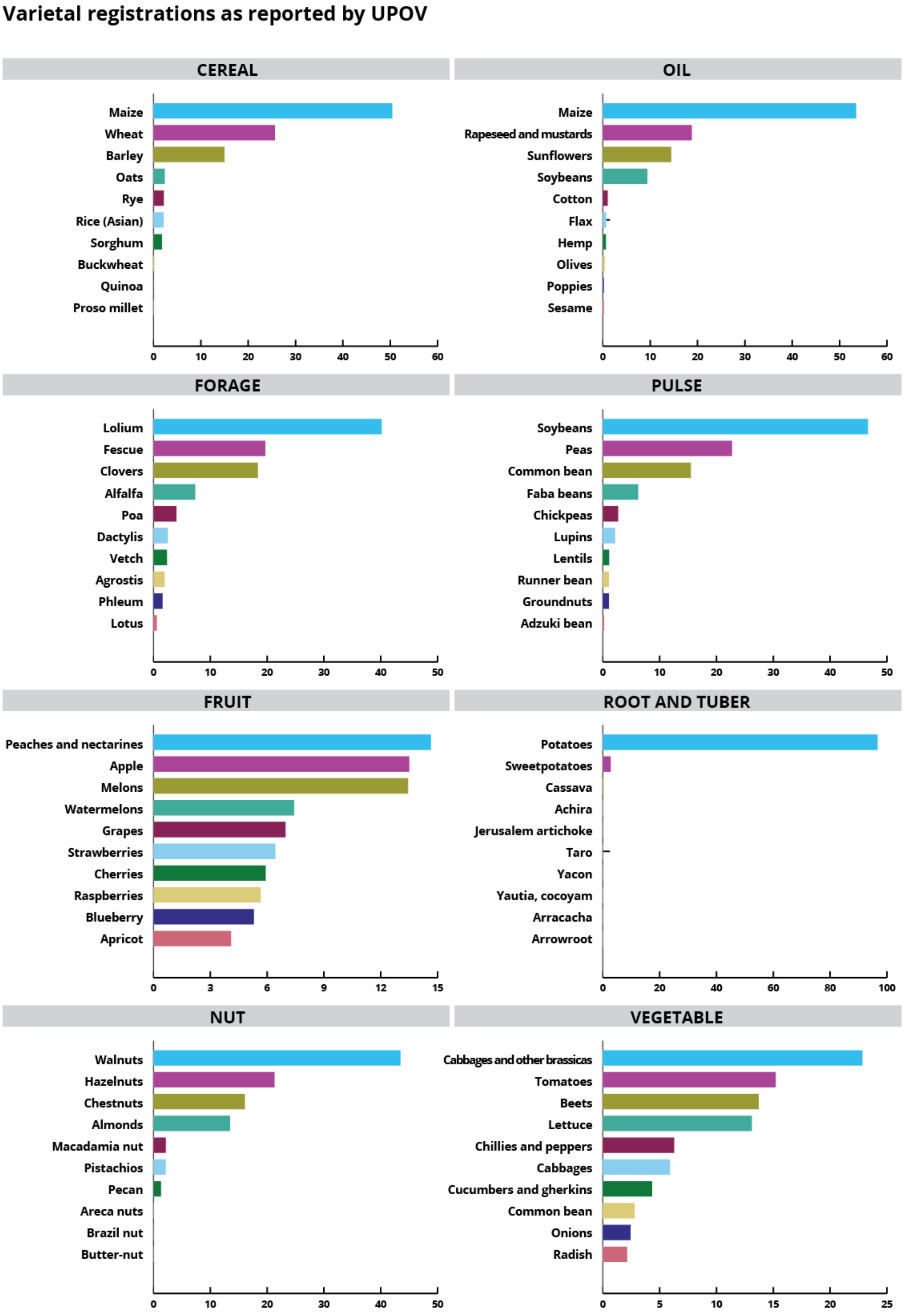

Figure 9: Varietal registrations as reported by UPOV. Metrics are presented per crop as a proportion of total registrations across all crops within each crop use type. The subfigures display the ten crops with most

registrations per crop use type. For crops such as maize with multiple uses, these are included in all relevant use type categories; values for these crops are total global, not separated by specific use.

In a complementary metric on new crop varieties, we calculated an average annual number of varietal releases for each crop worldwide from 2015 to 2019 using data from the FAO World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture (WIEWS). These data provide information in terms of counts of varieties released of different crops by country, as reported by national focal points to the FAO. Crops with the greatest number of varietal releases globally, for eight different crop use types of interest, are presented in **Figure 10**. The results are presented as the proportion of releases of the crop globally, compared to total releases of all crops globally per crop use type.

Varietal releases of a total of 204 different crops assessed in this study were reported in the FAO WIEWS varietal release dataset, with a total of 5933.3 releases made on average annually for the crops as a whole. Across all crop use types, in terms of crops with large numbers of varietal releases, a variety of crops and crop use types were among the most significant. These included various cereals (maize, wheat, sorghum, rice, and barley), vegetables (tomatoes, cabbages, lettuce, chillies and peppers, cucumbers, onions, beets, and carrots), oil crops (soybeans, sunflowers, and rapeseed and mustards), roots and tubers (potatoes), fruits (melons, watermelons, apples, and peaches and nectarines), pulses (common bean, soybeans, and peas), sugar crops (sugar beets), and forages (lolium and fescue). Also evident in this dataset was wide variation in numbers of varietal releases across the entire set of crops. As a whole, significant crops in terms of global varietal registrations include a broad range of plants from a variety of crop types.

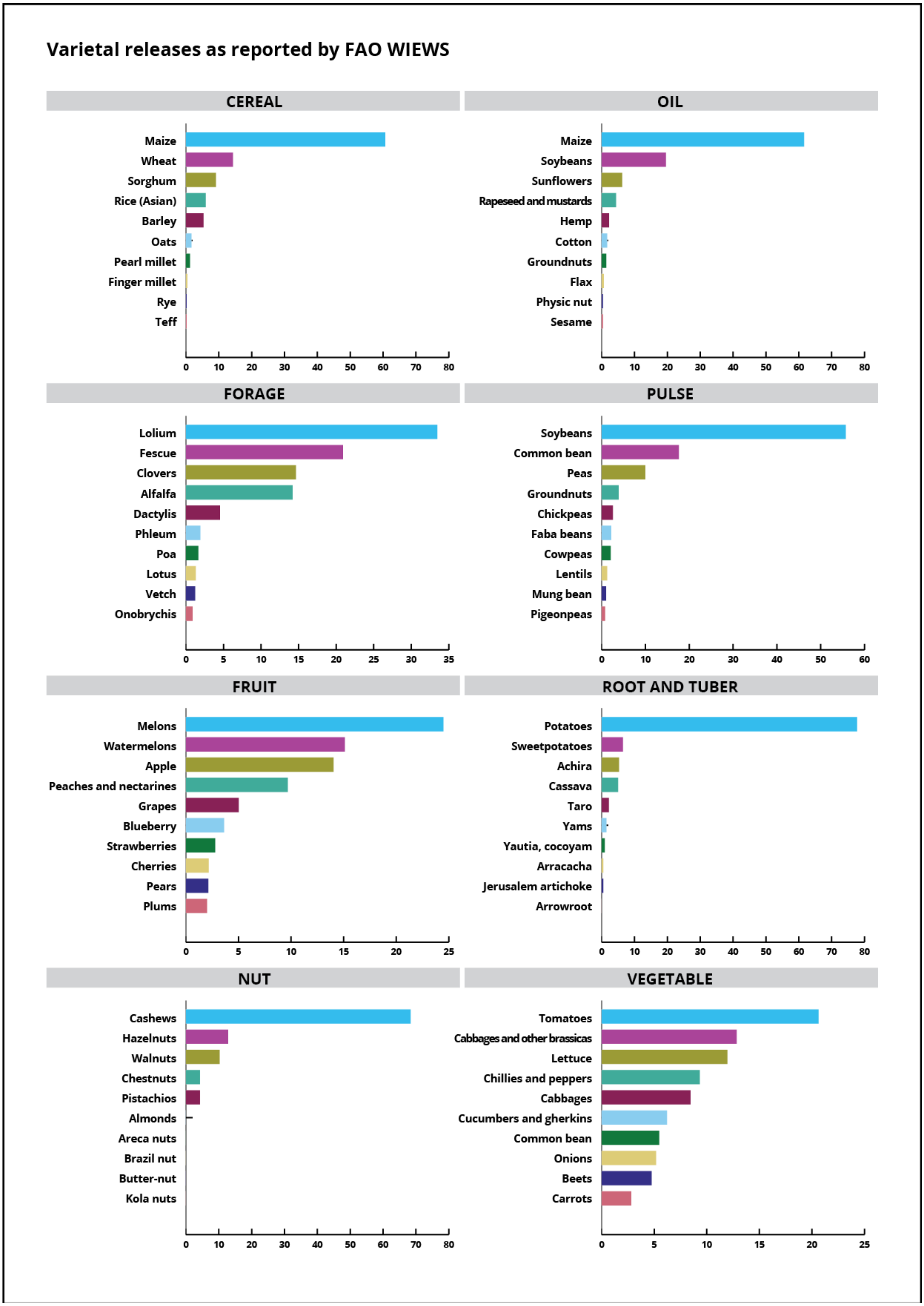

Figure 10: Varietal releases as reported by FAO WIEWS. Metrics are presented per crop as a proportion of total releases across all crops within each crop use type. The subfigures display the ten crops with most releases per

crop use type. For crops such as maize with multiple uses, these are included in all relevant use type categories; values for these crops are total global, not separated by specific use.

Box 6: PGRFA and climate change mitigation

The International Panel on Climate Change (IPCC) has estimated that agriculture is directly responsible for up to 8.5% of all greenhouse gas (GHG) emissions, with a further 14.5% arising from land use change, mainly due to deforestation in the conversion of wildlands to agricultural fields (Shukla *et al.* 2019). While agriculture must adapt to the effects of a warming climate (see **Box 5**), it is equally important that every effort be made to reduce its carbon and other major GHG footprints. This can be achieved in two main ways: a) increasing the amount of carbon captured and b) reducing the amount of GHG emitted. A third, more controversial approach by which agriculture can contribute to reducing anthropogenic GHG emissions is through increased production of biofuel (see **Box 8**).

While a range of agronomic and other measures can significantly reduce agriculture's carbon footprint, the use of PGRFA to breed new and productive but also climate-friendly varieties should not be overlooked. Increasing carbon capture can be achieved, for example, through:

- Breeding larger plants with more extensive and deeper root systems, that have greater above ground biomass or that are better suited to production in high C-capture cropping systems. Such measures are only effective, however, if the carbon remains locked up for a considerable period, e.g., through contributing to a sustained increase in soil carbon. Some major new initiatives are exploring the breeding of crops for greater C-capture (e.g., Salk Institute for Biological Studies 2022).

- Planting more perennial crops, which generally capture more carbon than annuals because of their larger root systems and greater overall biomass. There is thus a significant potential to increase soil carbon through replacing annual crops with perennials and by incorporating woody perennials in agroforestry systems (Scherr and Sthapit 2008). It may be feasible to convert annual crop species into perennials, for example maize, oat, rice, rye, sorghum, soybean, sunflower, and wheat (Cox *et al.* 2002; Porterfield 2019). In the Yunnan Province of China, a perennial rice cultivar (PR23), has been successfully developed through a cross between annual cultivated rice (*Oryza sativa* L.) and a perennial wild relative from Africa (*Oryza longistaminata* A. Chev. & Roehr.) (The Land Institute 2022).

Reducing agricultural GHG emissions can be achieved, for example, through:

- Reducing the need for artificial nitrogen fertilizer, the use, or over-use, of which is one of the main causes of GHG emissions from agricultural production. These arise both as CO_2 from fertilizer manufacture, transport and application, and as nitrous oxide (N_2O) from the denitrification of nitrate by microorganisms in the soil. While recognizing the importance of N fertilizer in maintaining productivity and hence reducing the need to farm additional land, every effort should be made to produce and use it as efficiently as possible. PGRFA can play an important role in helping reduce the use of N fertilizer through breeding varieties that can uptake and use N more efficiently. Genetic advances in nitrogen use efficiency (NUE) appear possible in many crops (ISAAA 2014; Lammerts van Bueren and Struik 2017).

- Reducing nitrous oxide emissions. Nitrous oxide (N_2O) is about 300 times more potent as a greenhouse gas than CO_2 over a 100 year period. 62% of the world's anthropogenic N_2O is from agricultural production and an additional 26% from land clearing and biomass burning (EDGAR 2022). Reducing N fertilizer application is key to cutting N_2O emissions. Other approaches are also being explored. Brachialactone, for example, a chemical released from the roots of forage *Brachiaria* species, can significantly reduce nitrification by microorganisms in the soil, resulting in less N_2O release (Subbarao *et al.* 2009). It should be possible to genetically enhance this effect as well as find or enhance compounds having a similar effect in other crops.

- Enhancing biological nitrogen fixation. Food and forage legumes get a large proportion of their N needs directly from the atmosphere through a symbiotic association with bacteria of the genus *Rhizobium*. Residual N from legume cultivation can also contribute to meeting the needs of companion crops or subsequent crops in the rotation. Currently around 30 food legume and 20 forage legume species are used extensively in agriculture (as tracked by FAOSTAT and/or Annex 1 of the Plant Treaty) and a greater use of these, and possibly other species, would help reduce the overall need for artificial N fertilizer. The amount of nitrogen 'fixed' can also be increased through genetic improvement of legume crops or their *Rhizobium* symbionts (Provorov 2003). Further, several breeding programmes worldwide aim to increase the amount of N fixed by non-leguminous species, in particular maize, rice, sorghum, and wheat (Rosenblueth *et al.* 2018).

- Reducing methane emissions from rice paddies. Methane (CH_4) has about 25 times the potency of CO_2 as a greenhouse gas over a 100-year period. 40% of all anthropogenic methane emissions are caused by agriculture, of which rice paddies contribute about 8% and ruminant livestock about 32% (UNEP 2021). Reduced CH_4 emissions from paddy fields could result from breeding rice varieties that perform well under reduced flooding or that release less C below ground, thereby reducing methanogenesis by soil microorganisms (Aulakh *et al.* 2001).

- Reducing methane emissions from livestock. Several approaches are currently being explored, for example, identifying and/or breeding plant-based feeds that have lower fiber or higher polyphenolic content, both of which have anti-methanogenic properties (Jayanegara *et al.* 2009) (see **Box 2**).

- Reducing carbon emissions through breeding of crops requiring shorter cooking times and thus less cooking fuel. Promising steps have been taken in this direction for crops such as common beans (Wiesinger *et al.* 2021).

Box 7: Building capacity to use PGRFA

In 1983, the FAO conference adopted the International Undertaking on Plant Genetic Resources, a voluntary agreement that was adhered to by 113 countries. The Objective of the Undertaking was to promote international collaboration "to ensure that plant genetic resources of economic and/or social interest, particularly for agriculture, will be explored, preserved, evaluated and made available for plant breeding and scientific purposes..." and furthermore that such resources "should be available without restriction." (FAO 1983).

The Undertaking also recognized that the global playing field was far from level and that unrestricted access to plant genetic resources was largely of benefit to those countries and institutions that had the capacity to use them. Article 6 therefore stated that international cooperation "will, in particular, be directed to … establishing or strengthening the capabilities of developing countries … with respect to plant genetic resources activities, including plant survey and identification, plant breeding and seed multiplication and distribution, with the aim of enabling all countries to make full use of plant genetic resources for the benefit of their agricultural development..." (FAO 1983).

Unfortunately, despite this stated intention and significant advances in many middle-income countries, only relatively limited progress was made in the 1980s and 1990s in advancing the capacity of the lowest income countries to make use of PGRFA (FAO 1997). Thus, the need to strengthen capacity was again reiterated in the text of the International Treaty on Plant Genetic Resources for Food and Agriculture that superseded the Undertaking when it came into force in 2004.

Article 13.1 of the Plant Treaty states: "The Contracting Parties recognize that facilitated access to plant genetic resources for food and agriculture which are included in the Multilateral System constitutes itself a major benefit of the Multilateral System …" (FAO 2002). However, in the absence of the ability to use the genetic resources to which countries have facilitated access, such resources are of limited value. Thus, Article 13.2 lists training and capacity building among the priority elements of benefit-sharing within the Multilateral System. Article 7.2a of the Plant Treaty, meanwhile, provides that international cooperation between Contracting Parties shall particularly be directed to "establishing or strengthening the capabilities of developing countries and countries with economies in transition with respect to conservation and sustainable use" of PGRFA.

The second Global Plan of Action for PGRFA (FAO 2011) likewise emphasizes the importance of building capacity to make use of materials in the Multilateral System, with 5 of the 18 priority activities focusing on strengthening institutional capacity and promoting greater international collaboration to support national programs. One priority activity specifically aims to build and strengthen human resource capacity.

While it is difficult to get accurate figures on how much institutional capacity has strengthened over recent years, and conversely how much remains to be done, available data would indicate there is still a considerable way to go. For example:

- Low-income economy countries as classified by the World Bank received the lowest proportion of total germplasm distributions between 2012 and 2019 made using the Standard Material Transfer Agreement (SMTA) of the Plant Treaty, totaling 10.8% of all distributions worldwide. This said, lower middle-income economies received the highest amount (38.7% of total), with upper middle- and high-income countries receiving somewhere in between (26.7% and 23.8%, respectively). Those 45 countries identified by the United Nations as a least developed country (LDC) were the recipient for 11% of total distributions; those 32 classified as landlocked developing countries (LLDC) 12.5% of total; and those 30 as small island developing states (SIDS) 0.3% of total (Khoury *et al.* 2022).

- In the FAO WIEWS database providing data from 2012 to 2014, three of the 27 countries listed by World Bank as having low-income economies provided data on the number of their cereal breeders: Ethiopia, Madagascar, and Uganda. They reported an average of 2.7 breeders per country. By contrast, the seven countries with high income economies (Australia, Italy, Japan, Estonia, France, Germany, and UK) reported an average of 21.7 cereal breeders per country. This means that, taking population size into account, the low-income countries had less than 30% of the number of cereal breeders per head of population compared to the high-income countries, yet according to World Bank Development Indicators for 2019 (World Bank 2022b), their agricultural sectors were 17x more significant as a percentage of national GDP.

- Another indicator of a country’s status with respect to its plant breeding capacity is the ratio of public to private breeders. Although there are obvious exceptions, with some countries investing heavily in their public plant breeding sector, for most free market economies, increased economic development has tended to lead to an increase in private sector plant breeding. This is reflected in the FAO WIEWS 2012 to 2014 data for cereal breeders: in the three reporting countries having low-income economies, less than 25% of the plant breeders were in the private sector while about 80% of the cereal breeders in the seven high income countries were working in the private sector.

- Membership in the International Union for the Protection of New Varieties of Plants (UPOV) is an indicator that a country has a sufficiently advanced plant breeding and seed sector to want to take advantage of Plant Breeders Rights. While there are political and other reasons why a country might not wish to join, nevertheless it is notable that of the 27 countries classified by the World Bank (World Bank 2022a) as having low-income economies in 2021-22 (having an annual per capita GDP of less than US $1,045), none are members of UPOV. Furthermore, of the 55 countries classified as lower-middle income (having an annual per capita GDP of between US $1,046 and US $4,095) only nine are members. Indeed, of the 76 UPOV country members, more than 85% are classified as having upper-middle- or high-income economies.

Despite gaps in accurate and up-to-date information, it is clear from available data that many countries still lack the ability to benefit significantly from having access to the vast genetic diversity that is available to them in the Multilateral System of Access and Benefit Sharing under the Plant Treaty.

3.4 Supply of food and agricultural crop plant genetic resources

3.4.1 Supply of food and agricultural crop plant genetic resources in terms of germplasm collections

Global tracking of *ex situ* crop collections holdings provides insights into the global supply of PGRFA. We calculated the number of *ex situ* germplasm accessions maintained worldwide for each crop combining data from the FAO World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture (FAO WIEWS), the Genesys Plant Genetic Resources portal (Genesys PGR) , and the Global Biodiversity Information Facility (GBIF) ('living specimens' only included from GBIF). Assessments were made both at the taxon/crop level as well as at the genus level, the latter to be inclusive of supply of associated genetic resources, including crop wild relatives.

Crops with the greatest PGRFA supply, in terms of numbers of accessions of the taxon/crop held in *ex situ* facilities reported in these databases, for eight different crop use types of interest, are presented in **Figure 11**. The results are presented as the proportion of accessions of the crop, compared to total accessions of all crops per crop use type.

Accessions of a total of 354 different crops assessed in this study were reported in the combined *ex situ* collections dataset, with a total of 3,724,231 accessions at the taxon/crop level and 7,973,490 accessions at the genus level in *ex situ* collections, as a sum of all crops. Across all crop use types, in terms of crops with the greatest supply of PGRFA, those crops with the greatest numbers of accessions included cereals (wheat, rice, barley, maize, sorghum, oats, and various millets), pulses (common bean, soybeans, chickpeas, peas, groundnuts, cowpeas, lentils, faba beans, and pigeonpeas), forages (clovers, alfalfa, and *Lolium*), vegetables (cabbages, tomatoes, and chillies and peppers), fruits (grapes and apples), fibers (flax and cotton, and roots and tubers (potatoes). Also evident in this dataset was wide variation in numbers of *ex situ* accessions across the entire set of crops. As a whole, significant crops in terms of global *ex situ* supply evidently include a broad range of plants from a variety of crop types.

Ex situ germplasm collections of crops

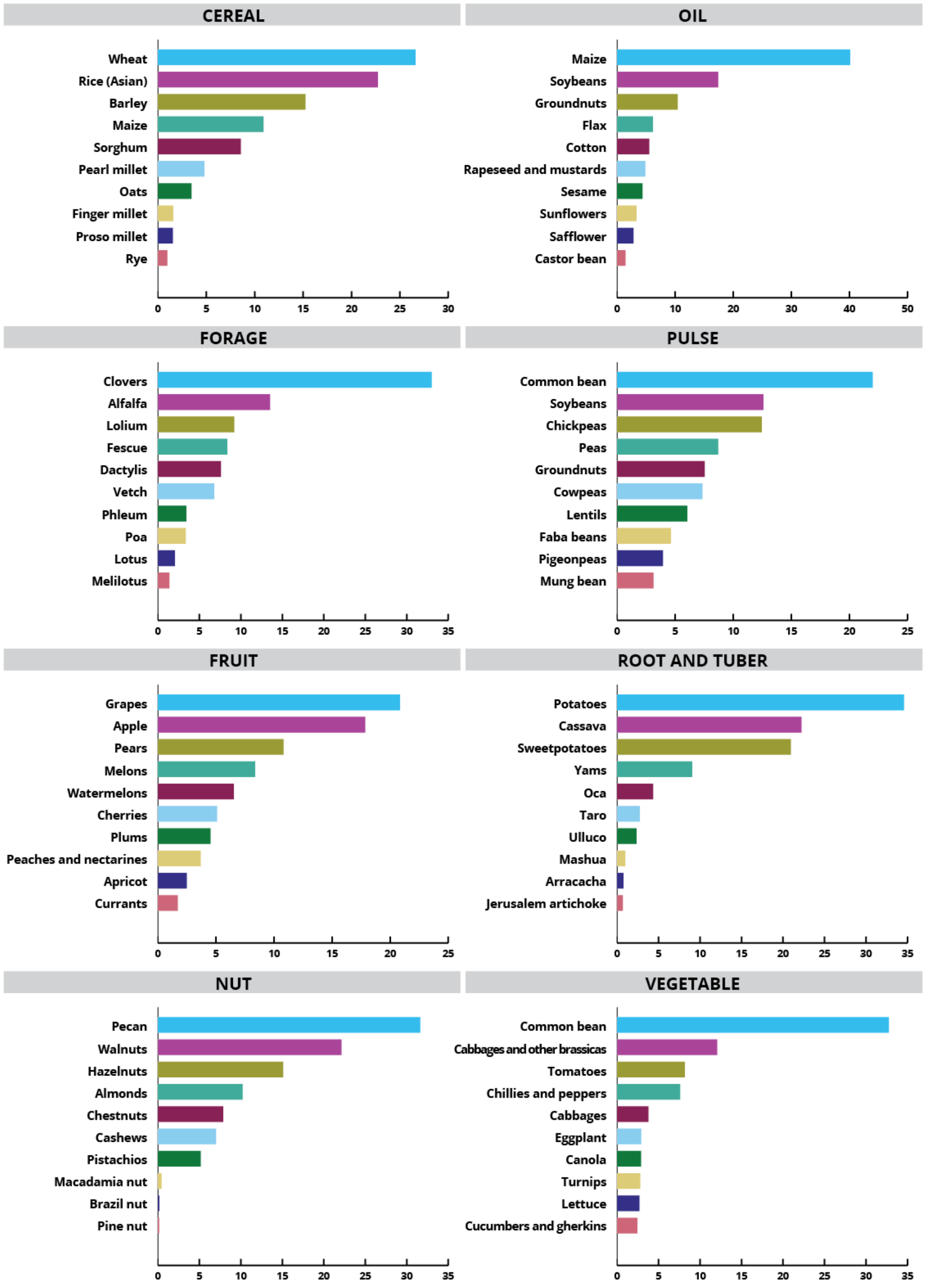

Figure 11: Supply of crop genetic resources as measured in terms of *ex situ* germplasm collections. Metrics are presented per crop as the proportion of accessions of the crop, compared to total accessions of all crops per crop use type. The subfigures display the ten crops with most accessions per crop use type. For crops such as maize with multiple uses, these are included in all relevant use type categories; values for these crops are total global, not separated by specific use.

3.4.2 Supply of food and agricultural crop plant genetic resources in terms of germplasm collection coverage in the Multilateral System of Access and Benefit Sharing of the International Treaty on Plant Genetic Resources for Food and Agriculture

An estimation of the degree to which the global supply of PGRFA is included within the Multilateral System of Access and Benefit Sharing (MLS) of the International Treaty on Plant Genetic Resources for Food and Agriculture was calculated using the same combined FAO WIEWS, Genesys PGR, and GBIF dataset. Coverage was first assessed based on direct notation in the datasets regarding inclusion in the MLS, with accessions with no information in these fields considered not included in the MLS. Because a large proportion of accessions (approximately 53%) had no direct notation, a second methodology was employed based on a combination of the Contracting Party status of country where the *ex situ* collections were held or if institute was an international center (CGIAR or other), and the list of crops covered in the MLS (i.e. Annex 1, as well as Article 15, of the Plant Treaty). As above, values were calculated both at the taxon/crop and genus level.

Crops with the greatest proportions of their PGRFA supply considered included in the MLS, using the direct notation methodology at the taxon/crop level, for eight different crop use types of interest, are presented in **Figure 12**. The results are presented as the proportion of accessions of the crop included in the MLS, compared to total global accessions of the same crop.

A total of 247 different crops assessed in this study were found to have *ex situ* accessions included in the MLS if assessed by direct notation, with a sum of 762,695 accessions in the MLS if calculated at the taxon/crop level and 1,704,166 accessions in the MLS if calculated at the genus level. If assessed by country/institute status/Annex 1 list, a total of 79 different crops assessed in this study were found to have *ex situ* accessions included in the MLS, with a sum of 2,137,646 accessions in the MLS if calculated at the taxon/crop level and 3,866,570 accessions in the MLS if calculated at the genus level.

Across all crop use types, in terms of crops with the greatest proportion of supply of PGRFA considered covered in the MLS, crops included a very diverse set of plants from all crop use types. As measured by direct notation, up to 89.2% of collections of forage crops such as *Galactia*, 80.7% of *Stylosanthes*, and 71.7% of *Indigofera*, were covered in the MLS. As measured by country/institute status/Annex 1 list, up to 100% of various citrus and forage (*Salsola*) collections were considered part of the MLS. Note that these are all relative proportions per crop. In terms of absolute numbers of accessions per crop considered part of the MLS, the crops with the largest representation in the MLS generally paralleled overall *ex situ* supply. Also evident in this dataset was wide variation in numbers and proportions of *ex situ* accessions included in the MLS, across the entire set of crops.

Coverage of *ex situ* germplasm collections of crops within the Multilateral System of Access and Benefit Sharing of the Plant Treaty

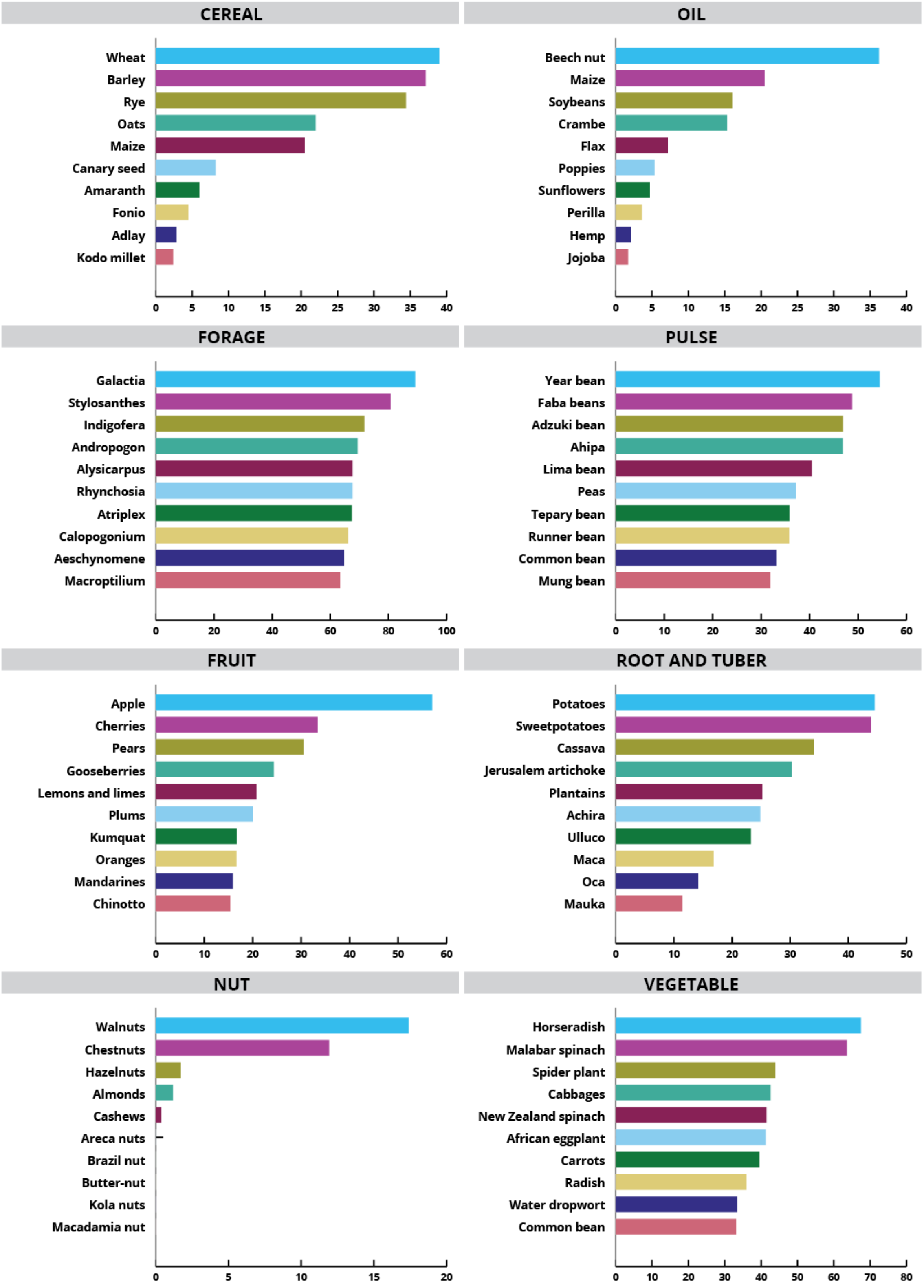

Figure 12: Coverage of crop genetic resources within the Plant Treaty's Multilateral System as measured by direct notation in global *ex situ* collections databases. Metrics are presented per crop as the proportion of accessions of the crop considered covered in the MLS, compared to total accessions of the same crop. The subfigures display the ten crops with most coverage in the MLS per crop use type. For crops such as maize with multiple uses, these are included in all relevant use type categories; values for these crops are total global, not separated by specific use.

3.4.3 Supply of food and agricultural crop plant genetic resources in terms of germplasm collection coverage of crops' primary region(s) of diversity

An estimation of the degree to which the global supply of PGRFA represents the range of diversity present in each crops' primary region(s) of diversity was calculated using the same combined FAO WIEWS, Genesys PGR, and GBIF dataset. Coverage was assessed by identifying the number of accessions originally collected within the primary region(s) of diversity and comparing this to the harvested area (Ha) of the crop (FAOSTAT data) within the primary region(s) of diversity. As above, values were calculated both at the taxon/crop and genus level. The results are presented as the proportion of accessions of the crop per unit area in the primary region(s) of diversity.

A total of 248 different crops assessed in this study were found to have *ex situ* accessions originally collected from their primary region(s) of diversity. In terms of crops considered best represented regarding coverage of their primary region(s), these include a broad range of crops of different crop use types, such as pawpaw, jojoba, canary seed, kiwicha, oca, amaranth, ulluco, kaniwa, beets, sweetpotatoes, jicama, mashua, lupins, dill, roselle, arracacha, cherimoya, faba beans, and many others. Also evident was wide variation in estimated coverage of crops' primary region(s) of diversity, across the entire set of assessed crops in this study.

3.4.4 Supply of food and agricultural crop plant genetic resources in terms of botanic garden germplasm collections

Significant *ex situ* germplasm collections of PGRFA are maintained outside of those national, regional, and international genebanks mainly represented in global databases such as FAO WIEWS and Genesys PGR, for example in botanic gardens. To assess the degree to which PGRFA of the assessed crops are represented in the world's botanic gardens, information on botanic institutes holding collections of each crop was calculated from Botanic Garden Conservation International's PlantSearch database, both at the taxon/crop and genus level.

Crops with the greatest PGRFA supply in botanic gardens, as calculated at the taxon/crop level, for eight different crop use types of interest, are presented in **Figure 13**. The results are presented as the proportion of unique botanic collection records for each crop, compared to total unique botanic collection records across all crops in each crop use type.

A total of 354 different crops assessed in this study were reported conserved in botanic institutions. In terms of crops represented in the greatest numbers of botanic gardens, the results are very different from the statistics for *ex situ* genebank collections. A wide variety of mainly perennial crops and their genera are in the most botanic institutions, with the top crops including apples, beech nuts, pears, sugar maple, currants, chillies and peppers, hazelnuts, lavender, plums, clovers, elderberries, rosemary, and cabbages. These crops represent the spectrum of crop use types, and mainly appear to reflect plants chosen for display in garden settings rather than predominantly for PGRFA purposes. Also evident was wide variation in numbers of botanic institutions across the entire set of assessed crops in this study. As a whole, assessed crops held in botanic gardens evidently include a broad range of plants from a variety of crop use types, and these differ widely from those conserved in national and international genebanks.

Botanic collections of crops

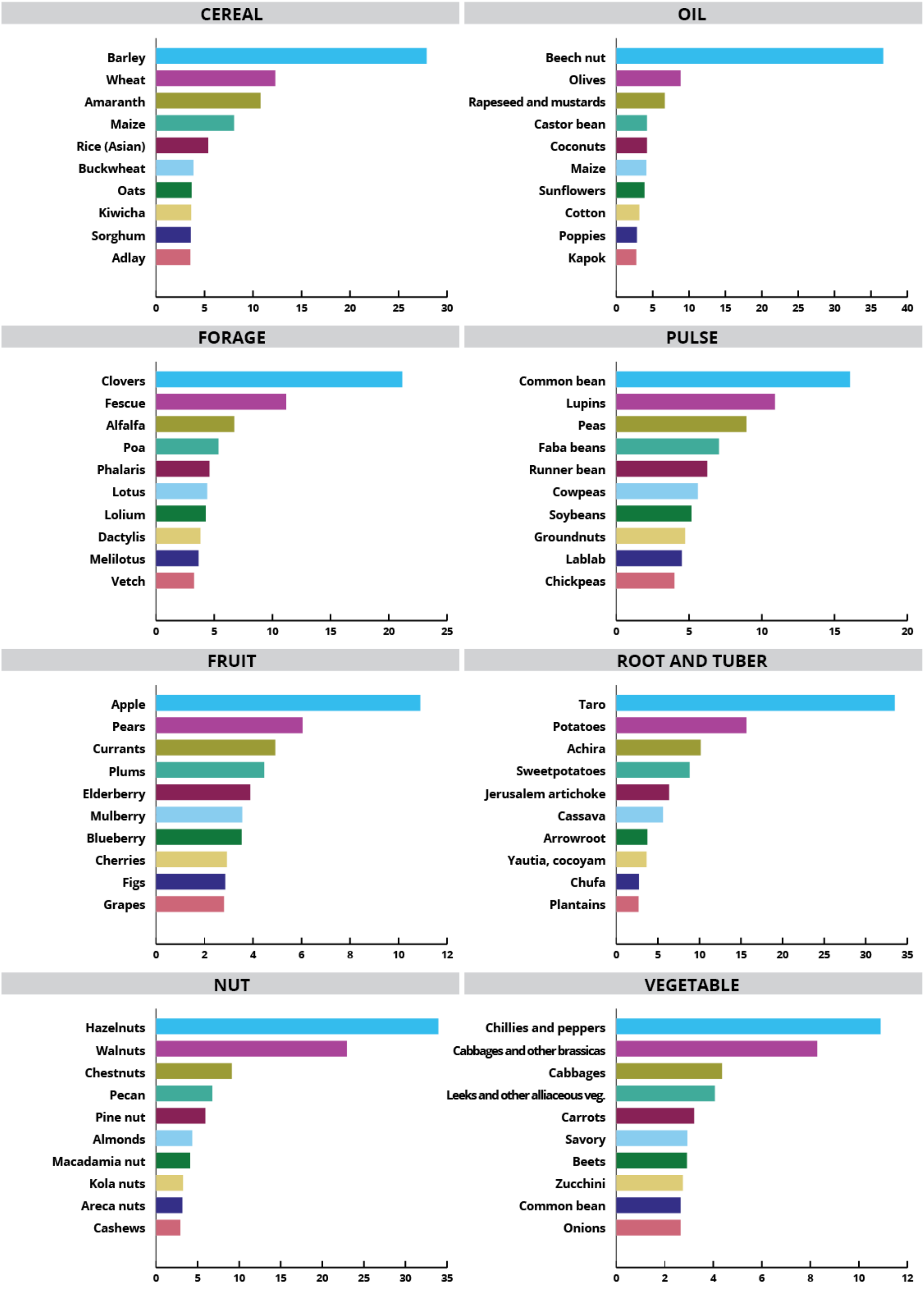

Figure 13: Supply of crop genetic resources in botanic garden collections. Metrics are presented per crop as the proportion of unique botanic garden records for each crop, compared to total unique botanic garden records across all crops in each crop use type. The subfigures display the ten crops with most records per crop use type. For crops such as maize with multiple uses, these are included in all relevant use type categories; values for these crops are total global, not separated by specific use.

3.4.5 Supply of food and agricultural crop plant genetic resources in terms of Global Biodiversity Information Facility research records

The Global Biodiversity Information Facility (GBIF) is the world's leading global repository for openly accessible biodiversity resources, including research specimens such as herbarium records and their associated data. We calculated research record supply of assessed crop PGRFA based on records reported in GBIF, both at the taxon/crop level as well as at the genus level. The results are presented as the proportion of records of the crop in GBIF, compared to total records of all crops in GBIF.

Research samples of a total of 321 different taxa/crops and 348 crop genera assessed in this study were reported available in GBIF, with a sum total of 95,876 records across all crops at the taxon/crop level and 310,985 records across all crops at the genus level found in GBIF. Across all crops and crop use types, in terms of crops with the greatest numbers of GBIF research samples, these include cereals (e.g. sorghum, maize, rice, pearl millet, wheat, barley, and finger millet), pulses (e.g. common bean, cowpeas, groundnuts, bambara beans, lupines, faba beans, and pigeonpeas), roots and tubers (e.g. sweetpotatoes, cassava, yams, and potatoes), vegetables (e.g. eggplants, okra, chillies and peppers, cabbages, and tomatoes), and forages (e.g. clovers, alfalfa, and vetch). Also evident was wide variation in numbers of samples in GBIF across the entire set of assessed crops in this study. As a whole, assessed crops with considerable GBIF records evidently include a broad range of plants from a variety of crop use types.

3.4.6 Supply of genetic sequence data (GSD) and other related data for food and agricultural crop plants

Understanding the availability of nucleotide, protein, structure, genome, genes, and other related information provides insights into the global supply of genetic sequence data (GSD) and other related data related to PGRFA. Policy discussions are ongoing about availability of this data (see **Box 9**) are ongoing, where the term Digital Sequence Information (DSI), which attempts to encapsulate all these data and potentially other forms of data on PGRFA, still requires a definition.

We calculated the supply of GSD and other related data at four levels - nucleotide, protein, genome, and gene - based on information held for each crop taxon in the National Center for Biotechnology Information (NCBI)'s Entrez database. This database comprises one of the three global GSD and other related data repositories, which are connected within the International Nucleotide Sequence Database Collaboration (INSDC). The other two repositories are the DNA Data Bank of Japan (DDBJ) and the European Molecular Biology Laboratory - European Bioinformatics Institute (EMBL-EBI); these share data across their platforms.

Crops with the greatest supply in terms of nucleotide sequences, as calculated at the taxon/crop level, for eight different crop use types of interest, are presented in **Figure 14**. The results are presented as the proportion of nucleotide resources of the crop, compared to total nucleotide resources of all assessed crops.

GSD and other related data entries of a total of 352 different taxa/crops assessed in this study were reported in the NCBI database, with a sum of 68,674,745 nucleotide sequences, 47,801,011 protein sequences, 317 genomes, and 6,434,966 gene sequences available. Across all crops and crop use types, in terms of crops with the greatest numbers of nucleotide sequence resources, these included cereals (e.g. wheat, maize, barley, rice, and sorghum), vegetables (e.g. cabbages, tomatoes, beets, chillies and peppers, turnips, and onions), pulses (e.g. soybeans, groundnuts, chickpeas, and common bean), tobacco, forages (e.g. lolium, clovers, and alfalfa), oil crops (e.g. soybeans and rapeseed and mustards), fruits (e.g. various citrus crops as well as grapes), and a variety of other crops such as cotton, hops, sugar beets, and agave. Those crops with the greatest amounts of GSD resources varied by the four metrics (nucleotide, protein, genome, and gene). Clearly evident was wide variation in numbers of GSD resources across the entire set of assessed crops as well as across the GSD metrics in this study. As a whole, assessed crops with considerable GSD resources evidently include a very broad range of plants from a variety of crop use types.

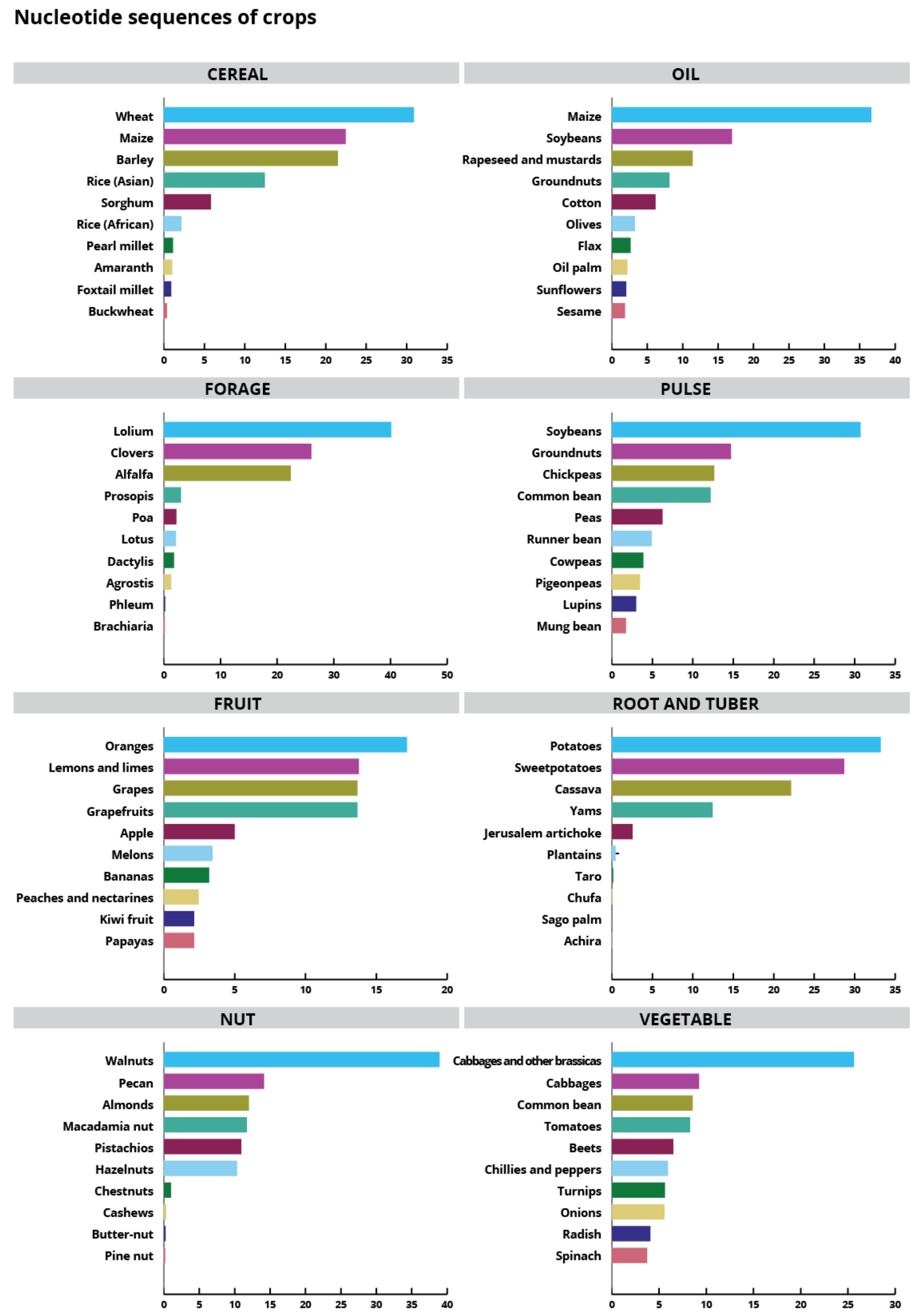

Figure 14: Supply of GSD and other related data on crops. Metrics are presented per crop as the proportion of nucleotide resources of the crop, compared to total nucleotide resources of all assessed crops per crop use type.

The subfigures display the ten crops with most nucleotide resources per crop use type. For crops such as maize with multiple uses, these are included in all relevant use type categories; values for these crops are total global, not separated by specific use.

Box 8: PGRFA and the future of biofuel crops

While humanity has burned wood and other forms of plant biomass from time immemorial, interest in its conversion into gaseous or liquid fuel (biofuel) has taken off in recent decades as attention has focused on finding alternatives to fossil fuels. Hailed by some as a significant contributor to reducing overall greenhouse gas (GHG) emissions, the net reductions in GHG emissions are frequently less than hoped for and in some situations might even be negative (Jeswani *et al.* 2020).

The real potential of biofuel is likely to be highly plant and process specific. The net reduction in emissions of biofuel compared to fossil fuel depends on many factors including the type of crop and the nature and amount of energy required for its production, processing, and transport. Recent efforts to compare the environmental impacts of biofuels using whole Life Cycle Assessment (LCA) methodologies (i.e., from production to final use) have shown a very wide range of potential impacts (Reijnders 2021).

Biofuel crops are also feared to be unwanted competitors with food crops for land and other resources (Muscat *et al.* 2020). Two main approaches are being explored to minimize resource competition between biofuel and food crops: a) producing biofuels from crop residues and other by-products and b) growing biofuel crops on marginal lands that are unsuitable for food production (or forestry).

While many food crops have been considered for use as biofuel material (including maize, canola, sugar beet, sugarcane, coconut, oil palm, and soya beans), it is their residues (straw, husks, etc.), that provide a much less controversial source of biofuel feedstock. The lignocellulose in such residues represents a potentially important source of energy, even though more processing is required than for starch or sugar to produce the sugar monomers required for fermentation into fuel. It thus makes sense to breed varieties of food crops that have more and better-quality straw and other by-products that can be used to produce biofuel after the food harvest. Present-day varieties of many crops having high lignocellulosic straw biomass tend to have a low grain yield potential. However, this association may be possible to break through further genetic improvement (Dash *et al.* 2021).

Many possibilities exist for developing biofuel crops for cultivation in areas not suitable for food crop production. C4 grasses, characterized by a high productivity and resource use efficiency, are among the most productive plants and most promising as cellulosic biofuel materials. *Miscanthus* spp., switchgrass (*Panicum virgatum* L.), Napier grass (*Cenchrus purpureus* (Schumach.) Morrone, syn. *Pennisetum purpureum* Schumach.) and sweet sorghum (*Sorghum bicolor* (L.) Moench) have received research attention. All could be significantly enhanced as biofuel feedstocks through improvements to their yield, stress tolerance and the content and composition of their lignin, cellulose, and hemicellulose. To maximize biomass yield, absence of flowering and grain set are considered desirable traits (Jakob *et al.* 2009).

An alternative to cellulosic by-products is the use of vegetable oil to produce fuel (biodiesel). This may be equally or even more problematic to actualize at scale. Vegetable oils tend to make up only a small proportion of most crop residues. Using commercially grown oil crops competes with food production, and in some cases, e.g., palm oil production, is associated with environmental and GHG emissions concerns. Some plants have shown promise for oilseed production from marginal areas, for example Jatropha (*Jatropha curcas*). However, large scale production has thus far met with mixed success (Lahiry 2018).

Despite various concerns, the production and use of biofuels is continuing to expand worldwide, especially for transport and circumstances where renewable electricity is not an option. According to the International Energy Agency (IEA 2021), in 2019, worldwide biofuel production reached 161 billion liters (43 billion gallons), up 6% from 2018, and biofuels provided 3% of the world's fuels for road transport. Given the on-going imperative to cooperate globally to limit greenhouse gas emissions, the exchange of PGRFA for biofuel use, including possibly under the Multilateral System, could be further explored by the international community.

Box 9: "Digital sequence information": the importance of access to data and the challenges regarding benefit sharing

Since the Convention on Biological Diversity (CBD) was established in 1992, the international community has had legally binding arrangements for negotiating access to, and sharing the benefits derived from the use of biodiversity. Through the CBD's 2010 Nagoya Protocol and through the International Treaty on Plant Genetic Resources for Food and Agriculture, mechanisms for access and benefit sharing (ABS) of physical crop genetic resources have been carefully formalized. Other international agreements dealing with ABS include the Pandemic Influenza Preparedness (PIP) framework, the Antarctic Treaty (AT), and the Biodiversity Beyond National Jurisdiction negotiations under the auspices of the United Nations Convention on the Law of the Sea (UNCLOS) (Aubry *et al.* 2021; Rohden and Scholz 2021).

These ABS instruments are complex, and their negotiations have been, and remain, among the most contentious of topics within the agreements (Aubry 2019; Rohden and Scholz 2021; Wynberg *et al.* 2021). Their varied interpretations and implementation across the world create confusion for practitioners and policy makers alike, including who is subject to their conditions, how ABS can be bilaterally negotiated, and how biodiversity outside of the timeframe of the instruments is governed (Bagley *et al.* 2020; von Wettberg and Khoury 2021).

Further complicating matters is the potential that information generated through research that is important to the use of genetic resources, such as genotypic or phenotypic data on crops, may soon come to be subject to ABS requirements alongside the physical genetic resources. The generation, storage, exchange, and use of these data - which are often called "Digital Sequence Information" (DSI) in policy negotiations - have all advanced rapidly over recent decades (Arora and Narula 2017; Crossa *et al.* 2017; Mir *et al.* 2019), but potentially relevant ABS mechanisms have not kept pace. A concern has begun to be voiced that without updating ABS mechanisms, the increasing use of this information may diminish the power of ABS frameworks governing only physical genetic resources. This has now come to a head, with the CBD, Plant Treaty, and other agreements actively discussing ABS for DSI.

These discussions could have major consequences regarding the international flow of information relevant to plant breeding and the conservation of PGRFA. New mechanisms may create increased benefit sharing deriving from the use of DSI, but also may hinder crop research. Since this data began to be generated in large quantities in the 1970s and 1980s, they have commonly been held in open access platforms (Benson *et al.* 2018; Sayers *et al.* 2019; Laird *et al.* 2020), and many crop researchers take the accessibility of DSI data for granted (Woefle *et al.* 2011). These formats have in many ways powered the genomics revolution (Molloy 2011; Pinowar *et al.* 2011, Gallagher *et al.* 2020).

In recent years a series of background papers and published research articles have attempted to clarify the issues around DSI and the potential and constraints regarding ABS (Rohden and Scholz 2021; von Wettberg and Khoury 2021). From this body of evidence, several major themes emerge.

First, the continued lack of clarity about the subject itself needs to be resolved. DSI (along with "genetic sequence data," "PGRFA information," and various other terms) as placeholders have been in use in the CBD and International Treaty for a number of years, but none represent ideal monikers for the range of sequence data (DNA, RNA, proteins, etc.), phenotypic and morphological information, passport or provenance data, and other information potentially intended to be included in negotiations (Laird and Wynberg 2018; Cowell *et al.* 2021; Rohden and Scholz 2021).

Second, rapid exchange of DSI has provided enormous societal benefits globally (Rohden *et al.* 2020). Perhaps the most visible recent example is the development and sharing of SARS-CoV-2 sequence information, leading to the quick development of vaccines around the world and critical information on the virus's diversity and adaptive capacity (Maxmen 2021).

Third, due to the importance of access to DSI and the lack of clarity around definitions and scope of this data and possible ABS obligations, constraints or nuanced complications regarding exchange are likely to be very difficult to implement and have considerable negative impacts, including on crop research (Bagley *et al.* 2020; Iob and Botigue 2021; Rourke 2021; Vogel *et al.* 2021). Multilateral or fully open systems of exchange are generally considered to be preferable for scientists and for managers of genetic resources (Brink and van Hintum 2021; Cowell *et al.* 2021).

Finally, the potential of DSI to contribute to food security and sustainable agriculture, of course, is dependent on the capacity to make use of these ever larger and more complicated datasets. This capacity, as with other aspects of utilization of PGRFA, still varies widely across institutions, countries, and regions (see **Box 7**) (Rohden *et al.* 2020). Further capacity building is critically needed for the benefits of DSI to be more widely and equitably realized (Rohden *et al.* 2020; De Jonge *et al.* 2021; Rouard *et al.* 2021).

3.5 Security of food and agricultural crop plant genetic resources

3.5.1 Security of food and agricultural crop plant genetic resources in terms of safety back-up of germplasm collections at the Svalbard Global Seed Vault

The Svalbard Global Seed Vault (SGSV) is considered the foremost safety-backup facility for *ex situ* PGRFA globally and is available as a resource for virtually any *ex situ* collection worldwide, with seed deposits made through a black box agreement (see **Box 10**). SGSV currently houses more than 1.25 million samples of almost 5500 agriculturally related species, deposited by 89 different genebanks and other institutions around the world (Norwegian Ministry of Agriculture and Food 2022; NordGen 2022).

We calculated the total number of accessions for each crop in SGSV based on information from its SeedPortal, compared to the total count of accessions for each crop in all *ex situ* repositories as reported in FAO WIEWS, Genesys PGR, and GBIF (living specimens) (see the supply domain, subsection 3.4.1). Assessments of safety backup were made both at the taxon (crop) level, as well as at the genus level, the latter to be inclusive of security of associated genetic resources, including crop wild relatives.

Crops with the greatest degree of safety backup, as calculated at the taxon/crop level, for eight different crop use types of interest, are presented in **Figure 15**. The results are presented as the proportion of records of the crop in the SGSV, compared to total records of the crop in all *ex situ* collections.

Accessions of a total of 206 different crops assessed in this study were reported conserved in SGSV if considered at the taxon/crop level (with a grand total of 859,167 accessions stored), and 223 at the genus level (with a grand total of 1,721,409 accessions stored). Across all crop use types, in terms of crops with the greatest absolute quantities of accessions in SGSV, the results largely mirror those of overall *ex situ* collections, with cereals such as wheat, rice, barley, sorghum, pearl millet, and maize, and pulses such as common bean, soybeans, chickpeas, cowpeas, groundnuts, and pigeonpeas having the largest representation in SGSV.

In terms of the proportion of accessions safety duplicated at SGSV per crop, relative to their overall *ex situ* collections worldwide, a variety of forage crops including *Galactia*, *Calopogonium*, *Stylosanthes*, and *Sesbania* were among the most well represented, as well as various cereal, pulse, (seed producing) root and tuber crops, fiber, and herb and spice crops. Quite evident in this dataset was wide variation in proportions of *ex situ* collections safety duplicated in SGSV across the entire set of crops. Internationally important crops with particularly low proportions of their *ex situ* collections conserved at SGSV included plants from many different crop use types, including fruits, oils, fibers, vegetables, pulses, herbs and spices, and roots and tubers. SGSV is a safety backup for seed, thus crops mainly conserved through other types of reproductive propagules typically have low values for safety duplication in this metric.

Safety backup of *ex situ* germplasm collections of crops at the Svalbard Global Seed Vault

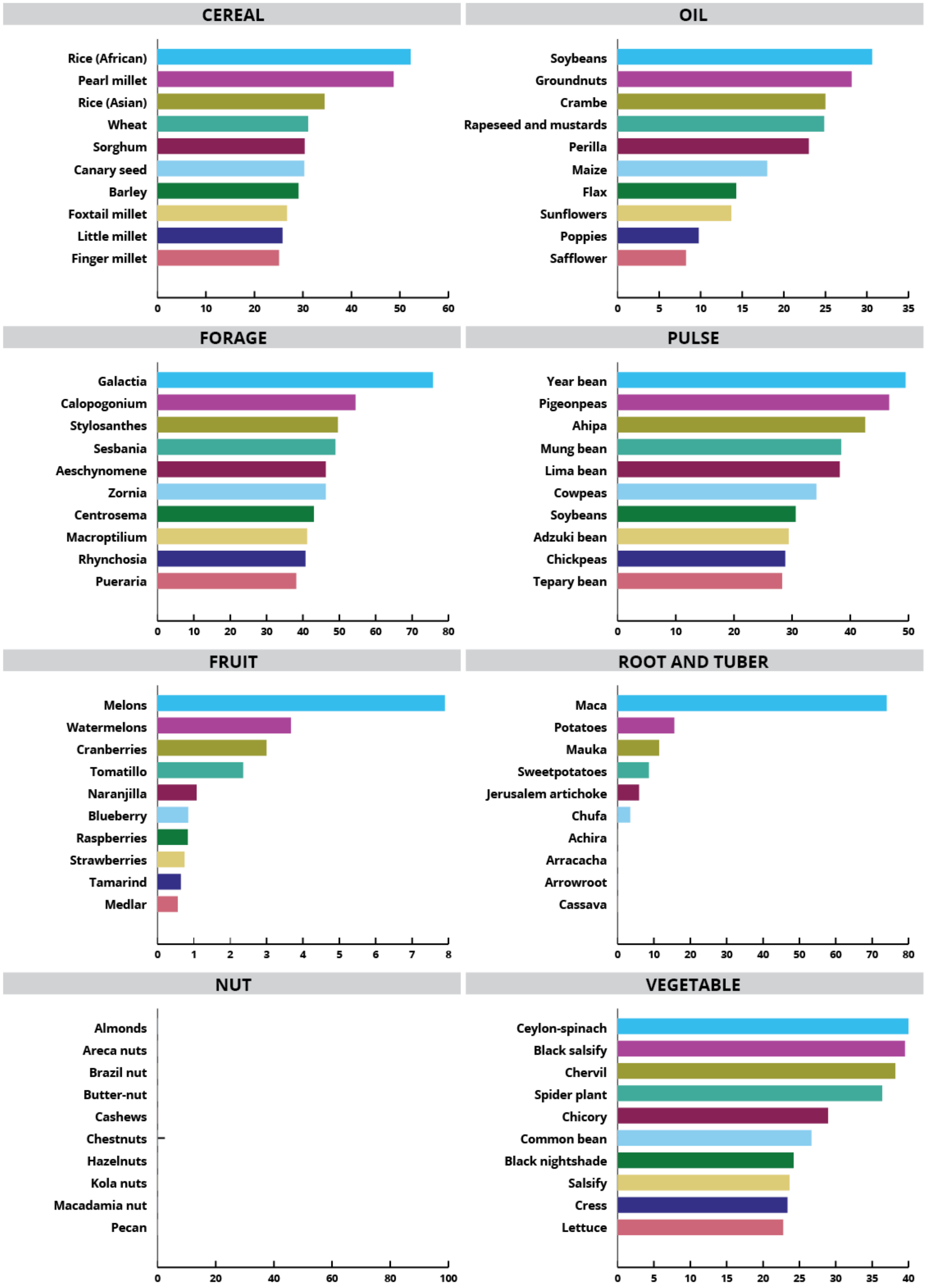

Figure 15: Safety back-up of crop genetic resources at the Svalbard Global Seed Vault. Metrics are presented per crop as the proportion of accessions of the crop considered backed up at the SGSV, compared to total accessions of the same crop. The subfigures display the ten crops with the highest degree of safety back-up per crop use type. For crops such as maize with multiple uses, these are included in all relevant use type categories; values for these crops are total global, not separated by specific use. No accessions of nut crops were recorded as backed-up at the SGSV.

Box 10: An ultimate safety net: Svalbard Global Seed Vault

Around the world there are approximately 1,750 genebanks and other *ex situ* germplasm repositories that conserve more than 7.4 million samples of different crop landraces, cultivars, breeding materials, and wild relatives, most of which are held as seeds. Of these, it is estimated that some 2 million are distinct accessions with the rest being duplicates (FAO 2010). Genebank facilities range from the rudimentary, perhaps comprising just a small laboratory with an air-conditioned room in which to store packets of seeds, to hi-tech complexes with sub-zero seed storage chambers and automated controls. Yet however securely seeds are conserved, there is always the potential for a disaster to hit - for electricity to be interrupted for an extended period, for a flood, earthquake, or typhoon to strike, or for collections to be looted during war or civil strife. Samples can also be lost through mismanagement or the ravages of pests and diseases (Khoury *et al.* 2021).

The danger of losing invaluable genetic resources, which may no longer be found in the wild or on farmers' fields, led FAO to recommend that a duplicate sample of every original accession should be stored in a geographically distant area, under the same or better conditions than those in the original genebank (FAO 2014). In many cases this has been carried out through depositing duplicate samples in a different country's genebank under 'black box' conditions, by which the depositor retains sole legal rights over the material.

It has long been recognized that additional safety measures are desirable if the world's crop diversity is to be truly secure. In the late 1980s the Norwegian government invited FAO and IBPGR (now the Alliance of Bioversity International and the International Center for Tropical Agriculture [CIAT]) to explore the feasibility of creating an international back-up seed store on the island of Spitsbergen in the Svalbard Archipelago. This would be open to deposits by any genebank or other *ex situ* collection around the world and modeled on a facility previously established by the Nordic Gene Bank (now NordGen) in a disused coal mine. Although found to be technically feasible, the idea was not pursued because of the absence of international, legally binding agreements covering ownership, access, and user rights. However, interest in the idea revived when, with the adoption of the International Treaty on Plant Genetic Resources for Food and Agriculture, an appropriate policy framework was put in place, and the way was open for the creation of the Svalbard Global Seed Vault (https://www.seedvault.no/).

Built by the Norwegian government as a highly secure, black-box, back-up seed store, the Svalbard Global Seed Vault is located north of the Arctic Circle, 120 m deep inside a mountain at an altitude of 130 m. It was constructed to hold 4.5 million back-up seed samples at a storage temperature of -18°C. Even with global warming, the vault will remain in one of the coldest and safest places on the planet. The Seed Vault was opened in 2008 in the presence of the Prime Minister of Norway, Jens Stoltenberg, the President of the European Union, José Manuel Barroso, Director-General of the Food and Agriculture Organization (FAO) of the United Nations, Jacques Diouf, and Nobel Peace Prize laureate, Wangari Maathai.

Overall responsibility for the Seed Vault rests with the Norwegian government, while the Crop Trust allocates funds to cover operating costs, and NordGen oversees the management and seed operation. In 2007, the Governing Body of the Plant Treaty endorsed the Seed Vault. Since then, the Governing Body has repeatedly encouraged Contracting Parties to deposit material. The Chairperson of the

Governing Body serves as the Chairperson of the International Advisory Panel of the Seed Vault, thus providing political and technical guidance.

Box 11: The need for a back-up facility network for vegetatively propagated and recalcitrant seeded crops

While a large proportion of the world's most important crops produce orthodox seeds, i.e., seeds that can be dried and frozen for long-term storage, there are many species that cannot be stored as seed, either because they generally don't produce seeds, e.g., many types of banana, or because their seeds do not breed true to desired type, e.g., potato, sweetpotato, yam, cassava, apple, and orange. In addition, there are crops that produce 'recalcitrant' seeds that cannot survive drying and freezing, e.g., cacao, rubber, coconut, breadfruit, avocado, mango, lychee, and many other tropical crops. Collections of crops that cannot be stored as seed in sub-zero temperatures are most commonly conserved as plants in field genebanks, or as tissue cultures in *in vitro* genebanks. However, these systems can be expensive and present risks to the long-term security of collections.

The securest long-term method for conserving most crops that cannot be stored as seed is to cryopreserve appropriate plant tissues in liquid nitrogen at -196ºC. However, suitable, robust cryopreservation protocols are not yet available for all crops, and some may ultimately prove impossible to conserve in this way. For many, there are also significant differences in how individual varieties and genotypes respond to different freezing and thawing techniques. Although much further research is needed, some crops are already being cryopreserved on a significant scale. In a survey of 15 of the world's leading institutions that hold collections of vegetatively propagated and recalcitrant seeded crops, it was found that of the total, almost 60% of banana, more than 30% of *Allium*, and about 25% of coffee and potato accessions were cryopreserved (Acker *et al.* 2017).

Unlike the situation for orthodox seeded crops, there is still a long way to go before the global PGRFA community can be confident that it has the necessary facilities and systems in place to ensure that the genetic diversity of vegetatively propagated and recalcitrant seeded crops is adequately safeguarded. A feasibility study in 2017 (Acker *et al.* 2017) recommended the establishment of a global back-up cryopreservation facility network be set up along the same lines as the Svalbard Global Seed Vault, to accommodate the estimated 5,000 to 10,000 accessions arising from current, on-going cryopreservation activities at CGIAR and other genebanks. These recommendations are starting to be implemented.

4. Discussion

4.1 Implications regarding the International Treaty on Plant Genetic Resources for Food and Agriculture and its Multilateral System of Access and Benefit Sharing

This report has assembled data on 355 important food and agricultural crops that are currently cultivated, traded, and/or available in food supplies, and whose PGRFA are researched, exchanged, and conserved around the world. Analyses of these data has concentrated on five major domains:

- Use, especially regarding global production, trade and contribution to food supplies
- Interdependence regarding PGRFA
- Demand for PGRFA
- Supply of PGRFA
- Security of PGRFA

The data on crop use show that hundreds of different crops are widely grown, traded, present in food supplies, and researched around the world. Crops that are valuable internationally are found in all the main crop use types examined in this study: ten food categories (cereal, fruit, herb and spice, nut, oil, pulse, root and tuber, stimulant, sugar, and vegetable crops) as well as fiber, forage, and industrial crops. Nevertheless, such crops represent only a small fraction of the total number of food and agricultural plants (**Boxes 3** and **4**). Humanity is making significant use of only a small proportion of the plants available to it.

The data also show that crop use is not static and that a plant's utilization can vary widely both spatially and temporally. Crops that were not considered important on a global or regional scale a few decades ago have become widely utilized today (**Boxes 1** and **2)**. Likewise, plants that are currently grown only on a small scale could become major crops of the future (**Box 3**), although it is impossible to predict with high accuracy which crops will flourish, and which will decline. The certainty is that the spectrum of globally and regionally important crops will change, possibly substantially, over time.

The data further show that for almost all the most utilized crops, there is a high level of interdependence among countries with respect to their PGRFA. A country may be the source of extensive genetic diversity of one crop, for example if it is in the crop's primary region(s) of diversity, but at the same time might not harbor substantial genetic diversity of another crop, even if that crop has been widely grown in the country for some time. Many of the crops studied have high estimated interdependence values as well as large directly quantified germplasm distributions to many different country and region recipients. This is not only true for global staple crops but also for a large variety of other plants of various crop use types.

There is evidence that the amount of PGRFA distributed between institutions and countries has increased over recent decades (see also Khoury *et al.* 2022) and it is probable that demand for the PGRFA of many different crops will continue to grow in the future. It is also likely that the specific crops and germplasm requested will shift over time; crops and genotypes that are rarely distributed today may become in high demand in the future as breeders and other researchers switch focus in response to changing opportunities and challenges. Shifts in the crops and germplasm requested may also occur as research programs become more active in various world regions **(Boxes 7** and **8**). Demand for germplasm of wild relatives of crops and for associated information on PGRFA, such as GSD, will also very likely increase substantially as their uses in plant breeding become more widespread.

All metrics studied showed a wide variation among crops in terms of the amount of PGRFA held *ex situ* and hence that is, in theory, available for use. For some crops, especially major, orthodox seed producing crops, there are very large, readily available collections such as those held in trust by the CGIAR Centers. However, for other crops, collections may be less available or much smaller, including for many of those that cannot be conserved as seed and must be maintained *in vivo* (in field collections) or *in vitro* (in specialized laboratory or cryopreservation facilities). Agricultural research institutions and botanic gardens appear to complement one another by focusing their conservation efforts on different crops.

The data also show that there are significant gaps in many *ex situ* collections, whether maintained by agricultural research institutions or botanic gardens. Geographic prioritization of primary region(s) of diversity of crops appears to continue to be relevant, especially for less well conserved crops as well as for the wild relatives of most crops (see Castañeda-Álvarez *et al.* 2016). Further collecting outside of these regions will also likely provide substantial value for the acquisition of new variants. The availability of botanical research specimens and GSD are likewise highly variable among crops, with large resources for many crops but substantial gaps for many others (**Box 9**).

With respect to the security of PGRFA, while much has already been duplicated in the Svalbard Global Seed Vault, particularly for major cereals, pulses, and a few other crop types (**Box 10**), the data show that many of the world's *ex si*tu accessions are not documented as safety duplicated. FAO recommends that: "A safety duplicate sample for every original accession should be stored in a geographically distant area, under the same or better conditions than those in the original genebank." Moreover "To minimize risks that can arise in any individual country, safety duplication will be ideally undertaken outside that country" (FAO 2014). Given the importance of safety duplication, special attention should be given to securing those accessions not currently safety duplicated, including those collections that must be maintained *in vivo* or *in vitro* (**Box 11**). Such collections frequently have very incomplete coverage and are often inadequately duplicated.

The findings of the study have significant implications that could be applied to the future development of the Treaty's Multilateral System (MLS) of Access and Benefit Sharing, and the crops listed in its Annex 1 as well as, potentially, Article 15 (CGIAR collections). In drawing up the original list some 20 years ago, crops were included in, or excluded from, the Annex primarily based on their perceived importance for food security at that time as well as the understood extent of interdependence among countries with respect to their PGRFA. As this study has shown, crop use and PGRFA demand and interdependence are dynamic, with many crops that are important for food security and sustainable agriculture today not currently included in Annex 1. Moreover, additional crops will almost certainly become more important than they are currently for future food security. Given the critical role that the use of PGRFA can play in helping ensure food security, sustainable agriculture, and climate adaptation (**Box 5**) and mitigation (**Box 6**), and the value of facilitated access to PGRFA under the Plant Treaty to achieve these aims, it is hoped that the findings of this study will prove useful in helping to guide discussions on the future coverage of the MLS. This is relevant not only for food and forage crops, but also the cornucopia of plants that provide other values such as fiber and industrial uses.

4.2 Information gaps and recommendations on data enhancements

This study aims to compile high quality, accessible, replicable information on crop use as well as on PGRFA interdependence, demand, supply, and security, across as many food and agricultural crops as possible. Its integration in one assessment has the potential to provide novel and valuable insights for PGRFA conservation, research, and use activities, including prioritizing across crops and activities. This said, we emphasize that, while crops have different status levels in terms of, for example, demand, supply, and security of PGRFA, every crop has some gaps in some of these aspects, and every crop assessed here is considerably important to many people around the world.

We therefore emphasize that not only the crops with the lowest/poorest status should be prioritized for conservation, research, and use efforts, nor only those with the greatest current use or estimated interdependence regarding their PGRFA. Some of the most useful metrics may be those that assess the status of crops in relation to themselves, rather than to the other crops, for example the metrics based on degree of coverage of *ex situ* collections in the MLS, or of their safety duplication in the SGSV.

In this same respect, while averaged values across the different metrics, groups, components, and domains assessed here have been provided in the supplementary results for each crop, each of these metrics represent different, and often equally valid or important, ways of understanding crop use as well as PGRFA interdependence, demand, supply, and security. Thus, overemphasis on prioritizing crops based on these averaged values is likely to lead to oversimplification and loss of important detail and nuance.

Several other limitations in the data should be mentioned. The metrics on crop use and on estimated PGRFA interdependence rely heavily on FAOSTAT data, which do not currently report production, trade, and food supply information on all crops covered in this study. Moreover, many of the assessed crops that are reported in FAOSTAT are contained within general commodity listings, sometimes encompassing dozens of crops, making accurate assessments of the current use of each specific crop extremely challenging to calculate.

Regarding the major global databases on PGRFA demand, supply, and security, including FAO WIEWS, the Data Store of the Plant Treaty, UPOV's PLUTO database, Genesys PGR, PlantSearch, GBIF, and SGSV's SeedPortal, lack of standardized reporting, for example of crop and taxonomic names, both within and between these databases, leads to considerable challenges in assigning values to specific crops.

Regarding recommendations to these critically important global information systems and their underlying data providers that, if implemented, would directly improve the quality of these crop metrics, we emphasize that the more comprehensive, disaggregated, verified, and annotated the FAOSTAT data are, the more accurate the metrics presented here are likely to be. Likewise, the more data providers participating in the global demand, supply, and security information systems, and the more that the data provided is consistent and standardized both within and across these systems, the more robust will be these metrics, as well as the more efficient it will be to periodically calculate the metrics.

Finally, we emphasize that this novel integration of many sources of data on the use of crops as well as issues around interdependence regarding, demand for, supply of, and security of their genetic resources represents a first iteration. Further sources of data useful to understanding the status of these crops could be explored and potentially integrated, and additional enhancements to the methods used to calculate existing metrics could be implemented. Through further periodic iterations, which will be useful to quantifying change over time in these metrics, we also expect that this resource can continue to grow and improve.

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Annex 1. Extended methodology and data sources

A1. Crop list

A1.1 Crop list compilation

To construct as comprehensive as possible a candidate list of food and agricultural plants to be included in this Study, we surveyed crops covered in FAOSTAT, Annex 1 of the International Treaty, CGIAR mandate major crops, and a variety of other information sources. We aimed to be comprehensive of all cultivated food and agricultural crops, including those used for food (including spices, herbs, and beverages), fiber, forage, and industrial crops. We did not aim to be comprehensive of crop plants strictly cultivated for non-food and agricultural purposes, such as for ornament.

For FAOSTAT (https://www.fao.org/faostat/en/), we reviewed in entirety all metadata (https://www.fao.org/faostat/en/#definitions) and added to the crop list all crops mentioned in food supply, production, and trade data, including all those listed specifically, as well as all those marked in the metadata as covered within general/nes commodities. In the compiled crop list, we noted whether the crop is listed in FAOSTAT, including whether or not it is listed specifically in FAOSTAT food supply data, production data, and trade data. The crop list documents the specific FAOSTAT commodity name within which each crop is included.

Regarding Annex 1 of the International Treaty (https://www.fao.org/plant-treaty/areas-of-work/the-multilateral-system/annex1/en/), we reviewed the Annex and included all crops, including forages. The crop list notes whether the crop is included in Annex 1.

Regarding CGIAR mandate crops, we reviewed CGIAR mandate lists and included all mentioned food crops. For forages, which are often not explicitly stated at the species/crop level in mandate lists, we included all genera with relatively large (>500 accessions) collections in pertinent CGIAR (i.e., International Center for Tropical Agriculture [CIAT] and International Livestock Research Institute [ILRI]) genebanks, as the list of genera with smaller amounts of accessions was exceedingly long. The crop list notes whether the crop is considered a CGIAR mandate crop.

In supplement to the above, we also reviewed and ensured the inclusion of crops:

- That have been specifically funded under the International Treaty Benefit Sharing Fund (https://www.fao.org/plant-treaty/areas-of-work/benefit-sharing-fund/overview/en/)
- Of priority focus within the Crop Trust's "Global Systems Project" (https://www.croptrust.org/our-work/our-projects/)
- Of priority focus within the Crop Trust's "Adapting Agriculture to Climate Change: Collecting, Protecting and Preparing Crop Wild Relatives" project (http://www.cwrdiversity.org/)
- Of focus in the Crop Trust's "Harlan and de Wet Crop Wild Relative Inventory" (https://www.cwrdiversity.org/checklist/)
- Of focus in the US Department of Agriculture (USDA)'s GRIN-Global Crop Wild Relative Inventory (https://npgsweb.ars-grin.gov/gringlobal/taxon/taxonomysearchcwr.aspx)
- That have a Global Crop Conservation Strategy published by the Crop Trust (https://www.croptrust.org/our-work/supporting-crop-conservation/conservation-strategies/); all forage crops on the crop list were assumed to be covered in the Global Strategy for the Conservation and Utilisation of Tropical and Sub-Tropical Forage Genetic Resources (https://www.croptrust.org/pgrfa-hub/ex-situ-conservation-strategies/).
- That have a published Bioversity International/IPGRI Crop Descriptor or Characterization Descriptor (https://www.bioversityinternational.org/e-library/publications/categories/descriptors/)

- That have a published Crop Trust/Bioversity International Regeneration Guideline (https://cropgenebank.sgrp.cgiar.org/index.php/crops-mainmenu-367 and https://cropgenebank.sgrp.cgiar.org/index.php/crops-mainmenu-367/other-crops-regeneration-guidelines-mainmenu-290)
- Essentially all crops proposed by negotiating regions to be included in the Multilateral System of Access and Benefit Sharing during International Treaty negotiations, as noted in FAO Commission on Genetic Resources for Food and Agriculture (2001). The exception is that the list submitted by European countries was very long and proposed several very minor crops which were not included.
- We also reviewed USDA's GRIN-Global World Economic Plants (https://npgsweb.ars-grin.gov/gringlobal/taxon/taxonomysearcheco) and Mansfeld's World Database of Agricultural and Horticultural Crops (https://mansfeld.ipk-gatersleben.de/apex/f?p=185:3) databases. We found the entire list of potentially applicable plants from those sources to be too long to be pragmatically usable here (e.g., 1,995 "FOOD" taxa in World Economic Plants, and 1,795 taxa with pertinent uses in Mansfeld's database). We did not add any additional crops from these sources not already listed due to their inclusion in the databases above.
- A few additional crop suggestions made during an expert stakeholder meeting in July 2019 (**Annex 2**) were added to the crop list.

A1.2 Crop list data processing and information additions

For each crop, the crop list offers one main common name, chosen based on our understanding of the most frequently used vernacular name worldwide. In a separate column we also list alternative common names; this is not an exhaustive list.

For scientific names, we first listed the pertinent genera and taxa for each crop, using USDA's GRIN Global Taxonomy (https://npgsweb.ars-grin.gov/gringlobal/taxon/taxonomysearch) for the main reference source. We included synonyms for some taxa as necessary to cover the majority of names likely to appear in the databases used in the study. In cases of not-clearly-defined taxa (e.g., forages listed in database sources by genus), we reviewed literature and attempted to list the most important taxa comprising those crops globally.

We assigned crop use type categories both at the general and detailed levels for each crop based on our own classification system, drawing from categories used by FAOSTAT and World Economic Plants. We developed 13 crop types, including 10 food types (cereal, fruit, herb and spice, nut, oil, pulse, root and tuber, stimulant, sugar, and vegetable), as well as fiber, forage, and industrial crops. Crops were assigned to more than one crop use category as appropriate; we note that many crops have multiple uses, and the alternate/secondary use information is not exhaustively documented in the crop list.

We added seed storage behavior information for each crop based on data from the Royal Botanic Garden Kew's Seed Information Database (https://data.kew.org/sid/ ©Copyright Board of Trustees of the Royal Botanic Gardens, Kew). In preparation for the interdependence analyses, we also listed the identified primary regions of diversity for each crop, drawing on literature sources (see the Interdependence Domain section further below).

A1.3 Crop list results

The crop list is available as a supplementary file to this report, currently at: https://docs.google.com/spreadsheets/d/1GHH4lp199BhrVOIr4E61C4DxHgD23KNHKNliuhfzNPk/edit?usp=sharing. In total, this list contains **355** crops from **307** distinct genera and **536** distinct taxa. The number of crops in each main crop use type category is shown in **Table A1**.

Table A1: Number of crops in each main crop use category

Crop use - general	Crop use - detailed	Number of crops
Fiber	Fiber	**20**
Food	Cereal	26
	Fruit	74
	Herb and spice	31
	Nut	14
	Oil	29
	Pulse	27
	Root and Tuber	19
	Stimulant	4
	Sugar	3
	Vegetable	57
Food Total		**284**
Forage	Forage	**42**
Industrial	Industrial	**9**
Grand Total		**355**

A2. Crop metrics

A2.1 Domain: Crop use

We calculated use metrics for the crops on the crop list regarding contribution to global food supply, production, and trade, using FAOSTAT data. To better inform the degree to which the use of crops is spread/balanced around the world, we also calculated metrics regarding the number of countries reporting the crops as significant for food supply, production, and trade, as well as the relative evenness of use (again, regarding food supply, production, and trade) across world regions. Finally, we analyzed the change over time in use of crops regarding their contributions to food supply, production, and trade globally.

To estimate the degree to which crops are actively investigated in research, we calculated a metric based on the number of scholarly publications/mentions for each crop, drawn from Google Scholar, and an equivalent metric drawn from PubMed Central. To estimate the degree of public interest in and/or awareness of each crop, we calculated metrics based on the number of pageviews of each crop seen on Wikipedia.

The crop use domain has 51 total metrics in 15 groups in 6 components:

- 11 metrics - Crop use data from FAOSTAT
- 11 metrics - Crop use data from FAOSTAT - Count of countries
- 11 metrics - Crop use data from FAOSTAT - Equality of use (GINI)
- 11 metrics - Crop use data from FAOSTAT - Change over time
- 4 metrics - Crop research investigation - Google Scholar and PubMed Central
- 3 metrics - Crop public interest/awareness - Wikipedia pageviews

A2.1.1 Component: Crop use data from FAOSTAT

FAOSTAT (https://www.fao.org/faostat/en/) metrics were summarized for each crop at the global level, calculating an average annual value as a mean across four recent years (2015-2018). FAOSTAT data was retrieved and analysis conducted in late 2021. To do so, crops were first identified in FAOSTAT Food Supply (Food Balance Sheets - https://www.fao.org/faostat/en/#data/FBS), Production (https://www.fao.org/faostat/en/#data/QCL), Value of Production (https://www.fao.org/faostat/en/#data/QV), and Trade (https://www.fao.org/faostat/en/#data/TCL) data, using metadata information (https://www.fao.org/faostat/en/#definitions) to associate crops on the crop list to the correct FAOSTAT commodity as accurately as possible. Multiple reported commodities belonging to the same crop were combined (e.g., 'Peas, dry' and 'Peas, green' were combined under the term Peas in production data by adding the two values together).

We included all available metrics deemed pertinent to Food Supply – calories (kcal/capita/day), protein (g/capita/day), fat (g/capita/day), and food weight (g/capita/day); to Production – harvested area (Ha), production quantity (tonnes); to Value of Production – current thousand US$; and to Trade – export quantity (tonnes), export value (1000 US$), import quantity (tonnes), import value (1000 US$). Eleven metrics in total were calculated, including four from group Food Supply, three from group Production (Value of Production was listed with the other two Production metrics), and four from group Trade.

While FAOSTAT data contains statistical information on the use of many crops (Food Supply data contains approximately 54 relevant crop plant commodities ['items'] with data from 173 countries; Production data contains approximately 142 relevant crop plant commodities with data from 205 countries; Value of Production data contains approximately 140 relevant crop plant commodities with data from 205 countries; and Trade data contains approximately 127 relevant crop plant commodities from 198 countries), the data are not comprehensive of all crops on the crop list, and, in addition, many crops are not specifically listed (especially in Food Supply data), but are instead grouped within general commodities (i.e. ‘Cereals, Other’, ‘Fruits, Other’, ‘Nuts’, ‘Oilcrops, Other’, ‘Pulses, Other’, ‘Roots, Other’, ‘Spices, Other’, ‘Tea and mate’, and ‘Vegetables, Other’ in Food Supply data). Applying the full reported values of these general commodities to each crop listed within these commodities would lead to clear overestimations of each crop’s value and to a distorted understanding of their value compared to other crops that are specifically measured in the data (i.e., not within a general commodity).

To resolve this challenge, we used production information for each crop (using the production quantity metric) as a factor by which to disaggregate the Food Supply values. As a simple example, the ‘Tea and mate’ Food Supply commodity contains two crops – tea and mate. Global production of these crops in terms of production quantity are approximately 85.8% tea and 14.2% mate, based on a sum of 2015 to 2018 production data. For a final Food Supply value (e.g., calories), the ‘Tea and mate’ general commodity value for kcal/capita/day was divided, with 85.8% of the total attributed to tea, and 14.2% to mate. Note we were unable to conduct this disaggregation for the various crops in ‘Beans’ and in ‘Millets’ Food Supply commodities because production data for crops pertinent to that commodity were also aggregated and thus not specific to individual crops. In this case, all crops in these two commodities were given the full value of the commodity. which should be noted has led to an overestimation of each crop’s individual use, especially for the minor bean and millet crops. An alternative could have been to equally divide the general commodity value across the crops within these commodities, but equal dividing led to much smaller values than likely accurate for many of the more major crops within these commodities, so we decided to implement the full value attribution.

Following this disaggregation of Food Supply values, the results appeared to be more accurate, except that many of the minor crops that are listed in Production metrics also within general commodities (i.e. ‘Agave fibres nes’, ‘Berries, nes’, ‘Cereals, nes’, ‘Fibre crops nes’, ‘Fruit, fresh nes’, ‘Fruit, tropical fresh nes’, ‘Nuts, nes’, ‘Oilseeds nes’, ‘Pulses, nes’, ‘Roots and tubers, nes’, ‘Spices, nes’, ‘Sugar crops, nes’, ‘Vegetables, fresh nes’) were calculated to have higher than expected Food Supply values compared to other crops that are specifically listed in Production metrics and which should have higher values than those minor crops (**Figure A1**). To attempt to resolve this additional challenge, we divided the values for these general Production commodities equally among all crops within them (e.g., bay leaf, dill, fenugreek, saffron, thyme, and turmeric - the 6 crops listed within the Production commodity ‘Spices, nes’ - were all assigned the same production value, each being ⅙ of the total value of ‘Spices, nes’). Following that transformation of Production data, we re-calculated the Food Supply transformation described above and assigned new Food Supply values for these crops.

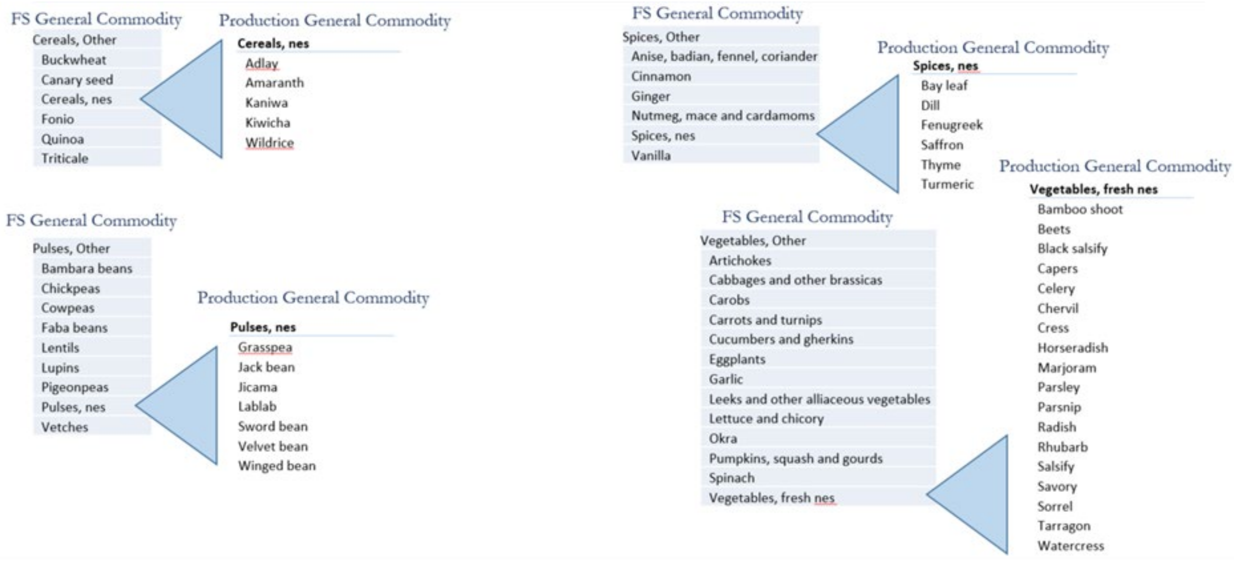

Figure A1. Examples of crops in general Food Supply commodities, and those within general Production commodities.

A total of 252 crops on the Crop List are reported in FAOSTAT Food Supply metrics, 280 crops on the Crop List are reported in FAOSTAT Production metrics (277 in the value of production metric), and 239 crops on the Crop List are reported in FAOSTAT Trade metrics. Pertinent fields for crops listed on the Crop List and without data in FAOSTAT were left blank (null values).

For each crop and for each of the 11 metrics, a global indicator of the global extent of use was calculated by dividing the value specific to the crop by the sum of values across all crops.

A2.1.2 Component: Crop use data from FAOSTAT - Count of countries

The same FAOSTAT metrics described above were used for an analysis of the degree of spread across countries in terms of crop use, using national rather than global data. As with above, 11 metrics in total were calculated, including four in group Food Supply (calories, protein, fat, food weight), three in group Production (production quantity, harvested area, production value), and four in group trade (export quantity, export value, import quantity, import value).

This component counts the number of countries in which the crop is reported as within the top 95% of crops in terms of contribution to Food Supply, Production, or Trade. The 95% threshold was selected after an examination of results based on 75% to 100% inclusion criteria; at 75% the list of crops per country became quite short in various cases; at 100% many countries reported almost all crops as contributing at least marginally; 95% provided a reasonable balance between these poles, allowing for a spread of results across assessed crops. This analysis was conducted in early 2022.

A total of 252 crops on the Crop List are reported in FAOSTAT count of countries Food Supply metrics, 280 crops on the Crop List are reported in FAOSTAT count of countries Production metrics (277 in the value of production metric), and 239 crops on the Crop List are reported in FAOSTAT count of countries Trade metrics. Pertinent fields for crops listed on the Crop List and without data in FAOSTAT were left blank (null values).

For each crop and for each of the 11 metrics, a global indicator of the geographic extent of use was calculated by dividing the number of countries listing the crop within its top 95% of use by the total number of countries in the dataset.

A2.1.3 Component: Crop use data from FAOSTAT - Equality of use (GINI)

The same FAOSTAT metrics described above were used for an analysis of the degree of balance/evenness across world regions in terms of crop use, using regional data calculated from national data. As with above, 11 metrics in total were calculated, including four in group Food Supply (calories, protein, fat, food weight), three in group Production (production quantity, harvested area, production value), and four in group trade (export quantity, export value, import quantity, import value).

World region values for Production and for Trade metrics were calculated by summing the individual values of countries included in each region (see the Interdependence Domain for an explanation of regions used in this study). For Food Supply metrics, regional values were created based on weighted averaging of the values of countries included in each region, with weighting based on national population (from the same years as the data - 2015 to 2018). See the Interdependence Domain for a full explanation of this calculation.

The degree of balance/evenness of crop use across regions was calculated using the Gini coefficient, a metric drawn from economics, which measures the inequality among values of a frequency distribution. The Gini coefficient formula was employed directly within our Python code software. To align this calculation with all other metrics, in which low values (close to 0) represent a poor state and high values (close to 1) represent a high/good state, we calculated our metric as = (1 - the Gini coefficient). The metric thus denotes perfect equality in use across regions when the value is 1, and very unequal use when close to 0. This analysis was conducted in early 2022.

A total of 252 crops are on the Crop List reported in FAOSTAT equality of use Food Supply metrics, 280 crops on the Crop List are reported in FAOSTAT equality of use Production metrics (277 in the value of production metric), and 239 crops on the Crop List are reported in FAOSTAT equality of use Trade metrics. Pertinent fields for crops listed on the Crop List and without data in FAOSTAT were left blank (null values).

For each crop and for each of the 11 metrics, a global indicator of the balance in geographic extent of use was calculated as the 1- Gini coefficient value.

A2.1.4 Component: Crop use data from FAOSTAT - Change over time

The same FAOSTAT metrics described above were used for an analysis of change over time in crop use, using data at the global level with a time series from 2015 to 2018. As with above, 11 metrics in total were calculated, including four in group Food Supply (calories, protein, fat, food weight), three in group Production (production quantity, harvested area, production value), and four in group trade (export quantity, export value, import quantity, import value). Change over time was calculated using relative change, i.e., the value in 2018 minus the value in 2015, divided by the value in 2015. This analysis was conducted in early 2022.

A total of 252 crops on the Crop List are reported in FAOSTAT change over time Food Supply metrics, 280 crops on the Crop List are reported in FAOSTAT change over time Production metrics (277 in the value of production metric), and 239 crops on the Crop List are reported in FAOSTAT change over time Trade metrics. Pertinent fields for crops listed on the Crop List and without data in FAOSTAT were left blank (null values).

For each crop and for each of the 11 metrics, a global indicator of change in the extent of use was calculated as the relative change fraction/quotient.

A2.1.5 Component: Crop research investigation - Google Scholar and PubMed Central

To estimate the degree to which crops are actively investigated in research, we calculated metrics based on the number of scholarly publications/mentions for each crop, drawn from Google Scholar (https://scholar.google.com/#d=gs_asd), similar to an analysis conducted by Galluzzi and López Noriega (2014), and PubMed Central (https://www.ncbi.nlm.nih.gov/pmc/).

A2.1.5.1 Google Scholar

The total count of publications listed in Google Scholar as published between 2009-2019 (including patents and citations, searching ‘in the title of the article’) was compiled per crop common name, genus, and taxon. For common names, terms were searched in the singular (‘Pea’, not ‘Peas’). At the level of taxon, in cases where crops had >1 scientific name, the first or most common scientific name was generally searched, with multiple names searched for some crops where multiple names clearly contribute importantly to the crop. This search was conducted in mid 2019. All 355 crops on the Crop List were assessed in this analysis.

For each crop and for each of the three metrics, a global indicator of the extent of research attention was calculated by dividing the number of publications for the crop by the number of publications for all crops combined.

A few challenges regarding this component should be mentioned. First, Google Scholar does not currently permit automated methods of data retrieval online, thus each search was conducted manually (totaling approximately 1065 searches done manually). Second, the occasional overlap of crop names with terms used in medicine, technology, or other fields likely inflated publication reporting for specific crops, e.g., apple (due to the same name for a technology corporation) and *Lens* (the genus for lentil, but also a term commonly used in optical research).

A2.1.5.2 PubMed Central

PubMed Central® is a free full-text archive of biomedical and life sciences journal literature at the U.S. National Institutes of Health's National Library of Medicine (NIH/NLM). The PubMed Central database can be accessed via the National Center for Biotechnology Information (NCBI) portal of the NIH. For this analysis, we accessed the portal using their API query link (https://eutils.ncbi.nlm.nih.gov/gquery), searching for the number of full text results for each crop, based on its taxonomic name, and returning results in xml format. This search and subsequent analysis were conducted in early 2022. All 355 crops on the Crop List were listed in NCBI and were thus assessed in this analysis. A full explanation of the code used is available in the Digital Sequence Information component of the Supply domain.

For each crop, a global indicator of the extent of research attention was calculated by dividing the number of full text results for the crop by the number of full text results for all crops combined.

A2.1.6 Component: Crop public interest/awareness - Wikipedia pageviews

To estimate the degree of public interest in and/or awareness of each crop, we calculated metrics based on the number of pageviews of each crop seen on Wikipedia, similar to an analysis conducted by Pironon *et al.* (2020), using their API query link (https://wikimedia.org/api/rest_v1/metrics/pageviews/per-article/en.wikipedia/all-access/all-agents/).

The total count of Wikipedia pageviews for the entirety of the year 2019 was compiled per crop common name, genus, and taxon. The search and subsequent analysis were conducted in early 2022. All 355 crops on the Crop List were assessed in this analysis.

For each crop and for each of the three metrics, a global indicator of extent of public interest in and/or awareness was calculated by dividing the number of pageviews for the crop by the number of pageviews for all crops combined.

While specific information about crops in Wikipedia may be of varied quality compared to that found in published articles, the analysis described here is not dependent on Wikipedia information quality. Rather, this analysis simply quantifies the degree of interaction between users (searchers/readers) and the Wikipedia website. This analysis searches Wikipedia pages only in English; this may result in underreporting for some crops of primary interest mainly in non-English speaking regions; it should be noted that English is the language with the highest number of Wikipedia pages overall and is often the source of translations into other languages on the website.

A2.2. Domain: Interdependence regarding food and agricultural crop plant genetic resources

We calculated crop plant genetic resource interdependence metrics regarding contribution to food supplies, production, and trade, using FAOSTAT data in combination with compiled information on the primary regions of crop plant diversity worldwide (i.e., where crops were mainly domesticated and are recognized to contain high diversity in cultivated [landraces] and wild [crop wild relatives] forms). These metrics are based on estimations of the significance of crops to food supplies, production, and trade, outside of their primary region(s) of diversity.

We also analyzed the change over time in crop plant genetic resource interdependence regarding food supplies, production, and trade.

The interdependence domain has 22 total metrics in 6 groups in 2 components:

- 11 metrics - Significance of each crop in terms of agricultural production, trade, and contribution to food supplies, outside of its geographic origins and primary region(s) of diversity

- 11 metrics – Change in significance of each crop in terms of agricultural production, trade, and contribution to food supplies, outside of its geographic origins and primary region(s) of diversity

A2.2.1 Component: Significance of each crop in terms of agricultural production, trade, and contribution to food supplies, outside of its geographic origins and primary region(s) of diversity

Food and agricultural plant genetic resource interdependence was estimated at the global level by calculating the significance of crops to food supplies, production, and trade, outside of their primary region(s) of diversity (i.e., outside of where the crops were largely domesticated and evolved for hundreds to thousands of years, and where diversity in landraces and crop wild relatives is particularly high). The underlying assumption is that if a crop has considerable use outside of its primary region(s) of diversity, then that use is dependent on genetic resource acquisition from elsewhere (including, notably, from the primary region[s] of diversity). Thus, a crop with a high use outside of its primary region(s) of diversity is likely to be a crop where there is high interdependence globally for its genetic resources.

To identify and compile information on primary regions of diversity of assessed crops, data for each crop regarding its origins and regions of diversity of cultivated and wild forms was gathered from pertinent literature (especially Khoury et al. 2015, 2016, USDA 2019), taking an inclusive approach (i.e., likely regions were included, even if some uncertainty exists). This information was converted to the regional level, using FAO regions as per FAO (2010), with modifications to better suit recognized ecogeographic regions of crop diversity (see Khoury et al. 2015, 2016 for a full explanation of regions and countries within each region. Note that countries can be included in more than one region, and crops can have more than one primary region of diversity. Only primary regions of diversity were identified per crop; secondary or other regions of diversity were not included or assessed here.

FAOSTAT food supply, production, and trade data at the national level for each crop (see the Crop Use Domain, component Crop use data from FAOSTAT) was re-calculated at the regional level, using the same regions mentioned above. For production and trade metrics, data was summed across countries comprising each region. For food supply metrics, regional values were calculated by taking a weighted average value across countries comprising each region, with country values weighted by country population (from the same years as the data - 2015 to 2018). Finally, for each crop, data was calculated both within the crop's primary region(s) of diversity, and outside of these regions. As with the previous step, production and trade data were summed across regions, while food supply data was calculated by weighted averaging across regions. This analysis was conducted in late 2021.

A total of 252 crops on the Crop List are reported in FAOSTAT interdependence regarding Food Supply metrics, 280 crops on the Crop List are reported in FAOSTAT interdependence regarding Production metrics (277 in the value of production metric), and 239 crops on the Crop List are reported in FAOSTAT interdependence regarding Trade metrics. Pertinent fields for crops listed on the Crop List and without data in FAOSTAT were left blank (null values).

For each crop and for each of the 11 metrics, a global indicator of extent of global interdependence was calculated as the quantity of use from outside of the crop's primary region(s) of diversity divided by the world total quantity of use. If the numerator (value outside of the crop's primary region(s) of diversity) was larger than the denominator (world value), the final value was set to 1 (the maximum); this circumstance can only occur for food supply values).

Through examination of the data and the results, it was noted that some crops have no values within their primary region(s) of diversity, which is highly unlikely, and therefore is probably due to underreporting within FAOSTAT data. To address this deficiency, any crops with null values in their primary region(s) of diversity were excluded from this component. Other challenges/vulnerabilities regarding this component include that a) primary regions of crop diversity do not in actuality follow political boundaries well; thus, some degree of generalization is expected, b) primary regions of diversity are still not well documented for some crops, and new information is continually being generated, for example regarding the origins of watermelon (Renner et al. 2021). Further, genetic resource interdependence exists in the geographic sense not only regarding primary regions of diversity, but also secondary and other regions with particularly high amounts of crop diversity, and because of the locations of *ex situ* repositories (genebanks and botanic gardens) in particular regions. We note that more direct measurements of demand for crop genetic resources are included in the Demand domain.

A2.2.2 Component: Change in significance of each crop in terms of agricultural production, trade, and contribution to food supplies, outside of its geographic origins and primary region(s) of diversity

The same crop plant genetic resource interdependence analysis described above was also used to assess change over time in genetic resource interdependence for each crop with a time series from 2015 to 2018. As with above, 11 metrics in total were calculated, including four in group Food Supply (calories, protein, fat, food weight), three in group Production (production quantity, harvested area, production value), and four in group trade (export quantity, export value, import quantity, import value). Change over time was calculated using relative change, i.e., the interdependence value in 2018 minus the value in 2015, divided by the value in 2015. This analysis was conducted in early 2022.

A total of 252 crops on the Crop List are reported in FAOSTAT change over time in interdependence regarding Food Supply metrics, 280 crops on the Crop List are reported in FAOSTAT change over time in interdependence regarding Production metrics (277 in the value of production metric), and 239 crops on the Crop List are reported in FAOSTAT change over time in interdependence regarding Trade metrics. Pertinent fields for crops listed on the Crop List and without data in FAOSTAT were left blank (null values).

For each crop and for each of the 11 metrics, a global indicator of change in extent of global interdependence was calculated as the relative change fraction/quotient.

A2.3 Domain: Demand for food and agricultural plant genetic resources

We calculated demand for crop plant genetic resources based on germplasm distributions data sourced from the Data Store of the International Treaty on Plant Genetic Resources for Food and Agriculture (Plant Treaty), as well as from the FAO World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture (WIEWS).

To better inform the degree to which demand for crop genetic resources is spread/balanced around the world, we also calculated metrics regarding the number of countries receiving crop genetic resources, as well as the relative degree of receipt of crop genetic resources compared across world regions, based on data from the Data Store of the Plant Treaty.

We further calculated demand for crop plant genetic resources based on varietal registration/release data, both from the FAO World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture (WIEWS) and from the International Union for the Protection of New Varieties of Plants (UPOV)'s PLUTO Plant Variety Database.

The demand domain has 7 total metrics in 4 groups in 4 components:

- 1 metric - Germplasm distributions - Plant Treaty
- 1 metric - Germplasm distributions - Plant Treaty - Count of countries
- 1 metric - Germplasm distributions - Plant Treaty - Equality of distributions (GINI)
- 2 metrics - Genebank distributions - FAO WIEWS
- 1 metric - Varietal registrations - UPOV
- 1 metric - Varietal releases - FAO WIEWS

A2.3.1 Component: Germplasm distributions - Plant Treaty

We calculated an average annual number of germplasm distributions for each crop worldwide from 2015 to 2019 inclusive, using data from the The Data Store of the of the International Treaty on Plant Genetic Resources for Food and Agriculture (Plant Treaty) (https://www.fao.org/plant-treaty/areas-of-work/global-information-system/en/). This dataset includes all distributions made under the Standard Material Transfer Agreement (SMTA) that have been reported to the Governing Body, and was retrieved in early 2022, with an update in June of 2022, with the analysis conducted shortly thereafter. This dataset reports numbers of samples distributed by any provider, including genebanks as well as breeding programs and other organizational types; it is primarily composed of distributions made by CGIAR centers (genebanks and breeding programs). Countries wherein providers and recipients are located, crop, year, and number of samples distributed are included in the dataset analyzed here; specific providers, recipients, or recipient types are not. One metric was thus mobilized (in one group, in one component).

A total of 142 crops on the Crop List were present in the Germplasm distributions - Plant Treaty dataset (i.e., these crops had 1 or more distributions listed in the Plant Treaty dataset). Remaining crops were assigned 0 values.

For each crop, a global indicator of the extent of demand for germplasm was calculated as the number of average annual distributions of samples of that crop divided by the total number of average annual distributions of samples for all crops in the dataset.

A challenge in the use of these data is that crops/genetic resources are not reported in a standardized manner across all data providers to the Data Store. Matching crop names in the Data Store to the crop list was performed both through manual methods, with a minor degree of error expected.

A2.3.2 Component: Germplasm distributions - Plant Treaty - Count of countries

The same Plant Treaty Data Store germplasm distribution data described above was used for an analysis of the degree of spread across recipient countries in terms of receipt of crop germplasm. As with above, one metric in total was calculated, in one group, in one component. This component counts the average annual number of countries to which the crop was distributed within the 2015 to 2019 period. This analysis was conducted in early 2022.

A total of 142 crops on the Crop List were present in the Germplasm distributions - Plant Treaty - Count of countries dataset (i.e., these crops had 1 or more distributions listed in the Plant Treaty dataset). Remaining crops were assigned 0 values.

For each crop, a global indicator of the geographic extent of demand for germplasm was calculated by dividing the average annual number of countries receiving germplasm of the crop by the total number of countries in the dataset (n = 179 recipient countries).

A2.3.3 Component: Germplasm distributions - Plant Treaty - Equality of distributions (GINI)

The same Plant Treaty Data Store germplasm distribution data described above was used for an analysis of the degree of balance/evenness across world regions in terms of receipt of crop germplasm, using regional data calculated from national data. As with above, one metric in total was calculated, in one group, in one component.

World region values were calculated by summing the individual values of countries included in each region (see the Interdependence Domain for an explanation of regions). The degree of balance/evenness of crop germplasm receipt across regions was calculated using the Gini coefficient, a metric drawn from economics which measures the inequality among values of a frequency distribution. To align this calculation with all other metrics, in which low values (close to 0) represent a poor state and high values (close to 1) represent a high/good state, we calculated our metric as = (1 - the Gini coefficient). The metric thus provides an indication of perfect equality in germplasm receipt (i.e., demand) across regions when the value is 1, and very unequal receipt when close to 0. This analysis was conducted in early 2022.

A total of 142 crops on the Crop List were present in the Germplasm distributions - Plant Treaty - Equality of distributions (GINI) dataset (i.e. these crops had 1 or more distributions listed in the Plant Treaty dataset). Remaining crops were assigned 0 values.

For each crop, a global indicator of balance in the geographic extent of demand for germplasm was calculated as the 1- Gini value across regions.

A2.3.4 Component: Genebank distributions - FAO WIEWS

We calculated an average annual number of germplasm distributions for each crop worldwide from 2014-2019 using data from the FAO World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture (WIEWS) (https://www.fao.org/wiews/en/) (Indicators 28 [https://www.fao.org/wiews/data/domains/detail/en/?code=28] and 29 [https://www.fao.org/wiews/data/domains/detail/en/?code=29]). These datasets primarily report distributions of germplasm from national genebanks. These data were retrieved, and analysis conducted in early 2022, with an update in July 2022. These data provide information in terms of counts of samples and of accessions distributed of different crops/genetic resources by distributing country. The term ‘sample’ typically represents an individual packet, while ‘accession’ represents a unique population/variety/collecting event. Two metrics were thus mobilized (in two groups, in one component).

A total of 256 crops on the Crop List were present in the Genebank distributions - FAO WIEWS dataset (i.e., these crops had 1 or more germplasm distributions listed in WIEWS). Remaining crops were assigned 0 values.

For each crop, a global indicator of extent of demand for germplasm was calculated as the number of average annual distributions of that crop divided by the total number of average annual distributions for all crops in the dataset.

A challenge in the use of these data is that crops/genetic resources are not reported in a fully standardized manner across all data providers to FAO WIEWS, with some reporters combining different crops in their total counts. Matching crop names in the WIEWS data to the crop list was performed through manual methods, with a minor degree of error expected.

A2.3.5 Component: Varietal registrations - UPOV

We calculated an average annual number of varietal registrations for each crop worldwide from 2014-2018 using data from the International Union for the Protection of New Varieties of Plants (UPOV)’s PLUTO Plant Variety Database (https://www.upov.int/pluto/en/). These data were retrieved in 2019, with the analysis conducted in late 2019. These data provide information in terms of varieties registered of different crops by country. We included “approved”, “proposed”, and “published” records, and did not count “rejected” records in the dataset. One metric was thus mobilized (in one group, in one component).

A total of 194 crops on the Crop List were present in the Varietal registrations - UPOV dataset (i.e., these crops had 1 or more varietal registrations listed in UPOV). Remaining crops were assigned 0 values.

For each crop, a global indicator of the extent of varietal registrations was calculated as the number of average annual varietal registrations of that crop globally divided by the total number of average annual varietal registrations of all crops globally in the dataset.

A2.3.6 Component: Varietal releases - FAO WIEWS

We calculated an average annual number of new varietal releases for each crop worldwide from 2015-2019 using data from the FAO World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture (WIEWS) (https://www.fao.org/wiews/en/) (Indicator 40 [https://www.fao.org/wiews/data/domains/detail/en/?code=40]). Data was retrieved and analyzed for this analysis in early 2022. These data provide information in terms of counts of varieties released of different crops by country. One metric was mobilized (in one group, in one component).

A total of 204 crops on the Crop List were present in the Varietal releases - FAO WIEWS dataset (i.e., these crops had 1 or more varietal releases listed in WIEWS). Remaining crops were assigned 0 values.

For each crop and for each metric, a global indicator of the extent of varietal releases was calculated as the number of average annual varietal releases of that crop globally divided by the total number of average annual varietal releases of all crops globally in the dataset.

A challenge in the use of these data is that crops/genetic resources are not reported in a fully standardized manner across all data providers to FAO WIEWS, with some reporters combining different crops in their total counts. Matching crop names in the WIEWS data to the crop list was performed through manual methods, with a minor degree of error expected.

A2.4 Domain: Supply of food and agricultural crop plant genetic resources

We calculated supply of crop plant genetic resources based on *ex situ* collections data from the FAO World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture (WIEWS), the Genesys Plant Genetic Resources portal (Genesys PGR), and the Global Biodiversity Information Facility (GBIF) (living specimens in GBIF). For these data, we also estimated the proportion included within the Multilateral System of Access and Benefit Sharing of the International Treaty on Plant Genetic Resources for Food and Agriculture (Plant Treaty), as well as the relative degree of *ex situ* collection coverage of each crop’s primary region(s) of diversity. We further calculated supply of crop plant genetic resources based on *ex situ* collections data from the Botanic Garden Conservation International’s PlantSearch database.

To estimate supply of research materials pertinent to crop plant genetic resources, we calculated supply of herbarium and other records in the Global Biodiversity Information Facility (GBIF) as well as supply of genetic, protein, and other digital sequence data in the National Center for Biotechnology Information (NCBI) global database.

The supply domain has 16 total metrics in 7 groups in 6 components:

- 2 metrics - *Ex situ* collections - FAO WIEWS, Genesys PGR, and GBIF
- 4 metrics - *Ex situ* collections - FAO WIEWS, Genesys PGR, and GBIF - MLS status
- 2 metrics - *Ex situ* collections - FAO WIEWS, Genesys PGR, and GBIF - primary region coverage
- 2 metrics - *Ex situ* collections - Botanic Gardens
- 2 metrics - Research supply - GBIF
- 4 metrics - Research supply - NCBI

A2.4.1 Component: Ex situ collections - FAO WIEWS, Genesys PGR, and GBIF

We calculated the number of *ex situ* germplasm accessions maintained worldwide for each crop using data from the FAO World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture (WIEWS) (https://www.fao.org/wiews/data/ex-situ-sdg-251/search/en/?no_cache=1), the Genesys Plant Genetic Resources portal (Genesys PGR) (https://www.genesys-pgr.org/), and the Global Biodiversity Information Facility (GBIF) (https://www.gbif.org/), filtering for 'living specimens' only in GBIF. These data were acquired in late 2018 and the analysis conducted in 2019.

Records from the three datasets were combined, eliminating duplicates as possible (mainly based on institution id), with preference for the original data source (thus records from Genesys PGR present in FAO WIEWS were removed, and only records directly from Genesys PGR included). Assessments of *ex situ* germplasm supply were made both at the taxon (crop) level, as well as at the genus level, the latter to be inclusive of supply of associated genetic resources, including crop wild relatives. Two metrics were thus mobilized (in one group, in one component).

A total of 354 crops on the Crop List are included in this *Ex situ* collections - FAO WIEWS, Genesys PGR, and GBIF analysis when assessed at the genus level, and 343 crops on the Crop List are included in this *Ex situ* collections - FAO WIEWS, Genesys PGR, and GBIF analysis when assessed at the species/crop level (i.e. these crops had 1 or more accessions in the genebank dataset). Remaining crops were assigned 0 values.

For each crop, a global indicator of extent of supply of genetic resources was calculated as the number of *ex situ* accessions of the crop divided by the total number of accessions of all crops in the dataset.

The main challenges regarding this component include that a) some *ex situ* collections are not represented in any of these databases, b) the challenge of identifying and removing all duplicates across these datasets, c) the challenge of aligning taxon names in these datasets with the crop list (taxon names are not highly standardized in these datasets), and d) that the assessment at the genus level, while being inclusive of wild relatives, likely overestimates relevant *ex situ* supply for crops with large genera (e.g. *Solanum* L.), as it is unlikely that all congeneric species will be used in crop improvement. For these reasons, some degree of error is expected.

A2.4.2 Ex situ collections - FAO WIEWS, Genesys PGR, and GBIF - MLS status

The same combined *ex situ* germplasm collections dataset described above was used for an analysis of the degree of current coverage of *ex situ* accessions in the Multilateral System of Access and Benefit Sharing (MLS) of the International Treaty on Plant Genetic Resources for Food and Agriculture (Plant Treaty) (https://www.fao.org/plant-treaty/areas-of-work/the-multilateral-system/overview/en/).

This calculation was conducted in two ways. First, coverage was assessed based on direct notation in the datasets in pertinent fields, e.g., values "Included" or "Not included" in field "Status under the Multilateral System" in FAO WIEWS; and values "True" or "False" in field "mlsStat" in Genesys PGR. Accessions with no notation in pertinent fields were assumed to not be included in the MLS. This analysis was conducted in 2019.

Because a large proportion of accessions (approximately 53%) had no pertinent notation, a second methodology was also employed, based on a combination of the country where the *ex situ* collections were held and the list of crops covered in the MLS (i.e. Annex 1, as well as Article 15, of the Plant Treaty). Institute country was matched with Contracting Parties to the International Treaty as noted on the Plant Treaty website on March 12, 2019), while crops were matched to Annex 1, or recognized as included if held in International genebanks of the CGIAR. As above, values were calculated both at the taxon and genus level. This analysis was conducted in 2019. Four metrics in total were thus calculated, in two groups, in one component.

A total of 354 crops on the Crop List are included in this *Ex situ* collections - FAO WIEWS, Genesys PGR, and GBIF - MLS status analysis when assessed at the genus level, and 343 crops on the Crop List are included in this *Ex situ* collections - FAO WIEWS, Genesys PGR, and GBIF - MLS status analysis when assessed at the species/crop level (i.e. these crops had 1 or more accessions in the genebank dataset). Remaining crops were assigned 0 values.

For each crop, a global indicator of the degree of coverage in the MLS was calculated as the number of *ex situ* accessions of the crop included within the MLS divided by the total number of accessions for the crop in the dataset.

Alongside the challenges to this component already listed in the component above, the large proportion of accessions lacking direct notation of whether included in the MLS, and difficulties in assigning accessions MLS status by institute country and Annex 1 (for example, some institutions in Europe and in the USA treat all their accessions as part of the MLS, regardless of whether they are crops listed in Annex 1) generate some degree of error in this component.

A2.4.3 Component: Ex situ collections - FAO WIEWS, Genesys PGR, and GBIF - primary region coverage

The same combined *ex situ* germplasm collections dataset described above was used for an analysis of the degree of current coverage of *ex situ* accessions sourcing from each crop's primary region(s) of diversity, i.e., the world region(s) where each crop was mainly domesticated and is recognized to contain high diversity in cultivated (landraces) and wild (crop wild relatives) forms. Primary region(s) of diversity for each crop were identified as described in the Interdependence domain. The number of accessions sourcing from primary region(s) of diversity was calculated using country locality passport information. This count of accessions, which was calculated both at the taxon and the genus level, was divided by the harvested area of the crop within the primary region(s) of diversity, drawing from FAOSTAT production data (year 2014). Harvested area was used as a proxy for the relevant size of the primary region(s) of diversity. Two metrics in total were thus calculated, in one group, in one component. This analysis was conducted in 2019.

A total of 259 crops on the Crop List are included in this *Ex situ* collections - FAO WIEWS, Genesys PGR, and GBIF - primary region coverage analysis when assessed at the genus level, and 248 crops on the Crop List are included in this *Ex situ* collections - FAO WIEWS, Genesys PGR, and GBIF - primary region coverage analysis when assessed at the species/crop level (i.e. these crops had 1 or more accessions collected from within their primary region of diversity, as listed in the genebank dataset). Remaining crops were assigned 0 values.

For each crop, a global indicator of the degree of representation in *ex situ* collections of the primary region of diversity was calculated as the number of *ex situ* accessions of the crop sourcing from within its primary region(s) of diversity divided by the harvested area of the crop within its primary region(s) of diversity. Values >1 were adjusted to a maximum of 1.

A2.4.4 Component: Ex situ collections - Botanic Gardens

Botanic Garden Conservation International's PlantSearch database (https://tools.bgci.org/plant_search.php) is the leading global information system for botanic garden *ex situ* collections, holding data on over 1.5 million records, representing ca. 650,000 taxa, held at around 1200 contributing institutions (BGCI 2022). The database currently only documents if a taxon is held at a given institution, not the number of accessions held. We retrieved the entire PlantSearch database and searched for all records for all taxa within the genus and species of the crop, in July 2021. The analysis was conducted in early 2022, with an assessment both at the genus and crop/taxon level.

A total of 354 crops on the Crop List are included in this *Ex situ* collections - Botanic Gardens analysis when assessed at the genus level, and 353 crops on the Crop List are included in this *Ex situ* collections - Botanic Gardens analysis when assessed at the species/crop level (i.e. these crops had 1 or more institutions listed in PlantSearch). Remaining crops were assigned 0 values.

For each crop and for each metric, a global indicator of the extent of botanic collections of each crop was calculated as the number of unique records of the crop listed in PlantSearch divided by the total number of records for all crops in the dataset. Two metrics in total were calculated, in one group, in one component.

A2.4.5 Component: Research supply - GBIF

The Global Biodiversity Information Facility (GBIF) (https://www.gbif.org/) is the world's leading global repository for openly accessible biodiversity resources, including research specimens and their associated data. We searched the entire GBIF database for records matching to our crop list, both at the taxon level as well as at the genus level, on May 22, 2019 (https://doi.org/10.15468/dl.rahcfx). Two metrics in total were calculated (at the genus and crop/taxon levels), in one group, in one component. The analysis was conducted in 2019.

A total of 348 crops on the Crop List are included in this Research supply - GBIF analysis when assessed at the genus level, and 321 crops on the Crop List are included in this Research supply - GBIF analysis when assessed at the species/crop level (i.e., these crops had 1 or more accessions listed in GBIF). Remaining crops were assigned 0 values.

For each crop, a global indicator of research supply was calculated as the number of samples of the crop listed in GBIF divided by the total number of samples for all crops in the dataset.

A2.4.6 Component: Research supply - NCBI

The National Center for Biotechnology Information (NCBI)'s Entrez database (https://www.ncbi.nlm.nih.gov/) comprises one of the three foremost global biodiversity digital information resource (often called "Digital Sequence Information" or "DSI" in current policy fora; here called genetic sequence data (GSD)) repositories, which are connected within the International Nucleotide Sequence Database Collaboration (INSDC). The other two repositories are the DNA Data Bank of Japan (DDBJ) (https://www.ddbj.nig.ac.jp/index-e.html) and the European Molecular Biology Laboratory - European Bioinformatics Institute (EMBL-EBI) (https://www.ebi.ac.uk/); the three share data across their platforms.

The NCBI database provides species level information regarding the number of nucleotide, protein, structure, genome, gene, and other related sequences/data available for use. We extracted information on the number of nucleotide, protein, genome, and gene resources for each crop, matching taxon (scientific) name to the NCBI taxonomy structure, accessing the portal using their API query link (https://eutils.ncbi.nlm.nih.gov/gquery). Four metrics in total were thus calculated, in one group, in one component. This analysis was conducted in early 2022. All 355 crops on the Crop List were listed in NCBI and thus assessed in this Research supply - NCBI analysis.

For each crop and for each metric, a global indicator of GSD research supply was calculated as the number of GSD resources of the crop listed in NCBI divided by the total number of GSD resources for all crops in the dataset.

A2.5 Domain: Security of food and agricultural plant genetic resources

We calculated security backup of crop plant genetic resources based on *ex situ* collections data from the Svalbard Global Seed Vault's SeedPortal.

The security Domain has 2 total metrics in 1 group in 1 component:

- 2 metrics - *Ex situ* backup - Svalbard Global Seed Vault

A2.5.1 Component: Ex situ backup - Svalbard Global Seed Vault

The Svalbard Global Seed Vault (SGSV) is considered the foremost safety-backup facility for *ex situ* crop plant genetic resource collections globally and is available as a resource for virtually any *ex situ* collection worldwide. We calculated the total number of accessions for each crop in SGSV based on the Svalbard Global Seed Vault's SeedPortal (https://seedvault.nordgen.org/) (downloaded March 15, 2019) and compared this number to the total count of accessions for that crop in all *ex situ* repositories (see the Supply domain, component 2.4.1). Assessments of *ex situ* germplasm safety duplication were made both at the taxon (crop) level, as well as at the genus level, the latter to be inclusive of security of associated genetic resources, including crop wild relatives. Two metrics were thus mobilized (in one group, in one component). This analysis was conducted in 2019.

A total of 223 crops on the Crop List are included in this *Ex situ* backup - Svalbard Global Seed Vault analysis when assessed at the genus level, and 206 crops on the Crop List are included in this *Ex situ* backup - Svalbard Global Seed Vault analysis when assessed at the species/crop level (i.e. these crops had 1 or more accessions in SGSV). Remaining crops were assigned 0 values.

For each crop, a global indicator of safety backup was calculated as the number of *ex situ* accessions of the crop in SGSV divided by the total number of accessions of the crop in all *ex situ* repositories.

SGSV is a safety backup only for seed, thus crops mainly conserved through other types of propagules will likely receive low values for safety duplication in this component. Further, a more exact assessment of safety duplication could potentially be made at the accession level (using accession id's); this information is not well standardized worldwide currently. Finally, this component presents the same challenges as do the supply components regarding assessment at the genus level. While being inclusive of wild relatives, the genus-level assessment likely overestimates relevant *ex situ* supply for crops with large genera (e.g., *Solanum* L.), as it is unlikely that all congeneric species will be used in crop improvement. For all these reasons, some degree of error is expected.

A3. Crop indicator calculation across metrics

Alongside real calculated values, indicator metrics in all groups, components, and domains were calculated on a scale from 0 to 1, with low numbers (close to 0) representing a low or poor status (low crop use, low interdependence regarding genetic resources, low demand for genetic resources, small supply of genetic resources, low degree of security of genetic resources), and high numbers (close to 1) representing a high or good status (high crop use, high interdependence regarding genetic resources, high demand for genetic resources, large supply of genetic resources, high degree of security of genetic resources). Change over time indicator metrics may also have negative values (decline in importance over time). Methods for calculation of each indicator metric are described in the section above.

Indicator results were further produced in normalized forms for each metric, by setting the crop with the lowest value at 0, and the crop with the highest value at 1 (i.e., for each crop, normalized value = (x - min) / (max - min)). This was calculated across all crops, and across the crops in each crop use type (e.g., cereals, pulses, vegetables). When calculated across crop use types, for crops such as maize or soybean with multiple uses, these crops were included in all relevant use type categories; values for these crops are total global, not separated by specific use.

The indicator and normalized indicator results were used for cross-group, -component, and -domain calculation, with average results per crop produced at each of those levels. Metrics with no values (i.e., the metric was not calculated for that crop) were not included in/did not influence calculation of mean results. We used simple averaging across metrics after assessing a variety of possible methodologies, including assessing correlations among metrics, and removing overly correlated variables, and weighting different metrics by expert opinion of their importance; we found none of these techniques to provide clear value beyond simple averaging, and note that each introduces further complexity, possible error, and difficulty in repetition in the future.

A4. Metric limitations and other potential sources of information

A4.1 Existing metric data limitations and gaps

While the Crop List was compiled based on crops for which substantial information on their use, as well as data on interdependence, demand, supply, and security of genetic resources exists, the number of crops for which data is contained in this analysis does vary considerably by metric. Data for approximately:

Crop use:

- A total of 252 crops on the Crop List are reported in FAOSTAT Food Supply metrics, 280 crops on the Crop List are reported in FAOSTAT Production metrics (277 in the value of production metric), and 239 crops on the Crop List are reported in FAOSTAT Trade metrics. Pertinent fields for crops listed on the Crop List and without data in FAOSTAT were left blank (null values).
- All 355 crops are reported in Crop research investigation - Google Scholar and PubMed Central
- All 355 crops are reported in Crop public interest/awareness - Wikipedia pageviews

Interdependence:

- A total of 252 crops on the Crop List are reported in FAOSTAT Food Supply metrics, 280 crops on the Crop List are reported in FAOSTAT Production metrics (277 in the value of production metric), and 239 crops on the Crop List are reported in FAOSTAT Trade metrics. Pertinent fields for crops listed on the Crop List and without data in FAOSTAT were left blank (null values).

Demand:

- A total of 142 crops on the Crop List were present in the Germplasm distributions - Plant Treaty dataset (i.e., these crops had 1 or more distributions listed in the Plant Treaty dataset). Remaining crops were assigned 0 values.
- A total of 256 crops on the Crop List were present in the Genebank distributions - FAO WIEWS dataset (i.e., these crops had 1 or more germplasm distributions listed in WIEWS). Remaining crops were assigned 0 values.
- A total of 194 crops on the Crop List were present in the Varietal registrations - UPOV dataset (i.e., these crops had 1 or more varietal registrations listed in UPOV). Remaining crops were assigned 0 values.
- A total of 204 crops on the Crop List were present in the Varietal releases - FAO WIEWS dataset (i.e., these crops had 1 or more varietal releases listed in WIEWS). Remaining crops were assigned 0 values.

Supply:

- A total of 354 crops on the Crop List are included in this *Ex situ* collections - FAO WIEWS, Genesys PGR, and GBIF analysis when assessed at the genus level, and 343 crops on the Crop List are included in this *Ex situ* collections - FAO WIEWS, Genesys PGR, and GBIF analysis when assessed at the species/crop level (i.e. these crops had 1 or more accessions in the genebank dataset). Remaining crops were assigned 0 values
- A total of 259 crops on the Crop List are included in this *Ex situ* collections - FAO WIEWS, Genesys PGR, and GBIF - primary region coverage analysis when assessed at the genus level, and 248 crops on the Crop List are included in this *Ex situ* collections - FAO WIEWS, Genesys PGR, and GBIF - primary region coverage analysis when assessed at the species/crop

level (i.e. these crops had 1 or more accessions collected from within their primary region of diversity, as listed in the *ex situ* collections dataset). Remaining crops were assigned 0 values.

- A total of 354 crops on the Crop List are included in this *Ex situ* collections - Botanic Gardens analysis when assessed at the genus level, and 353 crops on the Crop List are included in this *Ex situ* collections - Botanic Gardens analysis when assessed at the species/crop level (i.e. these crops had 1 or more institutions listed in PlantSearch). Remaining crops were assigned 0 values.
- A total of 348 crops on the Crop List are included in this Research supply - GBIF analysis when assessed at the genus level, and 321 crops on the Crop List are included in this Research supply - GBIF analysis when assessed at the species/crop level (i.e., these crops had 1 or more accessions listed in GBIF). Remaining crops were assigned 0 values.
- All 355 crops on the Crop List were listed in NCBI and thus assessed in this Research supply - NCBI analysis.

Security:

- A total of 223 crops on the Crop List are included in this *Ex situ* backup - Svalbard Global Seed Vault analysis when assessed at the genus level, and 206 crops on the Crop List are included in this *Ex situ* backup - Svalbard Global Seed Vault analysis when assessed at the species/crop level (i.e. these crops had 1 or more accessions in SGSV). Remaining crops were assigned 0 values.

Given the methodologies applied above, values are presented in this analysis for all crops for all metrics in the demand, supply, and security domains, as well as for the Crop research investigation - Google Scholar and PubMed Central, and Crop public interest/awareness - Wikipedia pageviews metrics in the crop use domain. It is thus only for metrics based on FAOSTAT, presented in the crop use and interdependence domains, where there are information gaps for some crops (i.e., approximately 29% of crops in the assessment do not have values in terms of Food Supply metrics, 21.1% in terms of Production metrics, and 32.7% in terms of Trade metrics). These data gaps can only be resolved through the inclusion of more crops/commodities reported in FAOSTAT.

A4.2 Other potential metrics and sources of information

Many other sources of information were explored during this study but were not integrated into the analysis at the present time, mainly due to insufficient or inaccessible data. These are described concisely below.

A4.2.1 Other crop use metrics

Significance of crops to micronutrients in food supplies - the contribution of crops to food supplies is only measured in four ways within FAOSTAT data - calories, protein, fat, and food weight. The contribution of crops regarding micronutrients is not currently reported in FAOSTAT Food Supply data. To attempt to find and use micronutrient data at the crop level for this global analysis, we examined multiple databases and literature sources, and spoke with various authors and experts, including:

- FAO/INFOODS Food Composition Database for Biodiversity and FAO/INFOODS/ IZiNCG Global Food Composition Database for Phytate (https://www.fao.org/infoods/infoods/tables-and-databases/faoinfoods-databases/en/) – have some crops, not many micronutrients with values, lots of variation.
- USDA Food Data Central (https://fdc.nal.usda.gov/) - challenging to assign data to crops

- The Global Nutrient Database (Schmidhuber *et al.* 2018) - aligned with (394) FAO commodities, with data on 156 nutrients across 195 countries from 1980-2013, using USDA composition data with the same conversion factor across countries.
- Global Expanded Nutrient Supply (GENuS) Model (Smith *et al.* 2016 - https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/GNFVTT) – Uses USDA composition data but also country/region specific data. Lots of values per crop (thus wide variation).
- IMPACT (https://nutrientmodeling.shinyapps.io/nutrientModeling/)- Have data for about 28 crops and another 10 or so general commodities. Have phytate, folate, ft acids, iron, magnesium, niacin, phosphorus, potassium, riboflavin, thiamin, fiber, vit A, B12, B6, C, D, E, K, zinc.- data from USDA food composition tables.
- FAO (2001) - Nutritional value of some of the crops under discussion in the development of a multilateral system. Background study paper 11. Rome, Italy. Not a very long list of crops and only a few micronutrients (lipids, iron, Vitamin A). Reported at global and regional levels.
- Remans *et al.* 2014 – author remarked that data was outdated compared to Smith *et al.* 2016 and Schmidhuber *et al.* 2018.
- Beal *et al.* (2017) – not pragmatically useful for crop scale.
- Herrero *et al.* (2017) – not pragmatically useful for crop scale.
- Beal *et al.* (2021) – not pragmatically useful for crop scale.
- World Vegetable Center micronutrient data.
- Crops for the Future - have data on dietary fiber mean values for about 200 crops; calcium - 231; crops; Iron - 227 crops; Magnesium - 181 crops; Phosphorus - 216 crops; Potassium - 214 crops; Zinc - 187 crops; B-carotene - 61 crops; Vitamin A - 119 crops; Vitamin B; Vitamin C - 90 crops; Vitamin E - 43 crops; Vitamin K - 47 crops

We thank the authors of these works for their generosity and explaining the potential of these datasets and in sending example data. Currently, our assessment is that generating and curating a global database with micronutrient values for crops remains a major challenge. A particular challenge is the current existence of a very wide range in micronutrient values within crops due to different assessment methods and statistical treatments, infraspecific variation, agronomic conditions, and post-harvest processing practices.

Cultural value of crops - we reviewed a number of databases listing cultural uses of crops, including USDA's GRIN-Global World Economic Plants (https://npgsweb.ars-grin.gov/gringlobal/taxon/taxonomysearcheco) and Mansfeld's World Database of Agricultural and Horticultural Crops (https://mansfeld.ipk-gatersleben.de/apex/f?p=185:3) databases. We did not find a straightforward way to create a metric based on cultural value/importance and did not pursue this component further.

A4.2.2 Other demand metrics

FAO WIEWS - Several other indicator metrics available from FAO WIEWS with data at the crop level may be useful to assess demand for crop genetic resources, including:

- Indicator 6: Number of farmers' varieties/landraces delivered from national or local genebanks to farmers (either directly or through intermediaries) (https://www.fao.org/wiews/data/domains/detail/en/?code=6)
- Indicator 30: Number of crops with active public pre-breeding and breeding programmes (http://www.fao.org/wiews/data/domains/detail/en/?code=30)

- Indicator 31: Number of crops with active private pre-breeding and breeding programmes http://www.fao.org/wiews/data/domains/detail/en/?code=31)
- Indicator 36: Number of new crop and wild species introduced into cultivation (http://www.fao.org/wiews/data/domains/detail/en/?code=36)
- Indicator 39: Number of farmers' varieties/landraces and underutilized species with potential for commercialization identified (http://www.fao.org/wiews/data/domains/detail/en/?code=39)

We did not assess these further.

Access to Seeds Index - At the time of assessment, the Access to Seeds Index (https://www.accesstoseeds.org/) provided data on numbers of varieties per crop in companies' portfolios per country, with data from 2017 on 64 countries (13 in South and Southeast Asia, 19 in East and Southern Africa, 22 in West and Central Africa, and 10 in LAC. Data focused on about 32 crops, as well as some additional data for 'local' crops, and include type of seed (open pollinated, hybrid, etc.); age of the newest variety of a crop on offer; number of companies with var <3 years; <5 years, etc.; total number of varieties per company; total number of companies per country. This Index aims to be repeated every 2-3 years. It should be noted that there are more companies active in countries than currently measured, as well as non-industry seed agents. We did not assess these data further.

International Food Policy Research Institute (IFPRI) Agricultural Science and Technology Indicators - At the time of assessment, ASTI (https://www.ifpri.org/project/asti-0) offered data on agricultural research spending and capacity (number of researchers) for low and middle income countries, with a total of approximately 78 countries, per commodity group. About 14 specific crops and 10 general commodity groupings were reported. We did not assess these data further.

FAO Global Partnership Initiative for Plant Breeding Capacity Building (GIPB) - the GIPB (https://www.fao.org/in-action/plant-breeding/en/) was active in previous years, assessing plant breeding capacity in many countries. We did not assess potentially pertinent and available data from this initiative further.

A4.2.3 Other supply metrics

Ex situ collections - FAO WIEWS, Genesys PGR, and GBIF - supply of landraces and crop wild relatives - both FAO WIEWS and Genesys PGR contain fields marking the improvement status of germplasm (e.g. landrace, wild, cultivar, etc.). These fields could in theory be used to calculate supply for each improvement status per crop. We note that these fields contain considerable data gaps in current datasets. We did not assess these data further.

FAO WIEWS - Several other indicator metrics available from FAO WIEWS with data at the crop level may be useful to assess supply of crop genetic resources, including:

- Indicator 16 - Number of samples resulting from targeted collecting missions in the country (http://www.fao.org/wiews/data/domains/detail/en/?code=16)
- Indicator 18: Number of crops conserved *ex situ* under medium or long-term conditions (http://www.fao.org/wiews/data/domains/detail/en/?code=18) - does not appear significantly different than data available from the core FAO WIEWS dataset mentioned in component 2.4.1.
- Indicator 22: Number of *ex situ* accessions regenerated and/or multiplied (http://www.fao.org/wiews/data/domains/detail/en/?code=22)
- Indicator 25: Average number of morphological traits characterized per accession of the *ex situ* collections (http://www.fao.org/wiews/data/domains/detail/en/?code=25)
- Indicator 26: Number of publications on germplasm evaluation and molecular characterization (http://www.fao.org/wiews/data/domains/detail/en/?code=26)
  We did not assess these further.

A4.2.5 Other security metrics

FAO WIEWS and Genesys PGR safety duplication fields - the FAO World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture (WIEWS) (https://www.fao.org/wiews/data/ex-situ-sdg-251/search/en/?no_cache=1) and the Genesys Plant Genetic Resources portal (Genesys PGR) (https://www.genesys-pgr.org/) databases contain fields enabling recording of whether specific accessions are safety duplicated (i.e. fields 'Genebank(s) holding safety duplications - code' and 'Genebank(s) holding safety duplications' in FAO WIEWS, and 'DUPLSITE' and 'DUPLINSTNAME' in Genesys PGR. These fields may be used to quantify the number of accessions per crop recorded as safety duplicated. It should be noted that the relevant fields in FAO WIEWS and Genesys PGR regarding safety duplication are not comprehensively filled currently and are an underestimate of true degree of safety duplication worldwide. For this reason, a considerable degree of error/underestimation is expected. We did not assess these data fields further.

FAO WIEWS - Several other indicator metrics available from FAO WIEWS with data at the crop level may be useful to assess security of crop genetic resources, including:

- Indicator 3: Percentage of PGRFA threatened out of those surveyed/inventoried (http://www.fao.org/wiews/data/domains/detail/en/?code=3)
- Indicator 21: Percentage of *ex situ* accessions safety duplicated (http://www.fao.org/wiews/data/domains/detail/en/?code=21) - does not appear significantly different than data available from the core FAO WIEWS dataset mentioned in component 2.5.2.
- Indicator 22: Number of ex situ accessions regenerated and/or multiplied (http://www.fao.org/wiews/data/domains/detail/en/?code=22)

We did not assess these further.

Conservation gap analysis - Various ecogeographic gap analysis methods are available for comparison of conservation collections to extant diversity growing in the wild or cultivated in farmers' fields, through programs (e.g. http://www.capfitogen.net/en/), codes (e.g. https://cran.r-project.org/web/packages/GapAnalysis/index.html), and published literature (e.g. Ramirez-Villegas *et al.* 2010; Castaneda-Alvarez *et al.* 2016; Khoury *et al.* 2019; Ramirez-Villegas *et al.* 2020; Carver *et al.* 2021; Ramírez-Villegas *et al.* 2022). None of these are presented currently online in a format that will be updated regularly in the future. We did not assess these further.

A5. Extended methodology and data sources references

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Annex 2: Expert stakeholder meeting information, agenda, and participants

The plants that feed the world: baseline information to underpin the conservation and use of plant genetic resources

Expert Workshop *24-25 July 2019*

It has been estimated that there are between 300,000 and 500,000 species of higher plants (i.e. flowering and cone-bearing plants), of which approximately 250,000 have been identified or described. About 30,000 are edible and about 7,000 have been cultivated or collected by humans for food at one time or another.

Although several thousand species may be considered to contribute to food security at local level, only a few hundred cultivated plants play a considerable role in food and agriculture at a global level. While the number of *plant species that feed the world* is relatively small, the genetic diversity within such species is often immense.

Investment in the conservation and improvement of these plants will be key for achieving the Sustainable Development Goals, including to achieve food security and sustainable diets, adapt agriculture to climate change or reduce the impact of farming in nature. The provision of baseline data and indicators on the genetic diversity of these plants is essential for decision-makers at global, regional and national levels in order to develop strategies to ensure the adequate conservation and use of these plant genetic resources.

The information on the plants that feed the world and of their genetic diversity is increasing available but scattered through a number of information systems, databases and the scientific literature. The publication *The plants that feed the world: baseline information to underpin strategies for their conservation and use* intends to bring together, for the first time, all the information available from these different sources to provide baseline and indicators for conservation and availability for use of plant genetic resources for food and agriculture (PGRFA). The Secretariat of the International Treaty on Plant Genetic Resources for Food and Agriculture, the Global Crop Diversity Trust and International Center for Tropical Agriculture (CIAT) are working together to prepare and publish this analysis jointly with the hope that it will become a flagship publication for the PGRFA community across the world.

The aim of the publication is to develop a reproducible sets of indicators that provide an evidence base to prioritize conservation and availability for use among crops, including: interdependence at global level; demand; supply and risk/resilience. These indicators would be use in a standardized manner for around 350 plants that are being used in food and agriculture. The methodologies being used will allow these indicators to be reproducible to enable identification of change in status and trends for PGRFA in the future.

The Secretariat of the International Treaty is organizing a technical consultation from 24 to 25 July in FAO Headquarters (Rome, Italy) with key experts on plant genetic resources and information systems and big data for agriculture to discuss the methodologies used to develop the draft indicator for all crops and enable participants provide suggestions on how to finalize the analysis.

Programme:

Wednesday, 24 July

9 - 9:15 **Welcome** - Kent Nnadozie, Secretary of the International Treaty on Plant Genetic Resources for Food and Agriculture

9:15 - 9:30 **Introductions by participants**

9:30 – 9:45 **Introduction to the Treaty and background on Crop Indicator project** – Alvaro Toledo, International Treaty Secretariat

9:45 - 10:30 **Overview of Indicator: What is this indicator for, exactly? What data should be in the indicator, and on what species?** – Colin Khoury, CIAT

10:30 – 11:00 Coffee and tea break

11:00 - 11:30 **Scope of the indicator: The Crop List**

11:30 - 12:30 **Analysis of crop importance: definition, data sources, data management and processing strategy, data shortcomings (Indicator domain 1)**

12:30 - 13:30 Lunch

13:30 - 14:30 **Assessing the global interdependence with respect to crops (Indicator domain 2)**

14:30 - 15:30 **Improving our understanding of the demand by users of crop genetic resources (Indicator domain 3)**

15:30 – 16:00 *Coffee and tea break*

16:00 – 16:45 **Progress towards analysing the supply of crop genetic resources (Indicator domain 4)**

16:45 - 17:30 **Determining Crop Genetic Resources Risk/Resilience (Indicator domain 5)**

Thursday, 25 July

9 - 9:15 **Summary and reflections on first day** – Luigi Guarino, the Global Crop Diversity Trust

9:15 - 10:30 **From individual data domains to a combined indicator for each crop**- Colin Khoury and Steven Sotelo (CIAT)

10:30 – 11:00 *Coffee and tea break*

11:00 - 12:30 **Discussion: Is the indicator fit for purpose? What's good about it?** - Alvaro Toledo (International Treaty Secretariat)

12:30 - 13:30 *Lunch*

13:30 - 15:00 **Discussion: Is the indicator fit for purpose? What's bad about it?** – Luigi Guarino, Global Crop Diversity Trust

15:00 - 15:30 *Coffee Break*

15:30 – 16:00 **Discussion: How best to present the improved indicator -** Colin Khoury and Steven Sotelo (CIAT)

16:00- 16:30 **Wrap up** – Alvaro Toledo (International Treaty Secretariat)

List of participants:

- Prof. Sayed Azam-Ali (Crops for the Future)
- Jan Engels (Bioversity International)
- Luigi Guarino - Global Crop Diversity Trust
- Michael Halewood (Bioversity International)
- Coosje Hoogendoorn - Access to Seeds Index
- Colin Khoury - International Center for Tropical Agriculture (CIAT)
- Irina Kovrova - Food and Agriculture Organization of the United Nations (FAOSTAT)
- Kudzai Kusena - Genetic Resources & Biotechnology Institute, Department of Research and Specialist Services, Zimbabwe
- Steven Sotelo - International Center for Tropical Agriculture (CIAT)
- Clive Stannard - PGRFA expert
- Alvaro Toledo - International Treaty on Plant Genetic Resources for Food and Agriculture
- Jose Valls (Cenargen)
- Maarten van Zonneweld - World Vegetable Center
- Stinike Oenema -- Food and Agriculture Organization of the United Nations (FAO nutrition)