Chapter

On-Farm Crop Diversity for Advancing Food Security and Nutrition

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Abstract

In 2019, nearly 690 million people were hungry, indicating that the achievement of Zero Hunger by 2030 is *not* on-track. The enhanced conservation and use of crop diversity, which demonstrably improves farm productivity and hence food security and nutrition, could be one of the solutions to this problem. The broadening of the inter- and intra-specific diversity of crops contributes to dietary diversification and nutrition and improves the resilience of production systems to shocks, especially the biotic and abiotic stresses attributed to climate change. Examples of successful interventions that resulted in enhanced on-farm crop diversity are provided. Relevant tools and guidelines to strengthen national capacities for the enhanced on-farm management of plant genetic resources for food and agriculture are also highlighted. Guidance, based primarily on the *Second Global Plan of Action for Plant Genetic Resources for Food and Agriculture*, is presented to enable the conservation of farmers' varieties/landraces, their genetic improvement and seed delivery systems; promote their cultivation, consumption and marketing; develop and implement policies; foster partnerships and strengthen requisite institutional and human capacities. Finally, the case is made for research and development, including using modern techniques, to achieve these aims.

Keywords: plant genetic resources, farmers' varieties, landraces, conservation, sustainable use

1. Introduction

The most recent edition of the report on the *State of Food Security and Nutrition in the World* [1] contains very worrying statistics: nearly 690 million people are hungry, i.e. 8.9 percent of the world's population! This represents an increase of 10 million people in a single year and nearly 60 million in five years. In fact, in 2019, close to 750 million – about one in ten people in the world – were exposed to severe levels of food insecurity. Conversely, the incidence of overweight children and adult obesity continues to rise [1]. Thus, the world is not on track to achieve Sustainable Development Goal (SDG) 2: Zero Hunger by 2030 [2]. Should recent trends continue, the number of people affected by hunger will surpass 840 million by 2030. It is crucial, therefore, to find effective, sustainable solutions to address hunger. As implicit in the Agenda 2030 [2], the eradication of hunger and malnutrition must be achieved through sustainable means, especially those that preclude further damage to the environment.

The conservation and use of crop genetic diversity is a key component of sustainable solutions to hunger and malnutrition as well as improving livelihoods. Unfortunately, this crop diversity is threatened by such factors as urban encroachment on farmland, unsustainable use of natural resources, the promotion of genetically uniform varieties in replacement of local varieties, introduction of alien invasive species, changing patterns of human consumption, absence of, or inappropriate, legislation and policy, as well as climate changes [3]. The loss of this genetic diversity reduces the options for sustainably managing resilient agriculture [4] in the face of adverse environments and rapidly fluctuating meteorological conditions. As such, it is essential to strengthen their improvement and management on-farm and to enhance their documentation and complementary conservation *ex situ* to safeguard these valuable resources [5].

The Second Global Plan of Action for Plant Genetic Resources for Food and Agriculture (Second GPA) [5] is the internationally agreed framework for the conservation and sustainable use of the full range of plant genetic resources used for food and agriculture, including farmers' varieties/landraces managed on-farm. The actions which countries commit to take in order to achieve these aims are enunciated in the Second GPA in 18 thematic Priority Activities, several of which are specific to crop diversity managed on-farm. Developed as the global policy response to the gaps and needs identified in the *Second Report on the State of the World's Plant Genetic Resources for Food and Agriculture* [6], the Second GPA provides guidance on:

- promoting farmers' varieties/landraces, which is used as an indication of overall crop diversity in this chapter, through developing and strengthening national programmes;

- increasing regional and international cooperation, including research, education and training and enhanced institutional capacity for the conservation and use of plant genetic resources for food and agriculture (PGRFA); and,

- developing and implementing evidence-based policies to promote and improve the effectiveness of on-farm conservation, management, improvement and use.

This chapter highlights the importance of inter- and intra-specific crop diversity managed on-farm as a mechanism to address malnutrition and food insecurity, especially under worsening climate change scenarios. To promote the cultivation and use of the widest possible crop diversity, guidance, based on the relevant Priority Activities of the Second GPA, is provided. These encompass the actions necessary for the conservation and on-farm management of PGRFA; enhanced access to, and use of, local crop diversity – including through responsive seed systems; and genetic improvement as means to the sustainable use of crop diversity. Relevant enabling policy instruments and initiatives for the conservation and sustainable use of crop diversity, developed over the last 50 years, are also described.

2. Important elements of crop diversity conservation and use

With about 80% of all foods being plant-based, any effective solutions for the current trend of worsening food insecurity and malnutrition must address the shortcomings of crop production systems. Crop genetic diversity not only represents the basis of food and agricultural systems, it is also an enormous reservoir of useful genes and gene complexes that endow plants with coping mechanisms for evolution and habitat changes [7, 8]. The inter- and intra-specific variation of crops provides the basis for more productive and resilient production systems that are better able to cope with stresses such as drought or overgrazing [9]. This diversity also enhances the nutritional status of people [10–12]. Changes in land use, together with high rates of urbanization and emigration, displacement of traditional crops in favor of a few starchy staples, and abandonment of marginal agricultural areas, are posing an unprecedented threat to this diversity. Exacerbating this are the threats posed by climate change manifested through the increasing frequencies, distribution and intensities of extreme weather events.

2.1 The narrow genetic base of crop production systems

There are approximately 380,000 vascular plant species [13, 14], of which less than 30,000 (or barely 7%) have been consumed as food by humans [15]. Of these, some 6 000 (or 22% of edible plants) have been actively cultivated for human consumption [16, 17]. Despite this diversity, agricultural production systems depend on a narrow list of crop species. This is illustrated by the fact that less than 200 plants were the sources of global food production in 2019, with only nine of them (sugar cane, maize, rice, wheat, potatoes, soybeans, oil palm fruit, sugar beet and cassava) accounting for over 66 percent of all crop production and 53 percent of global average daily calories [3, 18] (See **Figure 1**).

Agricultural production systems, based on just a few crops, are more vulnerable to biotic and abiotic stresses, including incidences of extreme weather events which, in the past, have resulted in crop failures. Compounding this, many local crops and varieties are cultivated as small and isolated populations and thus tend to lose genetic diversity [19]. These small populations undergo limited geneflow and are subject to genetic drift, founder effects and inbreeding. This, seen ever more frequently due to progressive introduction of commercial varieties, changing climatic conditions, migration to urban areas and expansion of land use for infrastructure and social development, represents an unprecedented threat to local crop diversity [20].

In order to address the impact of the above on changes on diversity, it is essential to monitor farmers' varieties/landraces on-farm [3]. Understanding changes in genetic diversity over time entails the assessment of:

- species richness and evenness and associated environmental variables;
- population size and genetic structure of farmers' varieties/landraces; and,
- the impact of management or farming practices on populations.

Further, at the genetic level, diversity can be assessed using a range of modern genomics-based approaches, such as molecular markers to determine changes over time as well as phylogenetic analyses. An overview of these approaches can be found in Bruford et al. [21] and Dulloo et al. [22].

The Second GPA [5] provides guidance on developing and strengthening systems for monitoring and safeguarding genetic diversity and minimizing genetic erosion of plant genetic resources for food and agriculture. Priority Activity 16 of the framework highlights the importance of establishing and implementing monitoring mechanisms for the regular assessments of genetic erosion. Information from extension services, local non-governmental organizations, seed sector and farming communities can be linked to early warning systems at the national and higher

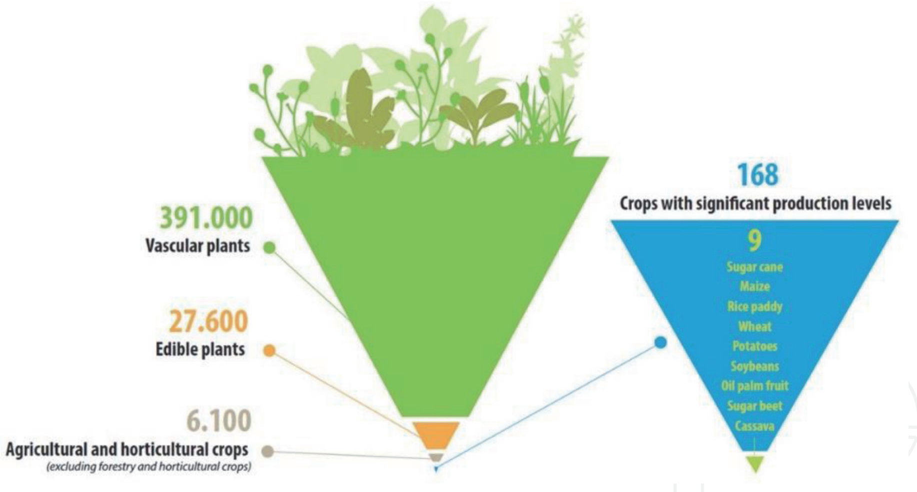

Figure 1.
The plant diversity 'funnel'. Humans rely on nine crops for most of their food while almost 400,000 higher plants have been described out of which a little less than 30,000 are edible.

levels. This Priority Activity also underscores the need to enhance the use of advanced methods, such as those based on information and communication technologies and molecular and spatial analytical tools, for monitoring the status of the most threatened diversity in crops.

2.2 Challenge of climate change

Crop production is affected by the consequences of climate change [23], such as increasing temperatures, changing precipitation patterns, higher concentration of carbon dioxide (CO_2) in the atmosphere and the occurrence of extreme weather events such as floods and drought conditions. Climate change is also affecting biotic factors such as emergence of new pests and diseases and change in the virulence of existing ones. While specific impacts in crop production vary by crop and the climate in which they are grown, there is a growing scientific consensus that increasing temperatures will be detrimental, especially in many developing tropical countries where food insecurity and malnutrition remain pervasive.

Temperature increase and prolonged drought affect a range of biological processes. For example, the physiological responses of plants to high temperature and/or drought conditions are translated into negative effects on growth rates, and therefore on yield. Substantial declines in yields of important crops have already been reported and are predicted to particularly affect those regions where food security is already a major concern [24, 25]. Fruit and vegetable crops are highly vulnerable to climate change during their reproductive stages and to more disease prevalence, and thus production of these crops is also expected to be affected [26]. A detailed study on data from 23 countries in different regions undertaken by Iizumi and Ramankuttym [27] identified temperature variation as a key constraint to maize, soybean, rice and wheat yields. The study showed that the year-to-year variations in yields of these crops from 1981 to 2010 significantly decreased by 19% to 33%.

Climate change also alters the quality of plant nutrients by affecting soil biology, physics and chemistry, and therefore impacts the availability of nutrients [28]. Food quality might similarly be negatively impacted. For example, temperature increases over the past decades in Japan have led to earlier blooming of apples, which in turn has impacted acidity, firmness and water content, and thereby reducing quality [29].

Climate change is expected to alter the range and severity of pest and disease incidence [25]. Predictive models forecast that there will be either increases or decreases of incidence, depending on the region and its climatic conditions; however, the mean probability of pest and disease incidence is expected to rise globally [30]. Quiroz et al. [31] report that climatic changes in the Andean region have led to an increase in pest and disease occurrence in potato cropping, which is driving farmers to shift their production to higher altitudes.

The effects of climate change on major crops are well studied, particularly at species level (i.e. [32–35]). The majority of studies focus mainly on the yield of a specific crop under climate change, yet there are fewer studies comparing the effects on climate change on different varieties of the same species. The use of inter- and intra-specific crop diversity is central to traditional risk management practices in many farming communities (e.g., [36–38]). Such practices will be even more essential as the effects of climate change become more frequent and profound. Many farmers' varieties/landraces are suited to local ecosystems, climatic conditions and farming practices, and have been shown to be more resilient to unpredictable and hardy conditions [8, 39–42].

The Second GPA [5] addresses climate change in most of its Priority Activities, which responds to concerns about the impact of climate change on agriculture. As mentioned above, climate change impacts farmers' varieties/landraces cultivated, with the result that farmers will need to have access to new germplasm. Priority Activity 2 of the Second GPA draws attention to the need for adapted crop varieties to cope with future environmental conditions. It recommends that a range of initiatives and practices should be employed to help farming communities benefit from local crop genetic diversity in their production systems.

2.3 Diversified diets and nutritional components

Plants are the basis of nutrition – whether directly or indirectly – providing key elements in the human diet. While it is clear that malnutrition overall is a major concern, the impact of malnutrition is disproportionately higher on women and children [1]. This can be addressed both through increasing the dietary diversity of the food consumed as well as increasing the quality of produce through breeding initiatives, such as biofortification, to develop nutrient-dense crop varieties.

In the last century, there have been major advances in food production, improving yields in many staple crops [43]. However, the focus of production has been on calorific intake – often negatively correlated to nutritional value in terms of protein content and quality [44–46].

In response to the above, systemic approaches to agriculture now include nutrition as a key component. This is essential for ensuring not only that sufficient calories are produced but that other key health requirements are addressed [43, 47]. In particular, there is a renewed interest in nutrient-rich neglected and underutilized species (NUS) [48–53]. While many of these species are environmentally resilient and cultivated in marginal areas as well as being rich in nutrients, bottlenecks for their increased production and consumption are common [16, 43, 54]. These include low yields, access to quality seeds and planting materials, low market demand and a lack of knowledge in their consumption. These issues, which occur along entire value chains, can be addressed through research and development (R&D) and coherent policy frameworks. In many cases however, financial resources are required to generate innovative solutions and build capacities for their implementation.

The Second GPA [5] provides guidance on promoting diversification of crop production; broadening crop diversity and promoting development and commercialization of all varieties, primarily farmers' varieties/landraces and underutilized species. Its Priority Activities 10 and 11 require that countries promote both the diversity of crops on-farm and the development and commercialization of the widest range of crops and their varieties, in particular farmers' varieties/landraces and NUS, respectively. Additionally, Priority Activity 11 highlights the need to develop and implement policies and incentives to create demands and the matching markets for the products of these crops.

Boxes 1 and **2** illustrate how local crops can be mainstreamed successfully, resulting in increased quality, availability and demand for these fruits and vegetables. The two examples presented, one in Micronesia and the other in Kenya, highlight the need for multisectoral approaches and strategies.

Vitamin A deficiency is one of the key causes of blindness in children [55]. This public health problem is prevalent in many countries, especially in Africa and South-East Asia [56]. One of the approaches for addressing the prevalence of Vitamin A deficiency has been to increase the nutritional diversity of local fruits and vegetables consumed.

Bananas are a key staple in many countries and one of the world's most popular fruits. Studies of different banana cultivars have revealed great differences in carotenoid content, from 5945 mgb-carotene/100 g in the some of the yellow/orange-fleshed Fe'i cultivars to 58mgb-carotene/100 g in the white-fleshed cultivar of the Cavendish subgroup [57, 58]. Fe'i banana (*Musa troglodytarum*) is indigenous to the islands of the Pacific (**Figure 2**) and is known to be rich in Vitamin A.

Figure 2.
Fe'i banana, showing the rich orange color of the fruit, an indicator of its high carotenoid content.

During the 1970s in the Federated States of Micronesia, diets based on non-local foods, together with an increase in consumption of refined white rice, flour, sugar, fatty meats and other processed foods [59], caused a serious Vitamin A deficiency [60]. In response, international agencies and local governments teamed up to promote the production and consumption of local banana cultivars, especially those identified as containing significant amounts of bio-available Vitamin A. The approaches included the development of policies promoting local cultivation, guidance on agronomic techniques, youth clubs, school activities and farmers' fairs. As a result of the various initiatives, the local production and consumption of the yellow/orange-fleshed banana variety, Karat, containing 2 230 μg/100 g of the provitamin A (50 times that found in white-fleshed bananas), was effectively promoted and these local nutritious bananas are now available in most markets. The success of this multisectoral approach – health, agriculture and education – is regarded as a model, linking dietary and agricultural diversity for healthy diets, to be replicated with other locally available, nutrient-dense crops in vulnerable populations.

Box 1.
Successes in mainstreaming local crops for better nutrition: Fe'i bananas in the Federated States of Micronesia.

There are many diverse species and varieties of indigenous leafy vegetables consumed locally in tropical sub-Saharan Africa. These include African nightshades (*Solanum scabrum*), leafy amaranth (*Amaranthus spp.*), spider plant (*Cleome gynandra*), cowpea (*Vigna unguiculata*), Ethiopian kale (*Brassica carinata*), mitoo (*Crotalaria ochroleuca* and *C. brevidens*), kahuhura (*Cucurbita ficifolia*), jute plant (*Corchorus olitorius*) and pumpkin leaves (*Cucurbita maxima* and *C. moschata*) [61]. The nutritional importance of African leafy vegetables (ALV) has been recognized by various experts over recent decades [62–65]. Yet, despite their nutritional advantage over many imported vegetables, levels of consumption had been decreasing in many countries, including Kenya [66].

One of the key reasons for the decline in the consumption of ALV includes migration to cities, causing a shift in production. With these changes, knowledge of the cultivation of ALV was also being lost, including, very importantly, methods of the production of quality seeds. Increasing the quality of seeds can increase yields. For instance, selecting those seeds with lower rates of dormancy results in higher germinability and hence, improved yields ultimately.

In this respect, African nightshades, for example, require the removal of the wet pulp that contains growth inhibitors, which affect germination rates [61]. Initiatives to improve ALV cultivation by disseminating this information, along with other techniques that enhance seed germination, to farmers through participatory methods were implemented successfully. The resulting uptake in the cultivation of quality ALV by smallholder farmers increased the production and quality of African nightshades in Kenya. Extension workers collaborated closely with researchers and international organizations to reconstruct a knowledge base, combining traditional and more technical information on these species.

Although these crops used to be considered a "poor man's food" until 15 years ago, due to, *inter alia*, improvements in seed quality, awareness raising and value chain interventions, ALV are now commonly found in Kenyan supermarkets [61, 63]. ALV, now gaining in popularity, as evidenced by seed companies' interest and the increase in area cultivated, are contributing to addressing malnutrition as well as to improving livelihoods [65].

Box 2.
Enhancing the quality of seeds to boost production: Seed dormancy in African leafy vegetables in Kenya.

3. Management of on-farm diversity

Enhanced crop diversity, including farmers' varieties/landraces, confers resilience on crop production and reduces vulnerability to shocks and are potential sources of traits for crop improvement, especially for developing varieties tolerant to biotic and abiotic stresses [3]. A significant amount of crop diversity, including farmers' varieties/landraces, is only maintained in farmer's fields, orchards or home gardens. Many farmers choose to cultivate farmers' varieties/landraces due to agronomic, culinary, or quality preferences [3, 40]. Much of this crop diversity also has locally important cultural values. The dynamic on-farm management of this diversity contributes to their continual evolution and adaptation due to farmers' selection and seed exchange systems [67].

In order to support countries in enhancing the diversity of crops and varieties which are cultivated by farmers, the *Voluntary Guidelines for the Conservation and Sustainable Use of Farmers' Varieties/Landrace*s [3], were developed. They serve as reference material for preparing a National Plan for the Conservation and Sustainable Use of Farmers' Varieties/Landraces and are a useful tool for development practitioners, researchers, students and policymakers who work on the conservation and sustainable use of these valuable resources.

3.1 Germplasm conservation and on-farm management

The diversity of crops and varieties maintained on farmers' fields must also be backed up *ex situ*, to ensure their conservation in an effective, integrated and rational manner in case of loss on-farm. Conserving this diversity *ex situ* is additionally advantageous in that it can be assessed and made more readily available to researchers and plant breeders. Crop germplasm, a significant proportion of which are farmers' varieties/landraces, is conserved in more than 650 genebanks worldwide [68]. Complementary *ex situ* conservation of crop diversity is essential for safeguarding global food security for the present and future. The application of standards and procedures that ensure their continued survival and availability is therefore essential. The *Genebank Standards for Plant Genetic Resources for Food and Agriculture* [69] set the benchmark for current scientific and technical best practices, and support key international policy instruments for conserving crop germplasm in genebanks.

Ex situ conservation of plant genetic resources in genebanks and other facilities safeguards a large and important amount of resources that are vital to global food security [6]. Genebank conservation entails acquisition, storage, characterization, evaluation, regeneration, safety duplication and documentation of germplasm accessions [69, 70]. The methods used include the storage of orthodox seeds in seed genebanks and safeguarding species that produce nonorthodox seeds or are propagated vegetatively as live plants in field genebanks or as plantlets through *in vitro* culture or cryopreservation [69]. Genebanks serve the dual aims of the conservation of PGRFA and the provision of these genetic resources to plant breeders, researchers and other users.

Many collections, especially at the national level, remain vulnerable as they are exposed to natural disasters, including those caused by climate change, and manmade calamities such as civil unrest. These collections are similarly at risk due to avoidable adversities resulting from lack of funding and/or poor management. Well-managed genebanks both safeguard genetic diversity and make it available to breeders. As such, genebanks require adequate and continuous levels of sustainable funding.

In this context, Priority Activity 2 of the Second GPA [5] underscores the need for improved on-farm conservation and the management and use of farmers' varieties/landraces and underutilized crops. It also highlights the need to foster linkages between these activities and the conserving this diversity in genebanks. The Second GPA also recommends that governments consider how production, research, economic incentives and other policies impact the on-farm management and improvement of PGRFA. The actions that should be taken to enhance the *ex situ* conservation of germplasm are provided in the following Priority Activities of the Second GPA:

- Priority Activity 5 on the targeted collecting of germplasm;
- Priority Activity 6 on sustaining and expanding effective *ex situ* conservation of diverse germplasm; and
- Priority Activity 7 on regeneration and multiplication of *ex situ* accessions, including for distribution and safety duplication.

3.2 Enhancing access to, and use of, local crop diversity

The development of farmers' varieties/landraces is commonly undertaken through participatory plant breeding (PPB), which aims to bridge the formal and informal seed systems by supporting smallholder farmers and their collective efforts [71, 72]. PPB often uses demonstration plots in Farmers Field Schools [73] to increase farmers' awareness of the quality of varieties and seed produced, and to support adoption. Vernooy et al. [74] reported that PPB resulted in both the conservation of farmer-preferred landraces and the development of new PPB-developed varieties, as well as farmer-managed seed production and distribution (e.g., in China and Mexico). Community seedbanks played a crucial role in these activities through seed collection and distribution; seed production of improved local varieties; and education and awareness activities. Community seedbanks are informal, locally governed institutions whose core function is to preserve seeds for local use. They play an important role in increasing access to diverse and locally adapted crops and varieties [74, 75], especially farmers' varieties/landraces. These community-based endeavors also enhance related local knowledge and skills in the workflow for seed delivery, i.e. selection, treatment, storage, multiplication and distribution [3].

Community seedbanks can be an effective part of a comprehensive strategy for the conservation and sustainable use of crop diversity. Community-based small-scale seed initiatives, often linked to community seed banks, will play a vital role in the improvement of, and access to, quality declared seeds and planting materials, maintenance of crop diversity for food security, and positively contribute to the national breeding programs. For example, the formation of seed clubs in Vietnam enabled working with farmers to promote varietal selection through participatory plant breeding and the national varietal registration of these local varieties. This has enhanced farmers' access to the quality seeds and planting materials of preferred varieties [76] (see **Box 3**).

Enhanced farmers' access to quality seeds and planting materials of well-adapted crops and varieties is realized through the strengthening of community-level seed production with suitable quality assurance regimes, including protocols for quality declared seeds and quality declared planting materials. The *Quality Declared Seed System* [78] consists of guidelines and protocols that aim at assisting small-scale farmers, specialists in seed production, field agronomists and agricultural extension services in the production of quality seed. This system provides an alternative for seed quality assurance and is particularly useful for countries with limited resources

In Vietnam, the Southeast Asia Regional Initiatives for Community Empowerment (SEARICE) and the Mekong Delta Development Research Centre of Can Tho University (MDI-CTU) have been collaborating with communities on the formation of seed clubs to drive community-based conservation and sustainable use of plant genetic resources. These clubs enable local seed supply systems through seed conservation, exchange, and crop improvement activities. In particular, they facilitated:

- participatory variety rehabilitation, i.e. whereby the original characteristics of the farmers' variety/landrace is restored through selection;
- participatory plant breeding, where farmers collaborate in the process of crop varietal development and have opportunities to make decisions throughout; and
- participatory variety selection, which involves farmers growing and selecting varieties in their own fields, providing a way for breeders to learn which varieties perform well on-farm and are preferred by farmers.

These activities, which bridged the formal and informal seed systems [77], have resulted in the development of 360 farmers' varieties, five of which are nationally certified [76]. The formal registration of farmers' varieties, made possible by the policy and technical assistance provided by MDI-CTU and funding provided by SEARICE, paved the way for the eventual production of quality declared seeds – thereby enhancing the confidence of the farmers in the seeds. This approach to community empowerment has been fundamentally important in the improvement of access to and availability of seeds, maintenance of crop diversity for food security, and positively contribute to the national breeding program through the linkages established between the formal and informal seed sectors.

Box 3.
Seed clubs in Vietnam.

[79]. The system is less demanding than full seed quality control systems yet guarantees a satisfactory level of seed quality. Its partner publication, *Quality Declared Planting Material* [80], was prepared in collaboration with the International Potato Centre and follows the principles and approach of FAO's Quality Declared Seed System.

It is necessary to develop and implement national seed regulatory frameworks and to enable the participation of multiple actors, including farmers. This can be undertaken through cooperatives and small- and medium-scale seed enterprises, and the private sector, while supporting institutional and human capacities along the entire seed value chain. Areas of intervention typically include strengthening capacities for the production and processing of seeds and their quality assurance, packaging, storage and marketing. Priority Activity 11 of the Second GPA recommends that countries promote the "development and commercialization of all varieties, primarily farmers' varieties/landraces and underutilized species" [5]. Linked to this, Priority Activity 12 of the Second GPA focuses on supporting seed production and distribution. It underscores the importance of developing/reviewing seed regulatory frameworks that facilitate the development of seed systems and their harmonization at regional levels, taking into account the specificities of different seed systems [5].

To support practitioners along the entire seed value chain, the six-module *Seeds Toolkit* [81–86] is a resource to enhance knowledge and skills for delivering quality seeds and planting materials of well-adapted crop varieties to farmers. The modules are designed as practical guidance to assist in the implementation of the national seed strategies and capacity building activities, especially for small-scale farmers and small- and medium-scale entrepreneurs.

For policy specific guidance, stakeholders may refer to the *Voluntary Guide for National Seed Policy Formulation* [87]. This explains seed policies and how they differ from seed laws; describes the participatory process of seed policy formulation, the nature and layout of seed policy documents and their key elements; and addresses issues involved in their implementation.

3.3 Genetic improvement as means to sustainable use of on-farm crop diversity

A continuous stream of improved crop varieties that are adapted to particular agro-ecosystems and production systems is required for meeting the challenges posed by food insecurity and malnutrition, especially in the face of climate change. In this regard, Priority Activity 9 of the Second GPA recommends countries to support "plant breeding, genetic enhancement and base-broadening efforts" [5].

Crop breeders must aim to develop varieties that are productive, nutritious, resistant to biotic and abiotic stresses, and are well-adapted to target agroecologies and meet consumer preferences and market demands. Genetic diversity is an essential resource for breeders to improve new cultivars with desirable characteristics [88]. For crop diversity to be useful in addressing malnutrition and climate change through breeding, their characteristics need to be measured, evaluated and recorded in information systems that are available to all relevant stakeholders. The process of characterization entails the description of a minimum set of standard phenotypic, physiological and seed qualitative traits. The evaluation of PGRFA requires an analysis of agronomic data obtained through appropriately designed experimental trials. Both characterization and evaluation use crop descriptor lists that are available for a large number of crop species [89–91]. Additionally, to support standardizing the information, FAO and Bioversity International published passport descriptors that are widely used for the documentation and exchange of germplasm [92]. The FAO World Information and Early Warning System on PGRFA (WIEWS) [68] provides access to passport data of materials held in genebanks worldwide. Other global germplasm management systems, such as GRIN-Global [93] and GENESYS [94], document not only passport but also characterization and evaluation data in genebanks. GENESYS also includes information on the climate at the origin of accessions, and provide the option to search for accessions originating from similar climates. These systems provide plant breeders with a catalog of traits and germplasm for crop improvement.

Conventional plant breeding procedures can be time-consuming and expensive [95]. For example, the breeding, delivery and adoption of new maize varieties has taken up to 30 years [96]. Advances in biotechnology have substantially increased the efficiency for the identification of desirable traits for crop improvement and the knowledge of the genetic mechanisms that control the expression of traits of interest [97]. More targeted breeding can be undertaken as the links between traits and genes are better understood. This is especially important for those traits under polygenic control such as yield and those conveying heat, drought and other stress tolerances [98].

Crossing high-yielding varieties with lower-yielding but resilient local germplasm such as landraces can reduce genetic vulnerability [99] through the broadened genetic base of the improved varieties. This is achieved most effectively through pre-breeding, i.e. the generation of intermediate materials by crossing non-adapted germplasm that possess novel traits with standard breeding lines [5, 100]. A detailed step-by-step overview of pre-breeding procedures is provided in an e-learning course [101], developed under the auspices of the Global Partnership Initiative on Plant Breeding Capacity Building (GIPB). This course is made up of five modules covering the introduction to pre-breeding; genebank management relevant to pre-breeding; pre-breeding project management; creating and managing variation; and the distribution and use of the pre-bred materials and associated regulatory considerations.

In situations where sourcing heritable variations from existing germplasm is not possible or otherwise impractical, the induction of allelic variations through mutagenesis is a viable option [102]. Mutations can be induced by physical (i.e., gamma and x-ray technology) or chemical means [103] for a comprehensive review on this topic). DNA mutations tend to be chance events and therefore require that scientists generate massive numbers of putative mutants that are then subsequently screened for particular traits, a lengthy and costly process. However, advances in high throughput molecular genetics, cell biology and phenotyping techniques mitigate these constraints and facilitate the integration of induced mutations into improved crop varieties [103].

Morphological assessments using traditional phenotyping methods can be labor intensive, time consuming, subjective, and frequently destructive to plants. In fact, the access to large-scale phenotypic data has been one of the major bottlenecks hindering crop breeding [104]. High-throughput phenotyping (HTP) is a recently developed method that has potential to overcome this bottleneck and offers large-scale, accurate, rapid, and automatic data acquisition for crop improvement [105, 106]. A large number of advanced technologies [107, 108], including sensors, information technology and data extraction, combined with systems integration and reduced costs, means that morphology and physiology can be assessed non-destructively and repeatedly across entire populations throughout their development [104, 109]. Novel HTP approaches are necessary to advance the understanding of genotype-to-phenotype cause and effect relationships and therefore accelerate plant breeding [110, 111]. This can be of great importance for assessing the production and resilience traits of farmers' varieties/landraces.

Many traits have been mapped to specific genes and as a result, more analyses are being conducted per unit of time that allow for more specific mapping of traits. Quantitative trait loci (QTL) mapping results provide useful information to understand the genetic mechanisms of important traits and improve the efficiency of marker-assisted selection and genomics-assisted breeding [112, 113]. Taken together, existing genomics knowledge and tools may be used to overcome the constraints to the development of adapted varieties that combat malnutrition and climate change [114, 115].

Advances in phenotyping technology and methodologies for multi-population data analysis have made possible the mapping of QTL [116, 117]. In addition, DNA sequencing has become more rapid, more precise and less expensive [104, 110]; the genomes of most staple crops, and some minor ones, have been sequenced [118]. A recent initiative driven through the African Orphan Crops Consortium (AOCC) is applying genome-enabled methods to improve the production of 101 under-researched ('orphan') crops on the continent [119]. To date, eight genomes have been sequenced and published and another 26 are underway [120]. The ultimate goal of this initiative is to develop resilient, palatable and nutritious varieties of local crops for local peoples to consume and sell – thereby enhancing their nutritional status and livelihoods.

4. Existing policy frameworks

As means to enhance intra- and inter-specific on-farm crop diversity, diverse initiatives, policies and global frameworks have been developed and implemented. In recent years, focus has been on areas of synergies and streamlining efforts among the health, environmental and agricultural sectors (**Figure 3**). The number of policy and legal frameworks targeting crop diversity, reflects the growing global interest and concern and the commitment of countries for their conservation and sustainable use [51, 121].

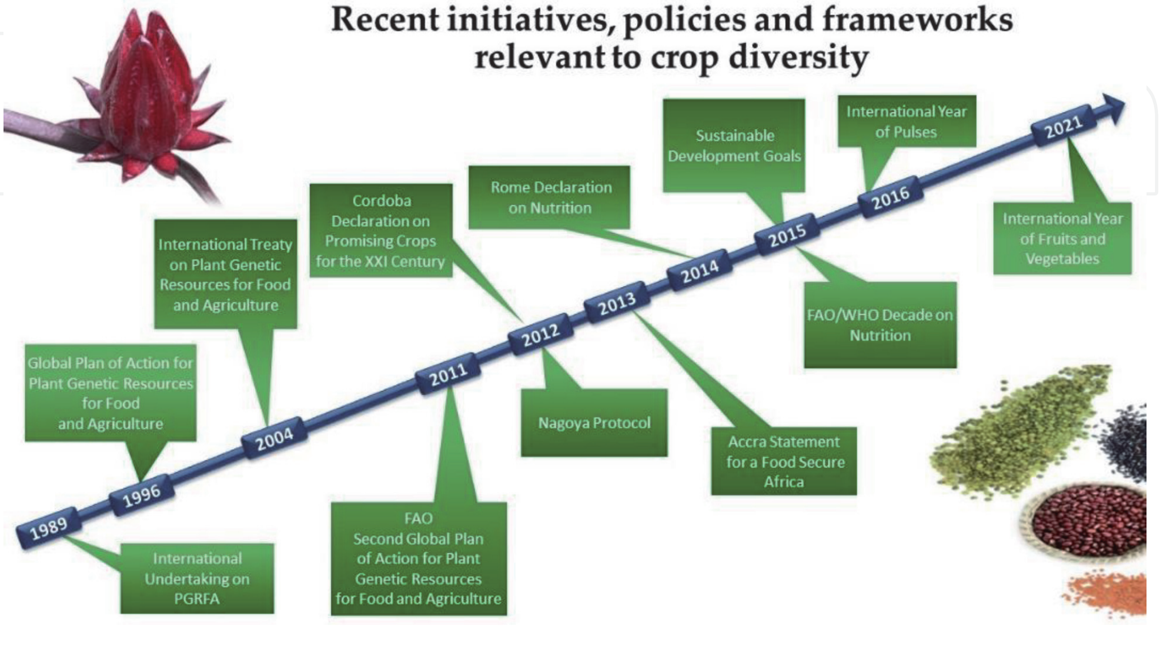

Figure 3.
Timeline showing the development of initiatives and frameworks important for the conservation and sustainable use of crop diversity (adapted with permission from [122]).

While crop diversity has been a key focus of many policy discussions since 1950 onwards [7], the International Undertaking on Plant Genetic Resources which was adopted by resolution 8/83 of the FAO Conference in 1983 was a watershed moment. The objective of this Undertaking was "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" [123].

This laid the groundwork for the development of cornerstone frameworks for crop diversity, especially:

- the Global Plan of Action (GPA) for the Conservation and Sustainable Use of Plant Genetic Resources for Food and Agriculture (PGRFA) adopted by 150 countries in 1996 [124];

- the International Treaty on Plant Genetic Resources for Food and Agriculture (the Treaty) that entered into force in 2004, providing a legal framework whereby governments, farmers, research institutes and agro-industries can share and exchange PGRFA and benefits derived from their use [125];

- the Global Crop Diversity Trust, established in 2004 by FAO and Bioversity International on behalf of the CGIAR, to support the efficient and effective *ex situ* conservation of crop diversity over the long term [126];

- the Second GPA in 2011 [5];

- the Cordoba Declaration [127], which emphasized the importance of underutilized and promising crops at the international level;

- the Second International Conference on Nutrition (ICN2) held in Rome in 2014 [128], which showcased the profile of NUS and adopted the Rome Declaration on Nutrition after which 2015–2025 was declared the UN Decade of Action on Nutrition [129]; and

- adoption of the 2030 Agenda for Sustainable Development by 193 Member States of the United Nations [130].

5. Looking forward

Addressing livelihood options for smallholder farmers requires that the focus of R&D be broadened to include a much wider range of crop species and cropping systems. This diversity is essential for breeding new plant varieties that confer the ability to adapt to changing environments, including new pests and diseases and adverse climatic conditions, on cropping systems. Thousands of years of farming and targeted selection have resulted in an invaluable heritage of locally adapted varieties of major and minor crops [16, 127]. The greater the diversity, the greater the chance that at least some of the individuals will possess an allelic variant suited to changing environments, and will produce offspring with that variant [7].

5.1 Bridging conservation, sustainable use and the seed sectors

To achieve the most benefits from PGRFA while at the same time safeguarding them, activities that address conservation must be linked to those concerned with

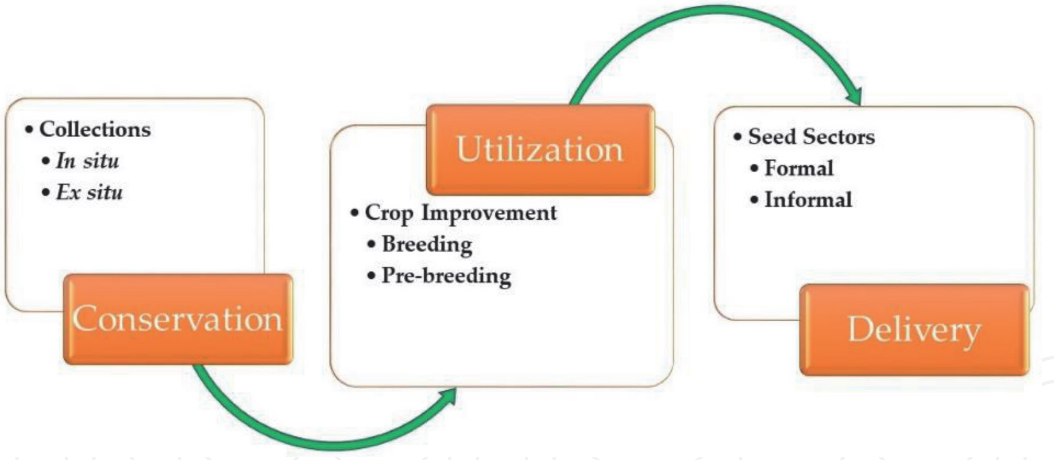

Figure 4.
Continuum of crop diversity, showing the linkages between conservation, sustainable use and seed systems.

plant breeding which in turn must feed into seed delivery systems. In many countries and regions, there is a lack of these linkages between these three modules of the PGRFA management continuum [131] (**Figure 4**).

This continuum approach is also relevant for the efforts to leverage farmers' varieties/landraces to enhance on-farm crop diversity and will require the concerted actions of extension workers, researchers, breeders, seed enterprises and farmers. Similarly, greater cooperation at different stages in the production chain, from the development and testing of new varieties, through value-adding activities, to the opening up of new markets is essential.

5.2 The enabling environment

In order to have long-term impact on the ground, clear and non-conflictual policies are needed, together with effective delivery systems. The policies must be evidence-based and offer relevant interventions that can rapidly be deployed on the ground. Often policies can be at variance with one another, with a resulting negative impact on crop diversity, livelihoods and/or diets. For example, subsidies for promoting staple crops may have a negative impact on the cultivation of minor, but highly nutritious and resilient crops and varieties [16]. Addressing this, FAO developed *Guidelines for Developing a National Strategy for Plant Genetic Resources for Food and Agriculture* [132]. These guidelines support countries in developing national strategies for PGRFA, which include identifying a national vision, goals and objectives, and the corresponding plan of action, including responsibilities, resources, and timeframes for activities. They take into account each country's needs, capacities and constraints.

Efforts must continue to target the development of appropriate national strategies and policies to promote the diversification of cropping systems, including the on-farm conservation and use of underutilized species, enable R&D and the uptake of their outputs. The Second GPA [5] highlights the importance of conservation and sustainable use of crop diversity in terms of policy and capacity development. National policies should aim to strengthen capacities in crop improvement in order to produce varieties that are specifically adapted to local environments. These policies may include appropriate for the protection of new varieties – as applicable, varietal release and seed certification – or other appropriate quality assurance regimes. These would promote and strengthen their use and ensure that they are included in national agricultural development strategies.

Building national programmes and institutional capacities is critically important as a means to promote public awareness on the importance of the diversity of PGRFA [5, 131]. The support to policy-makers as well as training and capacity building for scientists, breeders, extension specialists, seed producers, farmers, indigenous peoples and local communities on themes that enable the promotion of the development and commercialization of all crop varieties, primarily farmers' varieties, landraces and underutilized species, is recognized as a fundamental necessity [3]. Relevant topics for such training and capacity building activities include activities that promote the increased on-farm management of crop diversity such as the identification of all suitable materials and the development and implementation of sustainable management practices, postharvest processing and marketing methods and the documentation of relevant local and traditional knowledge. Additional activities include those that promote establishing, running and advising local small-scale seed enterprises.

The Second GPA [5] provides guidance on the human and institutional capabilities that should be strengthened for the conservation and sustainable use of PGRFA, including farmers' varieties/landraces. These are summarized below:

- Priority Activity 13 focuses on developing national programmes, recognizing that efforts to coordinate national planning, priority setting and fundraising are needed. Emphasis is placed on enhancing collaboration between the public and private sectors, national and international cooperation, strengthening links between PGRFA conservation and use, developing information systems and publicly accessible databases, identifying gaps in the conservation and use of PGRFA, increasing public awareness and implementing national policies and legislation and international treaties and conventions.

- Promoting and strengthening networks for PGRFA, as described in Priority Activity 14, are crucial for improved coordination, communication and organizational skills. Resources and capacity should be available for activities such as planning, communications, travel, meetings, network publications such as newsletters and meeting reports, and network strengthening, including the preparation of successful proposals for submission to donors.

- Information systems for PGRFA facilitates evidence-based decision making for their effective conservation and use. Priority Activity 15 provides guidance for national and regional programmes, including for strengthening and harmonizing documentation, characterization and evaluation of germplasm.

- In order to monitor and safeguard genetic diversity and minimize genetic erosion of crop diversity, capacities must to be strengthened for gathering and interpreting information in conducting inventories and surveys (Priority activity 16). Training on monitoring should be provided to breeders, farmers and indigenous and local communities. It is important to develop training materials, including self-teaching tools, in local languages as needed.

- As described in Priority activity 17, the long-term availability of adequate human resources capacity in all areas of PGRFA conservation and use, including management, legal and policy aspects, must be developed and strengthened. This includes support for enabling national and regional organizations and programmes to update curricula, provide advanced education and strengthen research and technical capacities in all relevant areas.

- Communicating effectively about the many benefits of crop diversity to food security and sustainable livelihoods is critical to the success of any intervention. Priority Activity 18 highlights the importance of national public awareness programmes and the development of international links and collaborative mechanisms such as networks, involving different sectors, agencies and stakeholders. The aim is to increase the value of crop diversity by bringing this information to the attention of policy-makers and the general public.

6. Conclusions

Five years after the world committed through the SDG to end hunger, food insecurity and all forms of malnutrition, we are not on track to achieve these objectives by 2030. The sense of urgency is even more pressing due to the looming 2030 deadline of the SDGs, which underscores the need to 'think outside of the box'. Options for addressing food insecurity and malnutrition should include increasing the diversity of crops and varieties cultivated. This chapter highlighted the danger of the continued overreliance on a few crops and their varieties. It prescribed the means for incorporating a wider diversity of farmers' varieties/landraces into crop production systems. These local crop genetic resources tend to be adapted to low input production systems, which is prevalent in many food insecure countries of the world. The underlying premise is that improving agricultural production while using the diverse plant genetic resources available can benefit directly the livelihoods of smallholder farmers and farming communities. The ensuing result is a positive impact on food security and nutrition, environmental resilience and effective management of crop diversity.

The Priority Activities of the Second GPA provide guidance for the enhanced integration of farmers' varieties/landraces into cropping systems. These include recommendations for promoting on-farm crop diversity directly and the conservation of these critical resources in genebanks. The Second GPA also addresses continued genetic improvement of germplasm and suitable seed delivery systems, especially those that are community-based and are tailored to low input production systems. Advances in molecular genetics, phenotyping and computing capacities enhance the prospects of generating compelling R&D outputs. In the same vein, policies and strategic partnerships – at local, national, regional and global levels – that facilitate the participation of a multiplicity of stakeholders are also critically important.

Notes/thanks/other declarations

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References

[1] FAO, IFAD, UNICEF, WFP and WHO. The State of Food Security and Nutrition in the World. Transforming food systems for affordable healthy diets. Rome: Food and Agriculture Organization of the United Nations; 2020. 289 p.

[2] United Nations. Transforming our world: the 2030 Agenda for Sustainable Development. Division for Sustainable Development Goals. New York: United Nations; 2015. 40 p.

[3] FAO. Voluntary Guidelines for the Conservation and Sustainable Use of Farmers' Varieties/Landraces. Rome: Food and Agriculture Organization of the United Nations; 2019. 135 p. DOI: 10.4060/CA5601EN

[4] CBD. Secretariat of the Convention on Biological Diversity. Global Biodiversity Outlook 5. Montreal: CBD; 2020. 208 p.

[5] FAO. Second Global Plan of Action for Plant Genetic Resources for Food and Agriculture. Rome: Food and Agriculture Organization of the United Nations; 2011. 91 p.

[6] FAO. The Second Report on the State of the World's Plant Genetic Resources for Food and Agriculture. Rome: Food and Agriculture Organization of the United Nations; 2010. 369 p.

[7] Rao VR, Hodgkin T. Genetic diversity and conservation and utilization of plant genetic resources. Plant cell, tissue and organ culture. 2002 Jan 1;68(1):1–19. DOI: 10.1023/A:1013359015812

[8] Jarvis DI, Hodgkin T, Brown AH, Tuxill JD, Noriega IL, Smale M, Sthapit B. Crop Genetic Diversity in the Field and on the Farm: Principles and applications in research practices. New Haven: Yale University Press; 2016. 395 p.

[9] Li X, Siddique KH, editors. Future Smart Food. Rediscovering hidden treasures of neglected and underutilized species for Zero Hunger in Asia. Bangkok: Food and Agriculture Organization of the United Nations; 2018. 178 p.

[10] Ceccarelli S. Specific adaptation and breeding for marginal conditions. In: Rognli OA, Solberg E, Schjelderup I, editors. Breeding Fodder Crops for Marginal Conditions. Developments in Plant Breeding, vol 2. Dordrecht: Springer; 1994. p. 101–127. DOI: 10.1007/978-94-011-0966-6_11

[11] Knüpffer H, Terentyeva I, Hammer K, Kovaleva O. Ecogeographical diversity-a Vavilovian approach In: Von-Bothmer R, Van-Hintum T, Knüpffer H and Sato K, editors. Diversity in Barley (*Hordeum vulgare*). Amsterdam: Elsevier; 2003. p. 53–76.

[12] Chalak L, Mzid R, Rizk W, Hmedeh H, Kabalan R, Breidy J, Hamadeh B, Machlab H, Rizk H, Elhajj S. Performance of 50 Lebanese barley landraces (*Hordeum vulgare L.* subsp. *vulgare*) in two locations under rainfed conditions. Annals of Agricultural Sciences. 2015 Dec 1;60(2): 325–334. DOI: 10.1016/j.aoas.2015.11.005

[13] RBG Kew. The State of the World's Plants Report – 2016. Kew: Royal Botanic Gardens; 2016. 80 p.

[14] Cheek M, Nic Lughadha E, Kirk P, Lindon H, Carretero J, Looney B, Douglas B, Haelewaters D, Gaya E, Llewellyn T, Ainsworth AM. New scientific discoveries: Plants and fungi. Plants, People, Planet. 2020 Sep;2(5): 371–388. DOI: 10.1002/ppp3.10148

[15] Food Plant International. Edible Plants of the World [Internet]. 2020.

Available from https://fms.cmsvr.com/fmi/webd/Food_Plants_World [Accessed 2020-12-01]

[16] FAO. Neglected and underutilized crops species. Information document COAG/2018/INF/7. FAO Committee on Agriculture Twenty-sixth Session; 1–5 October 2018; Rome. Rome: Food and Agriculture of the United Nations; 2018. 5 p. Available from: http://www.fao.org/3/mx479en/mx479en.pdf

[17] Mansfeld's World Database of Agriculture and Horticultural Crops [Internet]. 2020. Available from: https://www.re3data.org/repository/r3d100010097 [Accessed 2020-12-07]

[18] FAO. FAO Statistics [Internet]. 2018. Available from: http://www.fao.org/faostat/en/#home [202020–12-01]

[19] Brown AH, Hodgkin T. Indicators of genetic diversity, genetic erosion, and genetic vulnerability for plant genetic resources. In: Ahuja MR, Jain SM, editors. Genetic diversity and erosion in plants. Switzerland: Springer; 2015. p. 25–53.

[20] FAO. Save and grow: A policymaker's guide to sustainable intensification of smallholder crop production. Rome: Food and Agriculture Organization of the United Nations; 2011. 101 p.

[21] Bruford, M.W., Davies, N., Dulloo, M.E., Faith, D.P. and Walters, M. Monitoring changes in genetic diversity. In: Walters M, Scholes RJ, editors. The GEO handbook on biodiversity observation networks. Switzerland: Springer Nature; 2017. P. 107–128.

[22] Dulloo ME, Thormann I, Drucker AG. 39 What DoWe Have To Lose? Monitoring Crop Genetic Diversity. In: Maxted N, Dulloo ME, Ford-Lloyd BV, editors. Enhancing Crop Genepool Use: Capturing Wild Relative and Landrace Diversity for Crop Improvement. Oxfordshire: CABI; 2016. p. 421–435

[23] Ahmed I, Ullah A, ur Rahman MH, Ahmad B, Wajid SA, Ahmad A, Ahmed S. 2019. Climate change impacts and adaptation strategies for agronomic crops. In: Hussain S. Editor. Climate Change and Agriculture. IntechOpen; 2019. p. 1–14. DOI: /10.5772/intechopen.82697

[24] IPCC. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri RK, Meyer LA, editors]. Geneva: IPPC; 2014. 151 p.

[25] IPPC. IPCC Special Report on the Ocean and the Cryosphere in a Changing Climate. [Pörtner HO, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, Mintenbeck K, Nicolai M, Okem A, Petzold J, Rama B, Weyer N, editors. Geneva: IPPC; 2019. 755 p.

[26] Tripathi A, Tripathi DK, Chauhan DK, Kumar N, Singh GS. Paradigms of climate change impacts on some major food sources of the world: a review on current knowledge and future prospects. Agriculture, ecosystems & environment. 2016 Jan 15;216:356–373. DOI: 10.1016/J.AGEE.2015.09.034

[27] Iizumi T, Ramankutty N. Changes in yield variability of major crops for 1981–2010 explained by climate change. Environmental Research Letters. 2016 Feb 26;11(3):034003. DOI: 10.1088/1748-9326/11/3/034003

[28] Brouder SM, Volenec JJ. Future climate change and plant macronutrient use efficiency. In: Hossain MA, Kamiya T, Burritt D, Tran LS, Fujiwara T, editors. Academic Press; 2017. p. 357–379. DOI: 10.1016/B978-0-12-811308-0.00020-X

[29] Sugiura T, Ogawa H, Fukuda N, Moriguchi T. Changes in the taste and textural attributes of apples in response to climate change. Scientific reports. 2013 Aug 15;3:2418. DOI: 10.1038/srep02418

[30] Yan Y, Wang YC, Feng CC, Wan PH, Chang KT. Potential distributional changes of invasive crop pest species associated with global climate change. Applied geography. 2017 May 1;82:83–92. DOI: 10.1016/j.apgeog.2017.03.011

[31] Quiroz R, Ramírez DA, Kroschel J, Andrade-Piedra J, Barreda C, Condori B, Mares V, Monneveux P, Perez W. Impact of climate change on the potato crop and biodiversity in its center of origin. Open Agriculture. 2018 Aug 1;3(1):273–283. DOI: 10.1515/opag-2018-0029

[32] Chakraborty S, Murray GM, Magarey PA, Yonow T, O'Brien RG, Croft BJ, Barbetti MJ, Sivasithamparam K, Old KM, Dudzinski MJ, Sutherst RW. Potential impact of climate change on plant diseases of economic significance to Australia. Australasian Plant Pathology. 1998 Mar 1;27(1):15–35. DOI: 10.1071/AP98001

[33] Pautasso M, Döring TF, Garbelotto M, Pellis L, Jeger MJ. Impacts of climate change on plant diseases - opinions and trends. European Journal of Plant Pathology. 2012 May 1;133(1): 295–313. DOI: 10.1007/s10658-012-9936-1

[34] Juroszek P, von Tiedemann A. Climate change and potential future risks through wheat diseases: a review. European Journal of Plant Pathology. 2013 May 1;136(1):21–33. DOI: 10.1007/s10658-012-0144-9

[35] Zhao C, Liu B, Piao S, Wang X, Lobell DB, Huang Y, Huang M, Yao Y, Bassu S, Ciais P, Durand JL. Temperature increase reduces global yields of major crops in four independent estimates. Proceedings of the National Academy of Sciences. 2017 Aug 29;114(35):9326–9331. DOI: 10.1073/pnas.1701762114

[36] Meldrum G, Mijatović D, Rojas W, Flores J, Pinto M, Mamani G, Condori E, Hilaquita D, Gruberg H, Padulosi S. Climate change and crop diversity: farmers' perceptions and adaptation on the Bolivian Altiplano. Environment, Development and Sustainability. 2018 Apr 1;20(2):703–730. DOI: 10.1007/s10668-016-9906-4

[37] van Etten J, de Sousa K, Aguilar A, Barrios M, Coto A, Dell'Acqua M, Fadda C, Gebrehawaryat Y, van de Gevel J, Gupta A, Kiros AY. Crop variety management for climate adaptation supported by citizen science. Proceedings of the National Academy of Sciences. 2019 Mar 5;116(10):4194–4199. DOI: 10.1073/pnas.1813720116

[38] Morales-Castilla I, de Cortázar-Atauri IG, Cook BI, Lacombe T, Parker A, van Leeuwen C, Nicholas KA, Wolkovich EM. Diversity buffers winegrowing regions from climate change losses. Proceedings of the National Academy of Sciences. 2020 Feb 11;117(6):2864–2869. DOI: /10.1073/pnas.1906731117

[39] Corrado G, Rao R. Towards the genomic basis of local adaptation in landraces. Diversity. 2017 Dec;9(4):51. DOI: 10.3390/d9040051

[40] Fenzi M, Jarvis DI, Reyes LM, Moreno LL, Tuxill J. Longitudinal analysis of maize diversity in Yucatan, Mexico: influence of agro-ecological factors on landraces conservation and modern variety introduction. Plant Genetic Resources. 2017 Feb;15(1):51–63. DOI: 10.1017/S1479262115000374

[41] Ficiciyan A, Loos J, Sievers-Glotzbach S, Tscharntke T. More than

yield: Ecosystem services of traditional versus modern crop varieties revisited. Sustainability. 2018 Aug;10(8):2834. DOI: 10.3390/su10082834

[42] Coto A, de Sousa K, Fadda C, Gebrehawaryat Y, van de Gevel J, Gotor E, Gupta A, Madriz B, Mathur P, Mengistu DK, Paliwal A. Seeds for Needs: crop diversity for resilience; Technical Report – May 2019. Rome: Bioversity International; 2019. 4 p. DOI: 10.13140/RG.2.2.24932.22408

[43] FAO. The future of food and agriculture: alternative pathways to 2020. Rome: Food and Agriculture Organization of the United Nations; 2018. 224 p.

[44] Davis DR. Declining fruit and vegetable nutrient composition: What is the evidence?. HortScience. 2009 Feb 1; 44(1):15–19. DOI: 10.21273/HORTSCI.44.1.15

[45] Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, Mueller ND, O'Connell C, Ray DK, West PC, Balzer C. Solutions for a cultivated planet. Nature. 2011 Oct;478(7369):337–342. DOI: 10.1038/nature10452

[46] Garnett T, Appleby MC, Balmford A, Bateman IJ, Benton TG, Bloomer P, Burlingame B, Dawkins M, Dolan L, Fraser D, Herrero M. Sustainable intensification in agriculture: premises and policies. Science. 2013 Jul 5;341(6141):33–34. DOI: 10.1126/science.1234485

[47] Jones AD. Critical review of the emerging research evidence on agricultural biodiversity, diet diversity, and nutritional status in low-and middle-income countries. Nutrition reviews. 2017 Oct 1;75(10):769–782. DOI: 10.1093/nutrit/nux040

[48] Padulosi S, Heywood V, Hunter D, Jarvis A. Underutilized species and climate change: current status and outlook. In: Yadav SS, Redden RJ, Hatfield JL, Lotze-Campen H, Hall AJ, editors. Crop adaptation to climate change. Chichester: John Wiley & Sons; 2011. p. 507–521.

[49] Padulosi S, Hodgkin T, Williams JT, Haq N. Underutilized crops: trends, challenges and opportunities in the 21st century. In Engels JMM, Ramanatha Rao V, Brown AHD, Jackson MT, editors. Managing plant genetic diversity. Proceedings of an international conference, Kuala Lumpur, Malaysia, 12–16 June 2000. Wallingford: CAB International; 2002. p. 323–338.

[50] Padulosi S, Thompson J, Rudebjer P. Fighting poverty, hunger and malnutrition with neglected and underutilized species: needs, challenges and the way forward. Rome: Bioversity International; 2013. 56 p.

[51] Noorani A, Bazile D, Diulgheroff S, Kahane R, Nono-Womdim R. Promoting neglected and underutilized species through policies and legal frameworks. In: de Ron M, coordinator. Proceedings of the EUCARPIA International Symposium on Protein Crops, V Meeting AEL [V Jornadas de la AEL], May 2015; Pontevedra, Spain. Spain: Spanish Association for Legumes (AEL); 2015, p. 107–111. DOI: 10.5281/zenodo.1254012

[52] Oniang'o R, Grum M, Obel-Lawson E., editors. Developing African leafy vegetables for improved nutrition: Regional workshop, 6–9 December 2005. Nairobi: Rural Outreach Program; 2008. 160 p.

[53] Ulian T, Diazgranados M, Pironon S, Padulosi S, Liu U, Davies L, Howes MJ, Borrell JS, Ondo I, Pérez-Escobar OA, Sharrock S. Unlocking plant resources to support food security and promote sustainable agriculture. Plants, People,

Planet. 2020 Sep;2(5):421–445. DOI: 10.1002/ppp3.10145

[54] Kahane R, Hodgkin T, Jaenicke H, Hoogendoorn C, Hermann M, Hughes JD, Padulosi S, Looney N. Agrobiodiversity for food security, health and income. Agronomy for sustainable development. 2013 Oct 1;33(4):671–693. DOI: 10.1007/s13593-013-0147-8

[55] WHO. Guidelines: Vitamin A supplementation in infants and children 6–59 months of age. Geneva: World Health Organization; 2011. 24 p.

[56] Imdad A, Mayo-Wilson E, Herzer K, Bhutta ZA. Vitamin A supplementation for preventing morbidity and mortality in children from six months to five years of age. Cochrane Database of Systematic Reviews. 2017(3). 108 p. DOI: 10.1002/14651858.CD008524.pub3

[57] Davey MW, Van den Bergh I, Markham R, Swennen R, Keulemans J. Genetic variability in Musa fruit provitamin A carotenoids, lutein and mineral micronutrient contents. Food Chemistry. 2009 Aug 1;115(3):806–813. DOI: 10.1016/j.foodchem.2008.12.088

[58] Englberger L, Lyons G, Foley W, Daniells J, Aalbersberg B, Dolodolotawake U, Watoto C, Iramu E, Taki B, Wehi F, Warito P. Carotenoid and riboflavin content of banana cultivars from Makira, Solomon Islands. Journal of food composition and analysis. 2010 Sep 1;23(6):624–632. DOI: 10.1016/j.jfca.2010.03.002

[59] Englberger L, Marks GC, Fitzgerald MH. Insights on food and nutrition in the Federated States of Micronesia: a review of the literature. Public Health Nutrition. 2003 Feb;6(1): 5–17. DOI: 10.1079/PHN2002364

[60] Burlingame B, Dernini S., editors. Sustainable diets and biodiversity directions and solutions for policy, research and action. Rome: Food and Agriculture Organization of the United Nations; 2012. p. 309.

[61] Abukutsa-Onyango M. The diversity of cultivated African leafy vegetables in three communities in Western Kenya. In: Oniang'o R, Grum M, Obel-Lawson E., editors. Developing African leafy vegetables for improved nutrition: Regional workshop, 6–9 December 2005. Nairobi: Rural Outreach Program; 2005. p. 85–91.

[62] Guarino L, editor. Traditional African Vegetables. Promoting the conservation and use of underutilized and neglected crops. 16. Proceedings of the IPGRI International Workshop on Genetic Resources of Traditional Vegetables in Africa: Conservation and Use, 29–31 August 1995, ICRAF-HQ, Nairobi, Kenya. Gatersleben: Institute of Plant Genetics and Crop Plant Research/ Roe: International Plant Genetic Resources Institute; 1997.

[63] Maundu PM. The status of traditional vegetable utilization in Kenya. In Guarino L., editor. Traditional African vegetables; Proceedings of the IPGRI international workshop on genetic resources of traditional vegetables in Africa: conservation and use. IPGRI International Workshop on Genetic Resources of Traditional Vegetables in Africa: Conservation and Use; ICRAF-HQ, Nairobi 29–31 Aug, 1995 Kenya. Rome: IPGRI; 1997. p. 66–71.

[64] Fanzo J, Remans R, Pronyk PM, Negin J, Wariero J, Mutuo P, Masira J, Diru W, Lelerai E, Kim D, Nemser B. A 3-year cohort study to assess the impact of an integrated food-and livelihood-based model on undernutrition in rural western Kenya. In: Thompson B, Amoroso L, editors. Combating micronutrient deficiencies: food-based approaches. Oxfordshire: CABI; 2011. p. 76–91.

[65] Neugart S, Baldermann S, Ngwene B, Wesonga J, Schreiner M.

Indigenous leafy vegetables of Eastern Africa—A source of extraordinary secondary plant metabolites. Food Research International. 2017 Oct 1;100: 411–422. DOI: 10.1016/j. foodres.2017.02.014

[66] Gido EO, Ayuya OI, Owuor G, Bokelmann W. Consumption intensity of leafy African indigenous vegetables: towards enhancing nutritional security in rural and urban dwellers in Kenya. Agricultural and Food Economics. 2017 Dec 1;5(1):14. DOI: 10.1186/ s40100-017-0082-0

[67] Mercer KL, Perales HR. Evolutionary response of landraces to climate change in centers of crop diversity. Evolutionary applications. 2010 Sep;3(5–6):480–493. DOI: 10.1111/ j.1752-4571.2010.00137.x

[68] FAO. WIEWS - World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture [Internet]. 2020. Available from: http://www.fao.org/wiews/en/

[69] FAO. Genebank Standards for Plant Genetic Resources for Food and Agriculture. Rev. ed. edition. Rome: Food and Agriculture Organization of the United Nations; 2014. 166 p.

[70] Khoury C, Laliberté B, Guarino L. Trends in *ex situ* conservation of plant genetic resources: a review of global crop and regional conservation strategies. Genetic Resources and Crop Evolution. 2010 Apr 1;57(4):625–639. DOI: 10.1007/s10722-010-9534-z

[71] Ceccarelli S, Guimarães EP, Weltzien E, editors. Plant breeding and farmer participation. Rome: Food and Agriculture Organization of the United Nations; 2009. 685 p.

[72] Westengen OT, Winge T, editors. Farmers and Plant Breeding: Current Approaches and Perspectives. London: Routledge; 2019 Oct 2. 329 p.

[73] FAO. Global Farmer Field School Platform [Internet]. 2020. Available from: http://www.fao.org/farmer-field-schools/overview/en/ [Accessed 2020-12-01]

[74] Vernooy R, Clancy E, Diulgheroff S, Furman B, González Santos R, Kajtna B, Marino M, Mushita A, Shrestha P, Song Y, Egon Sosinski E. Joining forces to strengthen community seedbanks worldwide. Rome: Bioversity International; 2108. 8 p.

[75] Vernooy R, Shrestha P, Sthapit B, editors. Community seed banks: Origins, evolution and prospects. New York: Routledge; 2015. 270 p.

[76] Manalo C. SEARICE Highlights Importance of CSBs in International Event. In Southeast Asia Regional Initiatives for Community Empowerment [Internet]. 2019. Available from: https://www.searice.org .ph/searice-highlights-importance-of-cs [Accessed 2020-12-07]

[77] Tin HQ, Cuc NH, Be TT, Ignacio N, Berg T. Impacts of seed clubs in ensuring local seed systems in the Mekong Delta, Vietnam. Journal of Sustainable Agriculture. 2011 Oct 1;35 (8):840–854. DOI: 10.1080/ 10440046.2011.611746.

[78] FAO. Quality Declared Seed System. Rome: Food and Agriculture Organization of the United Nations; 2010. 243 p.

[79] Visser B. The impact of national seed laws on the functioning of small-scale seed systems: A country-case study. The Hague: Oxfam Novib. 2017. 38 p.

[80] FAO. Quality Declared Planting Material: Protocols and standards for vegetatively propagated crops. Rome: Food and Agriculture Organization of the United Nations; 2010. 126 p.

[81] FAO, AfricaSeeds. Seeds Toolkit Module 1: Development of small-scale

seed enterprises. Rome: Food and Agriculture Organization of the United Nations; 2018. 109 p.

[82] FAO, AfricaSeeds. Seeds Toolkit Module 2: Seed processing: principles, equipment and practice. Rome: Food and Agriculture Organization of the United Nations; 2018. 79 p.

[83] FAO, AfricaSeeds. Seeds Toolkit Module 3: Seed quality assurance. Rome: Food and Agriculture Organization of the United Nations; 2018. 111 p.

[84] FAO, AfricaSeeds. Seeds Toolkit Module 4: Seed Sector Regulatory Framework. Rome: Food and Agriculture Organization of the United Nations; 2018. 64 p.

[85] FAO. Seeds Toolkit Module 5: Seed marketing. Rome: Food and Agriculture Organization of the United Nations; 2018. 97 p.

[86] FAO. Seeds Toolkit Module 6: Seed storage. Rome: Food and Agriculture Organization of the United Nations; 2018. 102 p.

[87] FAO. Voluntary Guide for National Seed Policy Formulation. Rome: Food and Agriculture Organization of the United Nations; 2015. 60 p.

[88] Alipour H, Bihamta MR, Mohammadi V, Peyghambari SA, Bai G, Zhang G. Genotyping-by-sequencing (GBS) revealed molecular genetic diversity of Iranian wheat landraces and cultivars. Frontiers in Plant Science. 2017; 8:1293. DOI: 10.3389/fpls.2017.01293

[89] Bioversity International. Descriptors [Internet]. 2020. Available from: https://www.bioversityinternational.org/e-library/publications/descriptors/[Accessed 2020-12-01]

[90] UPOV. Test Guidelines [Internet]. 2020. Available from: https://www.upov.int/test_guidelines/en/ [Accessed 2020-12-01]

[91] USDA ARS. GRIN-Global - U.S. National Plant Germplasm System [Internet]. 2020. Available from: https://npgsweb.ars-grin.gov/gringlobal/descriptors [Accessed 2020-12-01]

[92] Alercia A, Diulgheroff S, Mackay M. FAO/bioversity multi-crop passport descriptors V. 2.1 [MCPD V. 2.1]-December 2015. Rome: Bioversity International; 2015. 11 p.

[93] GRIN Global. The GRIN-Global Project [Internet]. 2020. Available from: https://www.grin-global.org/ [Accessed 2020-12-01]

[94] Genesys. Genesys PGR [Internet]. 2020. Available from: https://www.genesys-pgr.org/ [Accessed 2020-12-01]

[95] Cattivelli L, Rizza F, Badeck FW, Mazzucotelli E, Mastrangelo AM, Francia E, Marè C, Tondelli A, Stanca AM. Drought tolerance improvement in crop plants: an integrated view from breeding to genomics. Field crops research. 2008 Jan 2;105(1–2):1–4. DOI: 10.1016/j.fcr.2007.07.004

[96] Challinor AJ, Koehler AK, Ramirez-Villegas J, Whitfield S, Das B. Current warming will reduce yields unless maize breeding and seed systems adapt immediately. Nature Climate Change. 2016 Oct;6(10):954–958. DOI: 10.1038/nclimate3061

[97] Wang W, Mauleon R, Hu Z, Chebotarov D, Tai S, Wu Z, Li M, Zheng T, Fuentes RR, Zhang F, Mansueto L. Genomic variation in 3,010 diverse accessions of Asian cultivated rice. Nature. 2018 May;557(7703):43–49. DOI: 10.1038/s41586-018-0063-9

[98] Atlin GN, Cairns JE, Das B. Rapid breeding and varietal replacement are critical to adaptation of cropping

systems in the developing world to climate change. Global food security. 2017 Mar 1;12:31–7. DOI: 10.1016/j.gfs.2017.01.008

[99] FAO. Climate-smart agriculture sourcebook. Rome: Food and Agriculture Organization of the United Nations; 2017.

[100] Saini P, Saini P, Kaur JJ, Francies RM, Gani M, Rajendra AA, Negi N, Jagtap A, Kadam A, Singh C, Chauhan SS. Molecular approaches for harvesting natural diversity for crop improvement. In: Salgotra RK, Zargar SM, editors Rediscovery of Genetic and Genomic Resources for Future Food Security. Singapore: Springer; 2020. p. 67–169. DOI: 10.1007/978-981-15-0156-2_3

[101] FAO. E-learning course on Pre-breeding [Internet]. 2011. Available from: https://elearning.fao.org/course/view.php?id=487 [Accessed 2020-12-01]

[102] Mba C, Guimaraes EP, Ghosh K. Re-orienting crop improvement for the changing climatic conditions of the 21st century. Agriculture & Food Security. 2012;1(1):7. DOI: 10.1186/2048-7010-1-7

[103] Mba C. Induced mutations unleash the potentials of plant genetic resources for food and agriculture. Agronomy. 2013;3(1):200–31. DOI: 10.3390/agronomy3010200

[104] Yang W, Feng H, Zhang X, Zhang J, Doonan JH, Batchelor WD, Xiong L, Yan J. Crop phenomics and high-throughput phenotyping: past decades, current challenges, and future perspectives. Molecular Plant. 2020 Feb 3;13(2):187–214. DOI: 10.1016/j.molp.2020.01.008

[105] Araus J., Kefauver SC, Zaman-Allah M, Olsen MS, Cairns JE. Translating high-throughput phenotyping into genetic gain. Trends in Plant Science. 2018; 23(5):451–466. DOI: 10.1016/j.tplants.2018.02.001

[106] Kim J, Kim KS, Kim Y, Chung YS. A short review: Comparisons of high-throughput phenotyping methods for detecting drought tolerance. Scientia Agricola. 2021;78(4). DOI: 10.1016/j.molp.2020.01.008

[107] Normanly J, editor. High-throughput phenotyping in plants: methods and protocols. Berlin: Humana Press; 2012. 362 p.

[108] Tattaris M, Reynolds MP, Chapman SC. A direct comparison of remote sensing approaches for high-throughput phenotyping in plant breeding. Frontiers in Plant Science. 2016 Aug 3;7:1131. DOI: 10.3389/fpls.2016.01131

[109] Chawade A, van Ham J, Blomquist H, Bagge O, Alexandersson E, Ortiz R. High-throughput field-phenotyping tools for plant breeding and precision agriculture. Agronomy. 2019 May;9(5):258. DOI: 10.3390/agronomy9050258

[110] White JW, Andrade-Sanchez P, Gore MA, Bronson KF, Coffelt TA, Conley MM, Feldmann KA, French AN, Heun JT, Hunsaker DJ, Jenks MA. Field-based phenomics for plant genetics research. Field Crops Research. 2012 Jul 11;133:101–112. DOI: 10.1016/j.fcr.2012.04.003

[111] Singh D, Wang X, Kumar U, Gao L, Noor M, Imtiaz M, Singh RP, Poland J. High-throughput phenotyping enabled genetic dissection of crop lodging in wheat. Frontiers in plant science. 2019 Apr 3;10:394. DOI: 10.3389/fpls.2019.00394

[112] Desta ZA, de Koning DJ, Ortiz R. Molecular mapping and identification of quantitative trait loci for domestication traits in the field cress (*Lepidium*

campestre L.) genome. Heredity. 2020 Apr;124(4):579–591. DOI: 10.1038/s41437-020-0296-x

[113] Seo JH, Kang BK, Dhungana SK, Oh JH, Choi MS, Park JH, Shin SO, Kim HS, Baek IY, Sung JS, Jung CS. QTL Mapping and Candidate Gene Analysis for Pod Shattering Tolerance in Soybean (*Glycine max*). Plants. 2020 Sep;9(9):1163. DOI: 10.3390/plants9091163

[114] Rivers J, Warthmann N, Pogson BJ, Borevitz JO. Genomic breeding for food, environment and livelihoods. Food Security. 2015 Apr 1;7(2):375–382. DOI: 10.1007/s12571-015-0431-3

[115] Gogorcena Y, Sanchez G, Moreno-Vázquez S, Pérez S, Ksouri N. Genomic-based breeding for climate-smart peach varieties. In: Cole C, editor. Genomic Designing of Climate-Smart Fruit Crops. Switzerland: Springer, Cham; 2020. p. 271–331. DOI: 10.1007/978-3-319-97946-5_8

[116] Kearsey MJ, Farquhar AG. QTL analysis in plants; where are we now?. Heredity. 1998 Feb;80(2):137–142. DOI: 10.1046/j.1365-2540.1998.00500.x

[117] Camargo AV, Mackay I, Mott R, Han J, Doonan JH, Askew K, Corke F, Williams K, Bentley AR. Functional mapping of quantitative trait loci (QTLs) associated with plant performance in a wheat MAGIC mapping population. Frontiers in plant science. 2018 Jul 9;9:887. DOI: 10.3389/fpls.2018.00887

[118] Kersey PJ. Plant genome sequences: past, present, future. Current opinion in plant biology. 2019 Apr 1;48:1–8. DOI: 10.1016/j.pbi.2018.11.001

[119] Jamnadass R, Mumm RH, Hale I, Hendre P, Muchugi A, Dawson IK, Powell W, Graudal L, Yana-Shapiro H, Simons AJ, Van Deynze A. Enhancing African orphan crops with genomics. Nature Genetics. 2020 Apr;52(4):356–60. DOI: 10.1038/s41588-020-0601-x

[120] AOCC. African Orphan Crops Consortium On-going Projects [Internet]. 2010. Available from: http://africanorphancrops.org/ongoing-projects/.

[121] Diulgheroff S. A global overview of assessing and monitoring genetic erosion of crop wild relatives and local varieties using WIEWS and other elements of the FAO Global System on PGR. In: Ford-Lloyd B, Dias SR, Bettencourt E, editors. Genetic erosion and pollution assessment methodologies. Rome: Bioversity International; 2006. p. 5–14.

[122] Noorani A., Bazile D, Diulgheroff S., Kahane R., Nono-Womdim R. Promoting neglected and underutilized species through policies and legal frameworks. Poster presentation at: de Ron M, coordinator. Proceedings of the EUCRPIA International Symposium on Protein Crops, V Meeting AEL [V Jornadas de la AEL], May 2015; Pontevedra, Spain. Spain: Spanish Association for Legumes (AEL); 2015b.

[123] FAO. Interpretation of the international undertaking on plant genetic resources. FAO Conference Twenty-fifth Session; 11–30 November 1989; Rome. Rome: Food and Agriculture of the United Nations; 1989. 10 p. Available from: http://www.fao.org/3/z4968en/z4968en.pdf

[124] FAO. The Global Plan of Action for the Conservation and Sustainable Utilization of Plant Genetic Resources for Food and Agriculture and the Leipzig Declaration. Rome: Food and Agriculture Organization of the United Nations; 1996. 63 p.

[125] FAO. International Treaty on Plant Genetic Resources for Food and Agriculture. Rome: Food and

Agriculture Organization of the United Nations; 2009. 68 p.

[126] Crop Trust. The Global Crop Diversity Trust [Internet]. 2020. Available from: https://www.croptrust.org/ [Accessed 2020-12-01]

[127] FAO. Cordoba Declaration on Promising Crops for the XXI Century. International Seminar on Traditional and New Crops to Meet the Challenges of the XXI Century. Cordoba, Spain, 10–13 December 2012. Rome: Food and Agriculture Organization of the United Nations; 2012b. 7 p.

[128] FAO. Conference Outcome Document: Framework for Action. Second International Conference on Nutrition Rome, 19–21 November 2014. Rome: Food and Agriculture Organization of the United Nations; 2014a. 8 p.

[129] FAO, WHO. United Nations Decade on Nutrition: Towards country-specific SMART commitments for action on nutrition. Rome: Food and Agriculture Organization of the United Nations; 2016. 4 p.

[130] FAO. FAO and the SDGs Indicators: Measuring up to the 2030 Agenda for Sustainable Development. Rome: Food and Agriculture Organization of the United Nations; 2017b. 40 p.

[131] Mba C, Guimaraes EP, Guei GR, Hershey C, Paganini M, Pick B, Ghosh K. Mainstreaming the continuum approach to the management of plant genetic resources for food and agriculture through national strategy. Plant Genetic Resources. 2012a Apr 1;10 (1):24–37. DOI:10.1017/S1479262111000943

[132] FAO. Guidelines for Developing a National Strategy for Plant Genetic Resources for Food and Agriculture: Translating the Second Global Plan of Action for Plant Genetic Resources for Food and Agriculture into National Action. Rome: Food and Agriculture Organization of the United Nations; 2015a. 55 p.