Safeguarding and Using Fruit and Vegetable Biodiversity

Maarten van Zonneveld, Gayle M. Volk, M. Ehsan Dulloo, Roeland Kindt, Sean Mayes, Marcela Quintero, Dhrupad Choudhury, Enoch G. Achigan-Dako, and Luigi Guarino

1 Fruit and Vegetable Biodiversity Contributes to a Diverse Food Supply and Quality Diets

From a dietary perspective, fruits are reproductive plant parts with high sugar or oil content that are usually eaten fresh, as a snack, in desserts, or in drinks (Bioversity International 2021). Vegetables are plant parts, such as leaves, fruits, or immature pods, that are eaten raw or cooked, in salads and as part of savoury dishes in general

M. van Zonneveld (✉)
World Vegetable Center, Taiwan City, Taiwan
e-mail: maarten.vanzonneveld@worldveg.org

G. M. Volk
National Laboratory for Genetic Resources Preservation, U.S. Department of Agriculture, Fort Collins, CO, USA

M. E. Dulloo
Bioversity International, Port Louis, Mauritius

R. Kindt
World Agroforestry, CIFOR-ICRAF, Nairobi, Kenya

S. Mayes
Crops For the Future, London, UK

M. Quintero
International Center for Tropical Agriculture (CIAT), Cali, Colombia

D. Choudhury
International Centre for Integrated Mountain Development (ICIMOD), Patan, Nepal

E. G. Achigan-Dako
Laboratory of Genetics, Biotechnology and Seed Sciences, University of Abomey-Calavi, Abomey-Calavi, Benin

L. Guarino
Crop Trust, Bonn, Germany

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_30

(Grubben and Denton 2004). What both fruits and vegetables have in common is that they are rich in micronutrients and present an astonishing diversity of forms, tastes, and colors, adapted to myriad environments. Fruit and vegetable biodiversity is part of agrobiodiversity, underpinning diverse food production systems for both local and global economies and contributing significantly to worldwide health and nutrition (Willett et al. 2019). While agrobiodiversity can be defined as the sum of all organisms at the genetic, species, and ecosystem levels for food and agriculture, fruit and vegetable biodiversity can be defined more narrowly as the variety of fruits and vegetables at the genetic, species, and ecosystem levels, including crop wild relatives (CWR) and pollinators and other associated organisms.

Fruits and vegetables play an increasingly prominent role in a new global research and development agenda that emphasizes nutrition and healthy diets, alongside spurring climate action, safeguarding biodiversity, ending poverty, and improving livelihoods (Willett et al. 2019; Caron et al. 2018). Even so, most fruit and vegetable biodiversity, which is the foundation for fruit and vegetable supply, remains unexplored, poorly conserved, and increasingly threatened.

About 1100 vegetable species are recognized worldwide (Meldrum et al. 2018), and there are at least 1250 documented fruit species native to Latin America alone (Bioversity International 2021), although this number is likely to be higher (Van Loon et al. 2021). The global number of fruit species is even larger when considering native species from other continents (Maundu et al. 2009).

This pool of diversity includes fruit and vegetable species with exceptionally high nutritional values and some that are adapted to harsh environments: it offers an untapped resource to make nutrient-dense foods accessible and affordable to consumers under the challenges of global climate change. Examples include micronutrient-rich African leafy vegetables adapted to rain-fed conditions (Maundu et al. 2009) and vitamin-rich Amazonian fruit trees that withstand flooding and waterlogging (Borelli et al. 2020; van Zonneveld et al. 2020a).

Below the species level, local fruit and vegetable varieties grown by people are part of a cultural heritage with unique tastes and histories (Dwivedi et al. 2019). Varieties vary widely in levels of micronutrient concentrations and phytonutrient concentrations in general, including antinutrients (Simon et al. 2009). This variation allows us to identify varieties with high nutritional quality for developing new climate-adapted varieties with novel flavors, high nutritional values, and resistance to pests and diseases. At the landscape level, wild fruit and vegetable species, including those that are actively managed, are a substantial food source for communities around the world and support key ecosystem functions (Bharucha and Pretty 2010; Van Zonneveld et al. 2018). Fruit species can serve as a direct food source, contributing up to 30% of the daily vitamin intake of rural and forest communities in certain local settings (Jansen et al. 2020). In Africa in particular, the human consumption of wild vegetables is reported in many countries (Maundu et al. 2009; Achigan-Dako et al. 2011; van Zonneveld et al. 2021). CWR, including wild ancestors of domesticated fruit and vegetable species, are a special group of genetically-related species of targeted fruits and vegetables that are increasingly used in breeding because they can contain traits related to climate resilience and other desirable traits (Kilian et al. 2021; Schouten et al. 2019). In addition, most fruit species and some vegetable species depend heavily on pollinators for sustainable yields (Klein et al. 2007). These pollinators, together with seed dispersers, are also key to maintaining the viability of wild populations of fruit and vegetable species and their relatives.

2 Declining Biodiversity Limits Options for a Sustainable and Healthy Food Supply

Fruit and vegetable biodiversity continues to decline in farmers' fields and natural ecosystems (Pilling et al. 2020) in line with the global rapid decline in biodiversity (Díaz et al. 2019). The loss of this heritage, and the resulting narrowing options for developing climate-resilient and nutritious foods, as well as a yield gap due to pollinator decline, will likely limit progress in achieving the 2030 Sustainable Development Goals (SDGs): SDG 1, No Poverty; SDG 2, Zero Hunger; SDG 12, Responsible Consumption and Production; SDG 13, Climate Action; SDG 15, Life on Land; and any future goals set thereafter.

Globally, ecosystems in 88% of the 846 terrestrial ecoregions are poorly conserved, degraded, or disappearing in the Anthropocene (Dinerstein et al. 2017). The degradation and loss of these ecosystems under the pressures of land-use change, global climate change, and other threats leads to a decline in richness and abundance of fruit and vegetable species, CWR, and pollinators and dispersers at the landscape level (Pilling et al. 2020; Díaz et al. 2019). For example, 39% of 883 assessed wild fruit and vegetable species requires urgent conservation because they are either poorly conserved in genebanks and protected areas or not conserved at all; another 58% has a medium priority for conservation; for only 3% is genetic variation already well conserved (Khoury et al. 2019) (Table 1).

Four out of five studies on crop genetic erosion found evidence of crop diversity loss, the magnitude varying by species, taxonomic and geographic scale, and region, as well as analytical approach (Khoury et al. 2022). However, most genetic erosion studies have been done on cereal crops and their wild relatives; no global estimates

Table 1 Classification of 883 wild fruit and vegetable species in priority categories for conservation actions by Khoury and co-authors as part of a global conservation assessment of wild edible plants

Priority for conservation actions	Number of fruit species	Number of vegetable species	Number of species combined[a]
High	200	185	346
Medium	341	246	510
Low	11	25	27
Total	552	456	883

Source: Khoury et al. (2019)

[a]Includes species that have been classified as both fruit and vegetable.

have been made of the rate of varietal and genetic losses in fruit and vegetable species (Khoury et al. 2022). For some crops, such as tomatoes (*Solanum lycopersicum*), farmers have already replaced most local varieties in many regions (Walters et al. 2018; Cebolla-Cornejo et al. 2012) and the development of new varieties relies almost entirely on the diversity safeguarded in genebanks (Bauchet and Causse 2012).

In contrast to tomatoes, as noted above, the genetic resources of most fruit and vegetable species are poorly conserved by genebanks or not at all. A quarter of the 1,100 recognized vegetable species worldwide is not conserved in any genebank (Meldrum et al. 2018). Similarly, the conservation of wild relatives of vegetables is poor. For example, 65% of the wild relatives of eggplant (*Solanum melongena*) is conserved poorly or is not conserved *ex situ* in crop genebanks and botanic gardens (Syfert et al. 2016), while 50% of the wild relatives of chili peppers (*Capsicum* spp.) and 25% of the wild relatives of yard-long beans and cowpeas (*Vigna* spp.) are poorly conserved *ex situ* (van Zonneveld et al. 2020b; Khoury et al. 2020). The varietal diversity of most fruit tree species and their wild relatives, particularly those of tropical origin, are not maintained in genebanks or botanic gardens. Botanic gardens maintain a high richness of fruit species, although not necessarily a high intra-specific diversity (Pearce et al. 2020). The seed of most fruit species is recalcitrant and does not tolerate desiccation or the low temperatures of conventional seed storage, while maintaining fruit trees in high-quality field genebanks is expensive (Dawson et al. 2013). All of these fruit and vegetable genetic resources, in the absence of genebank back-up, are at risk of being lost forever.

Over the last four decades, populations of terrestrial insects were found to have declined, on average, by 45% across several studies, and the annual decline in abundance is estimated to be between 1% and 2% (Wagner et al. 2021; Dirzo et al. 2014). These studies are thought to represent global trends of rapid decline, because insect biodiversity is affected worldwide by a multitude of pressures, including habitat destruction, pesticide application, and climate change, among others (Wagner et al. 2021). During the same time period, the mean relative yield of crops that depend on these insects for pollination was 13% lower compared to pollinator-independent crops (Garibaldi et al. 2011). This pollination-yield gap will likely further increase under the current trends of pollinator decline. It can be anticipated that this will affect the yields of the many fruit species and some vegetable species that rely on these pollinators for crop production. This decline will also further increase the extinction risk of wild plant populations, including those of fruit and vegetable species and wild relatives that depend on cross-fertilization by pollinators for propagation (Cunningham 2000; Biesmeijer et al. 2006).

Complex access and benefit-sharing policies and regulations (Brink and van Hintum 2020), in particular, domestic policies and regulations that implement the Nagoya Protocol of the Convention on Biological Diversity (CBD), increasingly govern international efforts to conserve and use the diversity of local varieties and wild populations. Many of these policies recognize the rights of countries and local communities over genetic resources in their territories, yet these countries and communities from different countries depend on each other for genetic resources of fruit and vegetable crops for food and nutrition, including for neglected and underutilized ones (van Zonneveld et al. 2021; Khoury et al. 2016). This interdependence is expected to increase in this century under global climate change (Burke et al. 2009). The International Treaty on Plant Genetic Resources for Food and Agriculture (the Plant Treaty) has a multilateral system for a negotiated list of crops to enhance the exchange of germplasm—including seed and any other living plant tissue—between countries for food and agriculture. Unfortunately, most fruit and vegetable crops and their wild relatives are not included on this list, which limits germplasm exchange for these species (Brink and van Hintum 2020).

There are at least six important trends increasing the conservation and use of fruit and vegetable biodiversity in food systems at global and local levels. First, there is greater global awareness about the benefits of diverse diets with sufficient fruits and vegetables (Willett et al. 2019; Caron et al. 2018). Second, the proportion of fruit and vegetable crops contributing to global food production is increasing (Martin et al. 2019; Khoury et al. 2014; Gould 2017). Third, advanced biotechnologies are now accessible to public and private breeders and researchers globally for the purpose of mainstreaming the genetic diversity of fruits and vegetables into new crop varieties (Schouten et al. 2019; Jamnadass et al. 2020). Fourth, some neglected and underutilized fruit and vegetable species have regained relevance in urban diets through public and private initiatives in gastronomy and niche markets for local, healthy, or ethnic food (Borelli et al. 2020). Fifth, cities are becoming important hubs of crop diversity, because immigrants bring planting material from their home areas (Taylor and Lovell 2014; Rimlinger et al. 2021). Sixth, the coverage of protected areas has tripled in the last 40 years (Pringle 2017), and at least 35% of the terrestrial protected areas is owned and/or managed by local and indigenous communities, who play an important role in maintaining agrobiodiversity (Díaz et al. 2019).

Although these trends could possibly bend the curve of decline in fruit and vegetable biodiversity, they may not completely halt, let alone reverse, it.

For example, the expansion of protected areas provides some opportunities for conservation, but ecosystems in these areas may be degraded and wild populations of fruit and vegetable species within the landscape may decline (Pringle 2017). While cities can be hubs for new crop diversity, urban expansion is also a driver of biodiversity loss, because urban planning commonly does not consider crop biodiversity (Shackleton et al. 2017). Global increases in crop diversification with limited numbers of new crops may also lead to less use, and therefore a decline in the abundance and richness of local fruit and vegetable crops as diets tend towards becoming more homogenous globally (Khoury et al. 2014). In addition, successful national and international markets for previously underutilized species, such as cherimoya (custard apple, *Annona cherimola*) and avocado (*Persea americana*), both originating from Latin America, can lead to a decrease in local varieties in their primary centers of diversity due to product homogenization and consumer preferences (Vanhove and Van Damme 2013). While the proportion of fruit and vegetables in global food production has increased in the last decades, consumption of crops such as pineapple (*Ananas comosus*), banana (*Musa* spp.), and avocado rely on high-input monoculture production systems that lead to excessive environmental degradation and biodiversity loss (Magrach and Sanz 2020; Shaver et al. 2015; Schreinemachers et al. 2020). Even though genetic resources are increasingly used in the production of some crops such as tomatoes, production systems of other fruit and vegetable crops remain genetically impoverished and are susceptible to pest, diseases and climate stress. An extreme case is banana production, which is dominated by a single clone that is susceptible to the Panama disease, threatening the global banana supply (Ploetz 2021). Genebanks and seed saver networks where genetic resources are conserved allow people to re-introduce new and more varieties so as to make the fruit and vegetable supply more sustainable.

Policies and initiatives should stimulate the positive trends mentioned above while counteracting the negative effects with i) better conservation of fruit and vegetable biodiversity *in situ* (on farm, at the landscape level, and in protected areas); ii) with back-ups in genebanks and other *ex-situ* settings to reduce and reverse the decline of fruit and vegetable biodiversity (Dulloo et al. 2017); and iii) with sustainable use of fruit and vegetable biodiversity in production systems through good practices such as on-farm diversification and agroecological intensification (Attwood et al. 2017). This will require a global awareness campaign around safeguarding and sustainably using fruit and vegetable biodiversity and a concerted, coordinated global rescue plan.

3 Raising Awareness to Safeguard and Sustainably Use Fruit and Vegetable Biodiversity

Long-term support for biodiversity conservation can be gained by engaging with young people to create increased awareness about why biodiversity matters (Pringle 2017). For fruits and vegetable biodiversity in particular, governments and NGOs can engage young people and their families by showing the benefits of conserving and using fruit and vegetable biodiversity for diets and business opportunities. School-feeding programs, in combination with biodiversity education, are a promising tool for achieving this; they become successful when they involve multiple stakeholders, rely on stable procurement markets, and are embedded in national policies (Roothaert et al. 2021) (Fig. 1a). For example, government programs in Brazil use farm-to-school models to purchase fruits and vegetables of local crops from nearby producers for the purpose of offering diverse school meals and diversifying farm systems with shorter supply chains for fresh produce (Borelli et al. 2020). In this way, local crops are being maintained in local and diverse food systems. About 368 million children worldwide are estimated to be fed daily through school-feeding programs, with a yearly investment of between US$47–75 billion (WFP 2013). It can be anticipated that linking these programs and their budgets to

Fig. 1 Examples of activities to safeguard and use fruit and vegetable biodiversity: (**a**) Engaging young people through school-feeding programs with fresh vegetables in Burundi; (**b**) A traditional Thai meal with local bananas and a rich variety of vegetables; (**c**) A fruit vendor in Lima, Peru, holding a cherimoya fruit (*Annona cherimola*) of the locally-grown Cumbe variety; (**d**) Populations of the multi-purpose tree species néré (*Parkia biglobosa*) are maintained in parklands in Benin, and so far do not have a genebank back-up; (**e**) *Cucumis* spp. – a cucumber wild relative from Nyika National Park, delimited as a crop wild relatives (CWR) genetic reserve in Malawi as part of the Darwin Initiative SADC/CWR project 26-023; (**f**) Heirloom apple (*Malus domestica*) trees in Yosemite National Park in the United States are identified for conservation efforts. (Photo credits: (**a**) WFP, Hugh Rutherford; (**b**, **c**) WorldVeg; (**d**) University of Abomey-Calavi, Enoch Achigan-Dako; (**e**) Malawi PGR Centre; (**f**) USDA, Gayle Volk)

biodiversity education and school-feeding programs will help to promote the consumption and sustainable cultivation of local fruit and vegetable crops. This requires pilots for further testing, learning, and scaling in different settings, focusing especially on the fast-growing group of young people in sub-Saharan Africa.

Cooks, chefs, and other food innovators can promote local fruit and vegetable crops as a complement to global staples among urban consumers by emphasizing the taste, cultural, and health aspects of local crops (Moreau and Speight 2019; Pereira et al. 2019) (Fig. 1b). To be successful, these efforts must be linked to value-chain development so as to increase and sustain the supply of local crops, including investment in good agricultural practices, effective postharvest management, product preservation and processing, food safety, and market access for farmers (Schreinemachers et al. 2018; McMullin et al. 2021) (Fig. 1c). These farmers need good quality, safe, and appropriate planting material. Often, this planting material is not available, which is a major bottleneck preventing farmers from adopting these local crops (McMullin et al. 2021). To develop and deliver appropriate planting material of fruit and vegetable species now and in the future, their genetic resources need to be conserved, characterized and accessible. Genebanks play a crucial role in making this germplasm available (Lusty et al. 2021).

4 Rescuing Fruit and Vegetable Biodiversity

A global rescue plan is needed to bend and halt the curve of decline in fruit and vegetable biodiversity. This plan should focus on crop-based conservation strategies for globally important fruit and vegetable species and include conservation actions in global hotspots that harbor high levels of fruit and vegetable biodiversity, including Latin America, sub-Saharan Africa and Southeast Asia. This plan should also aim to protect wild populations of fruit and vegetable species, their relatives, and their pollinators and dispersers in natural habitats and traditional production systems.

Large national fruit and vegetable germplasm collections have been established in North America, South America, Asia and Europe (Byrne et al. 2018; Cunha Alves and Azevedo 2018; Jacob et al. 2015; Loskutov 2020). These crop genebanks conserve fruit and vegetable species and varietal diversity and make this diversity available for the development of new varieties and foods. For instance, the Vavilov Institute in Russia has a famous collection of 75,000 fruit and vegetable germplasm samples (Loskutov 2020). Australia has recently established a seed bank for native food plants (Cochrane 2017). These national efforts are complemented with international initiatives that have resulted in the collection of at least 1330 banana and 12,000 other fruit and 39,000 vegetable germplasm samples (Thormann et al. 2012; Engle and Faustino 2007), and have resulted in the establishment of international collections of banana and fruit tree germplasm at, respectively, Bioversity International and the World Agroforestry Centre, and of vegetable germplasm at the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) and the World Vegetable Center (Lusty et al. 2021; Engels and Ebert 2021). Wild relatives of fruit and vegetable crops, and neglected and underutilized fruit and vegetable species, poorly represented in this network, should be the focus of new plant explorations worldwide (Fig. 1d). Sub-Saharan Africa presents a gap in the genebank network; investment in genebank infrastructure in this region will help to maintain and document sub-Saharan African fruit and vegetable genetic resources.

At the same time, several collections from the existing genebank network are vulnerable because they have large backlogs of old or original fruit and vegetable germplasm samples (Fu 2017). These collections need investment in germplasm multiplication and rejuvenation. Without such support, there is a risk that part of this already-conserved diversity gets lost, too.

Workable agreements for germplasm access and benefit-sharing provide a framework for the better use of these collections and for new plant exploration efforts. The 2011–2021 global CWR Project led by the Crop Trust showed how global partnerships for collection, conservation, and germplasm availability are possible for wild relatives of fruit and vegetable crops that fall under the framework of the Plant Treaty including eggplant (*Solanum* spp.), carrot (*Daucus carota*), apple (*Malus* spp.), and bananas (Pearce et al. 2020). In this way, germplasm becomes available for farmers, breeders, and researchers under internationally established policies and regulations. Similar agreements should be made for germplasm exchange and new plant explorations for other fruit and vegetable species following all applicable current laws and regulations at the national and international levels.

For *ex-situ* conservation, seeds of most vegetable species are usually dried and stored at low temperatures in conventional seed banks for national and international distribution and long-term conservation. In contrast, fruit species are usually maintained in field or greenhouse conditions. Apart from the fact that the recalcitrant seed behavior of many fruit species impedes conventional storage, most fruit cultivars have specific genetic combinations that can be maintained only through vegetative propagation.

The lack of international fruit conservation programs—with the exception of bananas—results in increased reliance on national genebanks to protect cultivars and wild relatives of fruit crops. National fruit conservation programs must become more synergistic on a global scale, as field and greenhouse collections are particularly vulnerable to environmental threats, theft, and pests and diseases.

For some economically important clonal fruit and vegetable crops, such as bananas and garlic (*Allium sativum*), collections can be secured in tissue culture or by using cryogenic storage (Panis et al. 2020). The development and application of tissue culture and cryopreservation protocols to a broader range of species, in combination with global investment in cryo-capacity, are essential in order to safeguard the diversity of clonal and recalcitrant fruit and vegetable species in *ex-situ* conditions.

A global rescue plan must be accompanied with documenting genetic variation in traits of newly-collected and already-conserved fruit and vegetable germplasm. This documentation should include screening for nutritional quality for the purpose of developing and growing more healthy food. The information about intra-specific variation in nutrition composition will therefore help in making food and nutrition policies that promote and stimulate healthy diets and nutrition more precise and effective (Harris et al. 2022).

There is, however, still a poor understanding of the intra-specific variation of traits related to nutritional quality, as well as the heritability of high nutritional values and the impact of climatic factors on nutritional quality (Harris et al. 2022; Meckelmann et al. 2015; Rouphael et al. 2018; Lutaladio et al. 2010). Closing this knowledge gap towards a better understanding of the intra-specific variation in nutritional quality and of genotype x environment effects on said quality will help in selecting nutrient-dense and climate-resilient varieties. These varieties can be used to develop and grow nutrient-dense varieties, minimize effects of micronutrient dilution in breeding for yield increase, and develop varieties with special flavors for niche markets such as tasty tomatoes and gourmet chilies (*Capsicum* spp.) (Simon et al. 2009; Schouten et al. 2019; Tieman et al. 2017; Meckelmann et al. 2013). The mapping of genomic regions related to high or low phytonutrient concentrations will greatly enhance the development of varieties with high nutritional quality and specific taste profiles (Tieman et al. 2017).

Besides the micronutrients that are well-studied for nutrition, fruit and vegetable species harbor a wide range of phytonutrients and bioactive compounds that increase bioavailability and that are beneficially for health, including in ways that are not yet understood and that still represent a large knowledge gap for further research (Harris et al. 2022; Lutaladio et al. 2010; CBD 1992).

The rescue plan must be further complemented with conservation *in situ* (on farms, at the landscape level and in protected areas) to maintain local fruit and vegetable crops and varieties that play important ecological and dietary roles, and to stimulate the evolution of new traits through natural and human selection. Recognizing the importance of *in situ* conservation and the sovereign rights of countries over their natural resources, the CBD encourages contracting parties to take measures to protect natural ecosystems and viable populations both within and outside protected areas, restore degraded habitats, and control invasive species, among other threats (CBD 1992). Countries must put in place enabling policies and regulations to protect threatened species and populations, as well as promote sustainable use and the protection of local communities' traditional knowledge. Both the Plant Treaty and FAO Second Global Plan of Action provide further support to *in situ* conservation of plant genetic resources for food and agriculture (FAO 2009, 2011).

A common strategy for *in situ* conservation of CWR is for countries to carry out conservation planning exercises that prioritize CWR according to specific criteria, given that large numbers of CWR species may exist in a given country and it will not be possible to target them all in national strategies (Dulloo and Maxted 2019). The development of a National Strategy and Action Plan for *in situ* conservation of CWR is recommended to guide the implementation and monitoring of conservation activities such as the establishment of genetic reserves in protected areas (Fig. 1e). Wild relatives of fruit and vegetable crops are seldom included as a priority on national inventory lists; it is important to raise awareness of the need to conserve the wild relatives of these crops.

Local fruit and vegetable crops and varieties are still maintained by champion farmers, male and female, and communities in different production systems—diversified farms, home gardens, orchards, or other cultivated areas of high species and varietal diversity (Dulloo et al. 2017) (Fig. 1f). These plants provide nutritional and food security, income-generating opportunities, and ecosystem services, and contribute to cultural identity (Sthapit et al. 2016). Governments should recognize and protect unique and traditional production systems, such as some countries are doing already for important agricultural heritage systems (Koohafkan and Altieri 2011). They should further support these farmers and communities in maintaining these local crops and varieties by linking them to farm-to-school programs and niche markets for more resilient livelihoods, and by providing other types of incentives to maintain diversity in traditional production systems (Dulloo et al. 2017).

Finally, good agricultural practices and national and regional conservation strategies to protect pollinators and dispersers and their natural habitats must be implemented to safeguard these critical associated organisms of fruit and vegetable species (Wagner et al. 2021; Vasiliev and Greenwood 2020). These strategies should be embedded in various biodiversity and agricultural policy frameworks at national and international levels to stimulate integrated approaches for agrobiodiversity conservation. Pollinator conservation strategies have already been developed in the

United States, and in several countries of the European Union and the Global South; such strategies require urgent development and implementation elsewhere.

5 Conditions for success

An effective rescue plan requires clear goals, prioritizes actions, and tracks progress in line with the 2030 Agenda for Sustainable Development. It should be developed by a global team of experts from different sectors and disciplines in consultation with custodians and users of fruit and vegetable biodiversity worldwide, and then implemented in a concerted way under the umbrella of a global initiative endorsed by the Plant Treaty. Only with sufficient, sustained funding can a global rescue plan for fruit and vegetable biodiversity become a success. As a ballpark estimate, a 10-year global rescue plan for fruit and vegetable biodiversity would require at least 250 million USD.

Acknowledgments The authors wish to thank the United National Food Systems Summit Fruit and Vegetables Working Group for their original input to the original UNFSS working paper. Funding for this research was provided by long-term strategic donors to the World Vegetable Center: Taiwan, UK aid from the UK government, United States Agency for International Development (USAID), Australian Centre for International Agricultural Research (ACIAR), Germany, Thailand, Philippines, Korea, and Japan.

References

Achigan-Dako EG et al (2011) Diversity, geographical, and consumption patterns of traditional vegetables in sociolinguistic communities in Benin: Implications for domestication and utilization1. Econ Bot 65:129–145

Attwood S, Carmona NE, DeClerck F, Wood S (2017) Using biodiversity to provide multiple services in sustainable farming systems

Bauchet G, Causse M (2012) Genetic diversity in tomato (Solanum lycopersicum) and its wild relatives. In: Çalışkan M (ed) Genetic diversity in plants. (IN-TECH Education and Publishing, pp 133–162

Bharucha Z, Pretty J (2010) The roles and values of wild foods in agricultural systems. Philos Trans R Soc Lond B Biol Sci 365:2913–2926

Biesmeijer JC et al (2006) Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. Science (80) 313:351–354

Bioversity International (2021) New World Fruits. Database

Borelli T et al (2020) Local solutions for sustainable food systems: The contribution of orphan crops and wild edible species. Agronomy 10:231

Brink M, van Hintum T (2020) Genebank operation in the arena of access and benefit-sharing policies. Front Plant Sci 10

Burke MB, Lobell DB, Guarino L (2009) Shifts in African crop climates by 2050, and the implications for crop improvement and genetic resources conservation. Glob Environ Chang 19:317–325

Byrne PF et al (2018) Sustaining the future of plant breeding: The critical role of the USDA-ARS National Plant Germplasm System. Crop Sci 58:451–468

Caron P et al (2018) Food systems for sustainable development: Proposals for a profound four-part transformation. Agron Sustain Dev 38:1–12

CBD (1992) Convention on Biological Diversity

Cebolla-Cornejo J, Soler S, Nuez F (2012) Genetic erosion of traditional varieties of vegetable crops in Europe: Tomato cultivation in Valencia (Spain) as a case Study. Int J Plant Prod 1:113–128

Cochrane A (2017) Saving seeds: Conserving our natural heritage. Aust Gard Hist 29:28

Cunha Alves AA, Azevedo VCR (2018) Embrapa network for Brazilian plant genetic resources conservation. Biopreserv Biobank 16:350–360

Cunningham SA (2000) Depressed pollination in habitat fragments causes low fruit set. Proc R Soc B Biol Sci 267:1149–1152

Dawson IK et al (2013) What is the relevance of smallholders' agroforestry systems for conserving tropical tree species and genetic diversity in circa situm, in situ and ex situ settings? A review Biodivers Conserv 22:301–324

Díaz S et al (2019) Pervasive human-driven decline of life on Earth points to the need for transformative change. Science (80) 366

Dinerstein E et al (2017) An ecoregion-based approach to protecting half the terrestrial realm. Bioscience 67:534–545

Dirzo R et al (2014) Defaunation in the Anthropocene. Science (80) 345:401–406

Dulloo ME, Maxted N (2019) Special issue: Plant genetic resources conservation and utilization-crop wild relatives. Plant Genet Resour Characterisation Util 17:101–102

Dulloo ME et al (2017) Conserving agricultural biodiversity for use in sustainable food systems. In: Mainstreaming agrobiodiversity in sustainable food system: Scientific foundation for an agrobiodiversity index. Bioversity International, Rome

Dwivedi S, Goldman I, Ortiz R (2019) Pursuing the potential of heirloom cultivars to improve adaptation, nutritional, and culinary features of food crops. Agronomy 9:441

Engels JMM, Ebert AW (2021) A critical review of the current global ex situ conservation system for plant agrobiodiversity. II. Strengths and weaknesses of the current system and recommendations for its improvement. Plan Theory 10:1904

Engle LM, Faustino FC (2007) Conserving the indigenous vegetable germplasm of Southeast Asia. Acta Horticulturae 752:55–60

FAO (2009) International treaty on plant genetic resources for food and agriculture

FAO (2011) Second Global Plan of action for on plant genetic resources for food and agriculture. Commission on Genetic Resources for Food and Agriculture

Fu YB (2017) The vulnerability of plant genetic resources conserved ex situ. Crop Sci 57:2314–2328

Garibaldi LA, Aizen MA, Klein AM, Cunningham SA, Harder LD (2011) Global growth and stability of agricultural yield decrease with pollinator dependence. Proc Natl Acad Sci U S A 108:5909–5914

Gould J (2017) Nutrition: A world of insecurity. Nature 544:S6–S7

Grubben G, Denton O (2004) Plant resources of tropical Africa 2. Vegetables. PROTA foundation

Harris J et al (2022) Fruit and vegetable biodiversity for nutritionally diverse diets: challenges, opportunities, and knowledge gaps. Glob Food Sec 33:100618

Jacob SR, Tyagi V, Agrawal A, Chakrabarty SK, Tyagi RK (2015) Indian plant germplasm on the global platter: An analysis. PLoS One 10:e0126634

Jamnadass R et al (2020) Enhancing African orphan crops with genomics. Nat Genet 52:356–360

Jansen M et al (2020) Food for thought: The underutilized potential of tropical tree-sourced foods for 21st century sustainable food systems. People Nat 2:1006–1020

Khoury CK et al (2014) Increasing homogeneity in global food supplies and the implications for food security. Proc Natl Acad Sci U S A 111:4001–4006

Khoury CK et al (2016) Origins of food crops connect countries worldwide. Proc R Soc B Biol Sci 283:1–9

Khoury CK et al (2019) Comprehensiveness of conservation of useful wild plants: An operational indicator for biodiversity and sustainable development targets. Ecol Indic 98:420–429
Khoury CK et al (2020) Modelled distributions and conservation status of the wild relatives of chile peppers (Capsicum L.). Divers Distrib 26:209–225
Khoury CK et al (2022) Crop genetic erosion: understanding and responding to loss of crop diversity. New Phytol 233:84–118
Kilian B et al (2021) Crop Science special issue: Adapting agriculture to climate change: A walk on the wild side. Crop Sci 61:32–36
Klein AM et al (2007) Importance of pollinators in changing landscapes for world crops. Proc R Soc B Biol Sci 274:303–313
Koohafkan P, Altieri MA (2011) Globally important agricultural heritage systems – a legacy for the future. FAO
Loskutov IG (2020) Vavilov Institute (VIR): Historical aspects of international cooperation for plant genetic resources. Genet Resour Crop Evol 67:2237–2253
Lusty C et al (2021) Envisaging an effective global long-term agrobiodiversity conservation system that promotes and facilitates use. Plan Theory 10:2764
Lutaladio NB, Burlingame B, Crews J (2010) Horticulture, biodiversity and nutrition. J Food Compos Anal 23:481–485
Magrach A, Sanz MJ (2020) Environmental and social consequences of the increase in the demand for 'superfoods' world-wide. People Nat 2:267–278
Martin AR et al (2019) Regional and global shifts in crop diversity through the Anthropocene. PLoS One 14:e0209788
Maundu P, Achigan-Dako E, Morimoto Y (2009) Biodiversity of African vegetables. In: Shackleton CM, Pasquini MW, Drescher AW (eds) African indigenous vegetables in urban agriculture. Routledge, pp 65–104
McMullin S et al (2021) Determining appropriate interventions to mainstream nutritious orphan crops into African food systems. Glob Food Sec 28:100465
Meckelmann SW et al (2013) Compositional characterization of native Peruvian chili peppers (Capsicum spp.). J Agric Food Chem 61:2530–2537
Meckelmann SW et al (2015) Capsaicinoids, flavonoids, tocopherols, antioxidant capacity and color attributes in 23 native Peruvian chili peppers (Capsicum spp.) grown in three different locations. Eur Food Res Technol 240:273–283
Meldrum G, Padulosi S, Lochetti G, Robitaille R, Diulgheroff S (2018) Issues and prospects for the sustainable use and conservation of cultivated vegetable diversity for more nutrition-sensitive agriculture. Agri 8:112
Moreau T, Speight D (2019) Cooking up diverse diets: Advancing biodiversity in food and agriculture through collaborations with chefs. Crop Sci 59:2381–2386
Panis B, Nagel M, Van Den Houwe I (2020) Challenges and prospects for the conservation of crop genetic resources in field genebanks, in in vitro collections and/or in liquid nitrogen. Plan Theory 9:1634
Pearce TR et al (2020) International collaboration between collections-based institutes for halting biodiversity loss and unlocking the useful properties of plants and fungi. Plants, People, Planet 2:515–534
Pereira LM et al (2019) Chefs as change-makers from the kitchen: Indigenous knowledge and traditional food as sustainability innovations. Glob Sustain 2:1–9
Pilling D, Bélanger J, Hoffmann I (2020) Declining biodiversity for food and agriculture needs urgent global action. Nat Food 1:144–147
Ploetz RC (2021) Gone bananas? Current and future impact of fusarium wilt on production. Springer, Cham, pp 21–32. https://doi.org/10.1007/978-3-030-57899-2_2
Pringle RM (2017) Upgrading protected areas to conserve wild biodiversity. Nature 546:91–99
Rimlinger A et al (2021) Trees and their seed networks: The social dynamics of urban fruit trees and implications for genetic diversity. PLoS One 16:e0243017

Roothaert R, Mpogole H, Hunter D, Ochieng J, Kejo D (2021) Policies, multi-stakeholder approaches and home-grown school feeding programs for improving quality, equity and sustainability of school meals in northern Tanzania. Front Sustain Food Syst 5:43
Rouphael Y, Kyriacou MC, Petropoulos SA, De Pascale S, Colla G (2018) Improving vegetable quality in controlled environments. Sci Hortic 234:275–289
Schouten HJ et al (2019) Breeding has increased the diversity of cultivated tomato in the Netherlands. Front Plant Sci 10:1606
Schreinemachers P, Simmons EB, Wopereis MCS (2018) Tapping the economic and nutritional power of vegetables. Glob Food Sec 16:36–45
Schreinemachers P et al (2020) How much is too much? Quantifying pesticide overuse in vegetable production in Southeast Asia. J Clean Prod 244:118738
Shackleton CM, Hurley PT, Dahlberg AC, Emery MR, Nagendra H (2017) Urban foraging: a ubiquitous human practice overlooked by urban planners, policy, and research. Sustain 9. Page 1884 9, 1884 (2017)
Shaver I et al (2015) Coupled social and ecological outcomes of agricultural intensification in Costa Rica and the future of biodiversity conservation in tropical agricultural regions. Glob Environ Chang 32:74–86
Simon PW, Pollak LM, Clevidence BA, Holden JM, Haytowitz DB (2009) Plant breeding for human nutritional quality. Plant Breed Rev 31:325–392
Sthapit B, Lamers HAH, Ramanatha RV, A. & Bailey A. (2016) Tropical fruit tree diversity: Good practices for in situ and on-farm conservation. Earthscan
Syfert MM et al (2016) Crop wild relatives of the brinjal eggplant (Solanum melongena): Poorly represented in genebanks and many species at risk of extinction. Am J Bot 103:635–651
Taylor JR, Lovell ST (2014) Urban home food gardens in the Global North: Research traditions and future directions. Agric Human Values 31:285–305
Thormann I, Gaisberger H, Mattei F, Snook L, Arnaud E (2012) Digitization and online availability of original collecting mission data to improve data quality and enhance the conservation and use of plant genetic resources. Genet Resour Crop Evol 59:635–644
Tieman D et al (2017) A chemical genetic roadmap to improved tomato flavor. Science 355:391–394
Van Loon R et al (2021) Barriers to adopting a diversity of NUS fruit trees in Latin American food systems. In: Orphan crops for sustainable food and nutrition security. Taylor & Francis Group, pp 88–108. https://doi.org/10.4324/9781003044802-8
Van Zonneveld M et al (2018) Human diets drive range expansion of megafauna-dispersed fruit species. Proc Natl Acad Sci U S A 115:3326–3331
van Zonneveld M, Turmel MS, Hellin J (2020a) Decision-making to diversify farm systems for climate change adaptation. Front Sustain Food Syst 4:32
van Zonneveld M et al (2020b) Mapping patterns of abiotic and biotic stress resilience uncovers conservation gaps and breeding potential of Vigna wild relatives. Sci Rep 10:1–11
van Zonneveld M, Kindt R, Solberg S, N'Danikou S, Dawson IK (2021) Diversity and conservation of traditional African vegetables: Priorities for action. Divers Distrib 27:216–232
Vanhove W, Van Damme P (2013) Value chains of cherimoya (Annona cherimola Mill.) In a centre of diversity and its on-farm conservation implications. Trop Conserv Sci 6:158–180
Vasiliev D, Greenwood S (2020) Pollinator biodiversity and crop pollination in temperate ecosystems, implications for national pollinator conservation strategies: Mini review. Sci Total Environ 744:140880
Wagner DL, Grames EM, Forister ML, Berenbaum MR, Stopak D (2021) Insect decline in the Anthropocene: Death by a thousand cuts. Proc Natl Acad Sci 118:e2023989118
Walters SA, Bouharroud R, Mimouni A, Wifaya A (2018) The deterioration of Morocco's vegetable crop genetic diversity: An analysis of the Souss-Massa region. Agri 8
WFP (2013) State of school feeding worldwide
Willett W et al (2019) Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393:447–492