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The contribution of seed systems to crop and tree diversity in sustainable food systems

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Seeds

KEY MESSAGES:

- Seed systems are crucial for sustainable food system outcomes: agricultural sustainability, food security and healthy diets.
- Production and distribution, innovation and regulation are the key functions of seed systems, which make a difference to sustainable food systems.
- Currently used methods to measure the performance of seed systems concentrate narrowly on their contribution to agricultural productivity, rather than to food system sustainability.
- There is a need to measure seed system performance in terms of their contribution to wider policy goals, moving away from current policy fragmentation.

Introduction

Seed is important to achieve sustainable food systems. Seed[i] has, therefore, been the main focus of many national and international agricultural development efforts, starting with the Green Revolution in the 1960s and 1970s. The Green Revolution increased the productivity of main staple crops by developing high-yielding varieties with wide adaptation. From the 1970s, these efforts were accompanied by important investments in seed sector development, as a way to ensure the dissemination of these new varieties in the necessary quantities and with the necessary quality. As seed emerged and increased in national, regional and global markets, seed actors started to define seed quality standards, as well as rules for seed sampling and testing. In the last decades, developing countries, often supported by international funders and initiatives, have made large efforts to develop nationwide seed sectors in which semi-public and private enterprises play a central role. These efforts have resulted in an increasing use of modern crop varieties, and a larger proportion of land covered by certified quality seed.

Between the 1960s and 2000s, more than 8,000 modern varieties of 11 crops were released by more than 400 public breeding programmes and seed boards in over 100 countries. However, the rate of release and adoption of modern varieties as well as productivity gains varied considerably across time, crops and regions. In Asia, the proportion of land planted with modern varieties of rice increased from 10% in the 1960s to 70% in the 1990s. In the Middle East and North Africa, it was wheat that made a dramatic increase in area planted to modern varieties, growing from less than 5% in the 1960s to around 50% in the 1990s (1). In developed countries, yields of major crops grew at an average of 1.46% per year between 1961 and 2008. Least developed countries experienced even faster yield increases, at 2.1% per year. But this trend missed sub-Saharan Africa, which achieved a tiny 0.02% annual increase over the same period of time (2). And, although breeders developed many varieties of wheat, rice and maize, they produced very few varieties of small cereals, legumes and root crops.

Two insights from recent scientific literature force us to take a fresh look at the role that seed-related policies and investments play to achieve sustainable food systems. The first insight is that the achievements of modern plant breeding and commercial seed sector development will not easily reach all farmers in the next decades. Farmers' own production and exchange of seed will continue to be important in the foreseeable future (3). The formal sector provides less than 5% of the seeds used to produce traditional staple crops in West Africa (sorghum, millet, cowpea), in spite of decades of breeding work. It provides less than 10% of the rice in Nepal, where it is a major crop. In Ethiopia and Syria, important wheat-growing areas, wheat production depends from 80 to 90% on informal seed sources (4–7).

Informal seed supply has a frugal efficiency that is difficult to beat. It is able to respond well to farmers' particular needs and preferences, complementing the commercial seed sector (3, 8, 9). In certain cases, modern breeding approaches focusing on broad adaptation have difficulty creating varieties suited to marginal niches (10). This means that sustainable food systems cannot be attained through a simple expansion of the formal seed sector, replacing informal seed provision. It often makes more sense to analyze formal and informal seed production as interacting, often complementary parts of a single 'seed system' (see Box 4.1 for more background on the concept of seed systems).

The second insight is that the emphasis of the Green Revolution on calorie-providing food production does not address the low quality of diets, which is currently one of the most pressing global health issues (see Chapter 2). This implies that seed-related investments need to be realigned to current policy goals in order to contribute to healthy food systems (11). In this realignment, crop and tree diversity acquires an important role. The production of nutrient-dense foods, such as vegetables, fruits and pulses, should be stimulated to contribute to healthy nutrition. Seed availability for more marginal areas is important, because in these areas food access relies greatly on local food availability.

This chapter will review the evidence that shows that farmers' access to seeds has an impact on the sustainability of food production and consumption. Diverse seeds are needed to support the diversification of agriculture, which in turn may contribute to more diverse diets, and to using species and varieties for the integrity of ecosystem services. In what follows, we define three functions of seed systems. We discuss the evidence that farmers' seed access influences food production and consumption. We then discuss each of the three key functions (production and distribution, innovation, regulation) in turn and review the evidence that differences in the capacity of seed systems to perform each function make a difference to fulfilling the overall goal of seed systems, in terms of their contribution to sustainable food systems. We also describe existing work to provide data and indicators to characterize each seed system function and assess how these can be used to measure the link between agricultural biodiversity and sustainable food systems in this context.

BOX 4.1 – Seed systems: formal, informal and 'intermediate' types

Seed systems are ensembles of individuals, networks, organizations, practices and rules that provide seeds for plant production (8, 9, 12, 13).

At present, several types of seed systems playing different roles co-exist. At one extreme, formal systems are managed by public, semi-public or private agencies, which follow regulations approved by the government, generally based on international standards. They provide certified seeds of registered, distinct, uniform and stable varieties of maize, wheat, rice and, to a lesser extent, sorghum, cassava, banana/plantain, horticultural and specific export crops.

At the other extreme, informal systems are managed by farmers and their communities, where seeds of preferred varieties and crops are multiplied, saved for production on the farm or distributed to other farmers largely based on customary and informal practices, rules and regulations. They provide seeds for all crops not covered by the formal system. The informal system prevails in many countries around the world: farmers get the majority of the seed they use from their own farms or from informal sources, such as relatives, friends, neighbours or local markets. In many cases, farmers are both the producers and consumers of seed and part of the grains produced on the farm become the seeds sown the following year. In this case, renewal of seed stock in terms of crops and varieties occurs when farmers face seed loss, seed degeneration or when farmers want to switch their crop or test different varieties. These circumstances encourage farmers to obtain seeds from other farmers or from local seed markets.

Between these two extremes of formal and informal seed systems, intermediate systems have emerged in a number of countries (14, 15). They integrate formal and informal elements. For example, farmers and farmer groups, working outside the formal channels that are regulated by public agencies, multiply and distribute improved varieties developed by the formal sector. Non-governmental organizations and projects provide support to the certification and distribution of farmer-produced seed, in line with national rules and regulations.

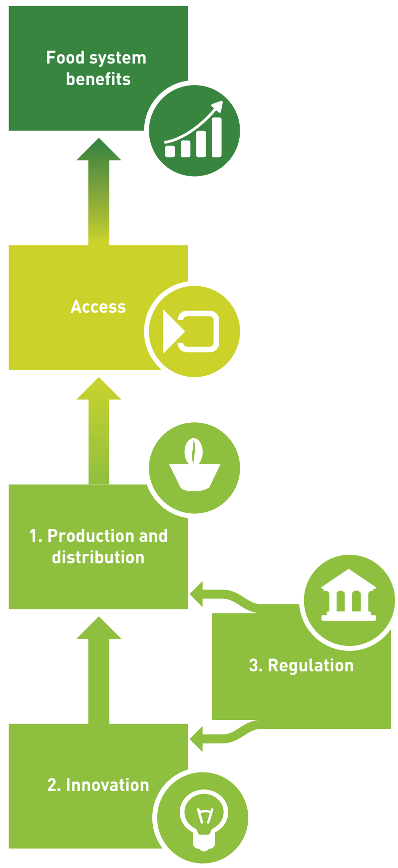
In one example, in Cochabamba (Bolivia), the international agricultural research centre Bioversity International and the NGO PROINPA[ii] worked with farmer groups to produce and commercialize certified seed of native potato varieties. Another example can be found in Nepal, where farmers have applied for registration of five local varieties of rice in the national catalogue of commercial varieties. In France, a participatory and decentralized seed system has emerged, in which farmers are organized to fulfil many of the tasks usually done by specialized agencies (16).

Key functions of seed systems

The overarching goal of functional seed systems is to ensure that seeds are available and accessible to all end users, notably smallholder farmers, in sufficient quantity, quality and diversity to produce sufficient nutritious food in a sustainable way for the household itself, other consumers, or both. In order to achieve this goal, seed systems rely on the interconnected performance of three key functions: (1) seed production and distribution, (2) innovation, (3) regulation (8, 9, 13) (Figure 4.1). Genebanks and the function of biodiversity conservation are sometimes also considered to be part of the seed system (8), but here conservation is discussed separately in Chapter 5.

FIGURE 4.1 – Three key functions of a well-functioning seed system

In a well-functioning seed system, three key functions together lead to farmers' access to diverse seeds, which in turn leads to food system benefits.



Credit: Bioversity International

The three key functions should be present in any type of seed system, from a highly informal seed system to a fully developed commercial seed sector.

1. *Production and distribution* of quality seeds is crucial to have sufficient volume of quality seeds in a timely way for a diverse set of crop species and varieties, making these available to satisfy demand of seed for food production.
2. *Innovation* is a key function in any seed system as continuous knowledge creation about seed is needed for enhancing productivity, resilience and product quality, as well as for selecting the right seed for the right location, in response to changing growing conditions and consumer preferences over time. Innovation can arise from research largely linked to the formal system (public and private) or from the informal seed system, or the combination of knowledge and genes from different sources through participatory breeding and the ingenuity of individual farmers. Innovation not only arises from the creation of new varieties, but also includes the identification and selection of local seeds and seed sources that can be matched to other environments to adapt to new climates.
3. *Regulation* of seed ensures seed quality. Regulation includes both formal and informal regulation (e.g. customary rules around seed exchange). It is often only evident after seeds have been sown – whether purchased or self-saved – if their quality is satisfactory and whether the seeds indeed are of the expected variety. Well-performing seed systems are able to ensure the quality and varietal identity of seeds circulating in the system to prevent the negative consequences of deficient seeds on production and to establish trust in seed sources and distribution systems. The extent and conditions of formal regulation determine to a large extent the space available for the informal seed system.

Seed access affects food production and consumption

Several factors influence crop and tree diversity in food systems, but the importance of seed access becomes highly evident when it is constrained (Box 4.2). Extreme climatic events or political violence reveal how important seed access is for maintaining an adequate mix of species and varieties on farm. After civil wars in Guatemala and Nicaragua, resettling communities had trouble accessing seeds of vegetables and species grown in home gardens, and suffered a substantial decrease in their production and consumption (17). Likewise, after Hurricane Mitch, farmers in Honduras could obtain access to maize seed, but much less to bean seed, as beans were more affected by the bad weather than maize (18). Contrasting levels of access to crop seeds after emergencies have also been found in other studies (19, 20). A decrease in crop diversity – and especially in nutrient-dense foods such as legumes and vegetables – can have important negative effects on human nutrition (21, 22).

Access to seed plays an important role in strengthening communities' capacity to adapt to new circumstances or needs, such as climate change. This was demonstrated by a comparative study of two communities that occupy similar environments on Mt. Kenya and that both had to deal with climate change. The study found a substantial difference between the communities in adapting to drought conditions. One was more able to obtain drought-adapted seeds from the drought-prone lowlands due to good social connections with community members there. The other was more isolated and had trouble finding adapted seeds (23).

BOX 4.2 – Rebuilding access to seed to recover from shocks: the example of Nepal

During the 2015 earthquake in Nepal, the bulk of seed stocks saved by Nepal's farmers in the affected districts were destroyed and farmers could no longer access their preferred seeds. According to the Food and Agriculture Organization of the UN (FAO), about 60% of the food and seed stocks in farming households were destroyed. Scientists were concerned that seeds unsuitable for local conditions were being rushed in. Supplying people with seeds of unsuitable crops and varieties risked resulting in poor harvests, wasting scarce labour and land, and extending the period of food insecurity.

In response to this challenge, community seedbanks outside the 14 earthquake-affected districts, for the first time, extended their services outside their client base to provide farmers in affected districts with seeds. Agricultural biodiversity scientists, together with a local NGO called LI-BIRD (Local Initiatives for Biodiversity, Research and Development) used crowdsourcing to involve the farmers themselves in multiplying and supplying the seeds appropriate for their needs and environment. Through this method, farmers become citizen scientists, testing and sharing knowledge about different varieties, so that suitable crops and varieties could rapidly be made available.

Adapted from (24)

Some community-led and participatory practices can increase access to seed diversity and crop diversity on farms. For example, community seedbanks, a conservation and access mechanism that facilitates farmers' access to crop diversity (See Box 5.2 in Chapter 5), can contribute to household use of this diversity. Participation in community seedbank schemes has been found to increase households' crop varietal diversity as well as their productivity (25). Evolutionary plant breeding is an alternative, inexpensive way to increase farmers' access to diversity, by introducing seed lots that consist of a mixture of a large number of different varieties, which under local selection pressure adapt to local conditions (26). This strategy effectively led to more barley diversity on farms in Iran (27). Researchers introduced diverse barley seed lots to five farmers in 2008. By 2016, hundreds of farmers were growing the mixtures and sharing them with their neighbours. Generally this strategy is well suited to extreme or marginal environments, such as drought-prone, flooded or mountainous areas, or for specific purposes such as quality (Box 4.3).

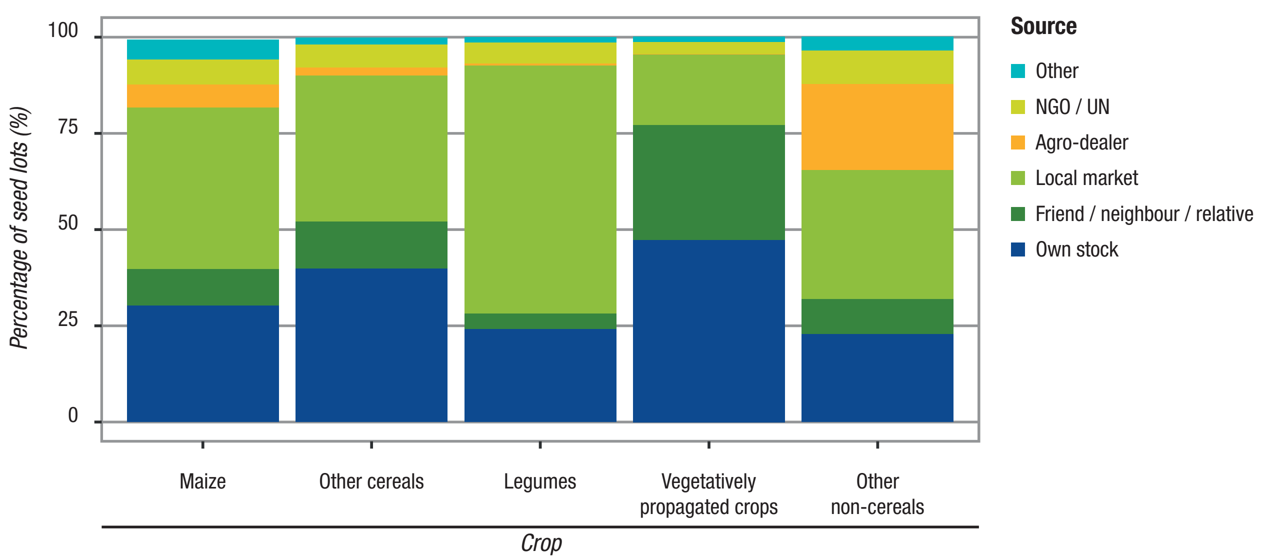
The importance of seed access for obtaining crop diversity is also evident in farmers' seed sourcing choices. A large study on seed sources reveals that informal sources including local markets are an important source of seeds for smallholder farmers (28, Figure 4.2). Availability of varietal diversity in markets influences how important markets are as a seed source relative to other seed sources (28). Marginalized farmers, such as recent migrants, with fewer social connections and thus less access to seeds from local social networks and family, are more heavily reliant than those with strong connections on local markets as a seed source (28).

BOX 4.3 – The aromatic rice variety Jethobudho in Nepal

Jethobudho is an aromatic rice landrace from the Pokhara valley in the central hills of Nepal. Although local consumers are willing to pay a high price for its purchase, the landrace has a problem with inconsistent quality. Decentralized participatory population improvement for specific market-identified traits was conducted on Jethobudho populations collected from farmers' fields in seven geographic regions of the valley in Nepal. Farmers established, through a consumer market survey, the traits they most appreciated: tolerance to a common fungus (rice blast), resistance to being flattened (lodging) and superior post-harvest quality. These traits were used to screen the materials. Starting from 338 sub-populations of Jethobudho, 183 populations were screened in on-farm and on-station nurseries, and in succeeding years populations were further screened by plant breeders and expert farmers in research trials, resulting in the selection of 46 populations for post-harvest quality traits. Six accessions with similar agronomic traits, field tolerance to blast and lodging, and superior post-harvest quality traits, were bulked and evaluated on farm using participatory variety selection (PVS). The enhanced Jethobudho accessions were also evaluated for aroma using DNA analyses and found to have a unique aromatic genetic constitution. Community-based seed production groups were formed, linked to the Nepal District Self Seed Sufficiency Programme (DISSPRO), and trained to produce basic seeds (truthfully labelled) of Jethobudho. The National Seed Board of Nepal released the enhanced landrace with the name of 'Pokhareli Jethobudho' in 2006, as the first bulk variety of traditional high quality aromatic rice improved through participatory plant breeding to be formally released in Nepal for general cultivation under the national seed certification scheme. Landrace improvement, linked to farmer-based seed producers, has enhanced access to a high-value rice variety.

FIGURE 4.2 – Sources of seed for smallholder farmers in sub-Saharan Africa and Haiti

Seed sources from a large sample of farmers in sub-Saharan Africa and Haiti (n=9,660). Regardless of the crop, informal sources (own stock; friends, neighbours, relatives; local markets) account for over 60%, and usually over 80%, of sources.



Source: Elaborated with numbers supplied by McGuire and Sperling (Table 3 in 28).

One of the seedbank managers at Jogimara Community Seedbank, Dhading, Nepal.
Credit: Bioversity International/R.Vernooy

Key function 1: Seed production and distribution

Seed production and distribution underlie farmers' access to seed. Key features of seed production and distribution include: quality and quantity of the seeds, timely availability, responsiveness to demand and the needs of farmers, affordability, suitability to agroecological conditions, and the supply of information about the characteristics of each seed. If these conditions are not met, seed production becomes a limiting factor for crop diversity to be used. Public and private investments in extension services and the crop and varieties covered by these services can greatly influence the range of seeds that are eventually chosen by farmers (30).

Seed production and distribution feature in all types of seed systems, although they need to be seen differently for formal and informal seed systems. The formal seed system can only produce varieties that are officially released and registered, whereas informal seed systems can produce seeds for all crops and varieties. The limiting factors for the two types of system are also different. Seeds produced and distributed by the formal system are of high quality because of regulatory systems. Yet, in a large number of cases, although new crop varieties are developed or identified for a certain region and found to be in demand, seed production does not take off. So the system fails to deliver the right amount of seeds at the right time. In addition, in order to produce seeds of released varieties, private or public seed companies need to have access to foundation seeds and multiply them either on their own land or, most often, by contracting farmers. Finally, marketing of those seeds requires a strong retail network. The chain to produce and bulk the seeds is therefore quite complex and any delay in the process may cause a failure to deliver seeds. As a result, despite large investments in formal seed sector development, many projects fail (31, 32). In many cases, the commercial seed sector of field crops is limited to hybrid seeds only. Hybrids are produced by crossing inbred lines in order to create new varieties that have high yield. However, if farmers recycle the seeds of hybrids, their yield generally drops, so that farmers need to buy fresh seed every new growing season to maintain the same yield level. Buying seed every season may not be affordable for poor farmers. Not all formal seed systems focus on hybrids, however. For example, in the vibrant rice seed sector in Andhra Pradesh, India, private companies and farmer cooperatives produce non-hybrid varieties of rice bred by the public sector, which farmers can, once purchased, continue to replant in the future (33).

The particular form that seed delivery takes influences the diversity that reaches seed users. There is a wide range of seed supply systems within the informal or intermediate seed systems, from government-centralized models based on community- and village-level seed production, supply systems facilitated by NGOs, to small-scale commercial seed supply models established with temporary public support (34, 35). Each of these models has advantages and disadvantages. The main problem of the government-centralized models is that they have often been ineffective in reaching smallholders. A problem with the NGO-facilitated seed supply systems, at least as they were organized in the past, is that they were not able to operate at a sufficiently wide geographical scale beyond the community, and thus could not become viable business ventures. Furthermore, NGO-facilitated operations overly focused on the commercial and operational aspects of seed production, often overlooking the importance of the genetic quality of planting material (34, 36). This is because, generally, these models also work with the same varieties used in the formal systems (sometimes because of policy requirements which prohibit the commercialization of non-registered varieties) so, although they contribute to enhancing distribution of seeds, they do not add much to the diversity of crops and varieties that become available to farmers.

Efficient seed supply is achieved when it is part of a decentralized commercial commodity chain in a market that encourages the operation of small, competitive seed and seedling retailers. This approach takes into account the high transaction costs for seed producers and distributors in catering for a dispersed clientele often requiring small individual sales and served by poor infrastructure. Additionally, this model fits the objectives of developing and producing planting material that is suitable for specific agroecological zones and that specifies user-defined needs particularly well (34).

Another model for seed provision is the community seedbank, which often includes seed production as one of its functions (37–39). Community seedbanks generally rely on seed barter or delayed payback in the form of grains or seeds rather than seed sales. This makes them more flexible, as they can also exchange non-registered varieties and thus increase the portfolio of varieties that becomes available to farmers, since exchange is generally not prohibited by laws. These mechanisms seem to work well to facilitate seed exchange in economies in which little cash circulates and for crops that are mainly grown for home consumption, as well as for varieties that are not registered but are considered superior by farmers or have high value in local markets (Box 4.4). As noted above, community seedbanks have been found to increase the number of varieties grown by each household.

BOX 4.4 – The case of Kiziba Community Seedbank, Uganda

Kiziba Community Seedbank in Uganda was established in 2010 during a project[iii] seeking to improve productivity and resilience for farmers through the enhanced use of crop varietal diversity, primarily focusing on common bean (*Phaseolus vulgaris*). The problem it addressed was the poor quality of bean seeds, particularly the proportion of diseases carried by seeds. There were few seed providers giving high quality, disease-free seeds. Varieties to be managed in the community seedbank were identified in a participatory way with farmers. As a result, the number of varieties available to farmers increased from 49 in 2010 to 69 in 2016 and the amount of seeds delivered increased from 100kg at inception to 1 tonne in 2016.

The community seedbank team provides training on agronomic practices. The combination of improved practices and adoption of superior varieties increased yields by over 50% for almost all farmers. The fame of the Kiziba Community Seedbank spread well beyond the borders of the four villages in which it started its operations to the point that it was agreed to open a commercial branch to sell seeds to farmers outside the current area. This is necessary as it is not possible for the managers of the community seedbank to move far from their location due to lack of transport. This model allowed a very large diversity of varieties to be delivered, including registered and farmers' varieties and let the farmers select which they prefer for home consumption and for the market. In 2016, the seed quality assurance manager at the Kiziba Community Seedbank, farmer Joy Mugisha, won an award for Best Farmer in the Southwest Region, Uganda, and fourth best in Uganda out of 710 farmers. This is an additional recognition of the validity of the model.

Public policies that support seed production can undermine the ability of seed producers to respond to information signals about demand and its variation in space and time, limiting the diversity on offer. This happens when governments distribute seeds of a very narrow range of varieties (sometimes just one) without much analysis of demand. In Malawi, a government seed subsidy scheme distributed varieties that leading seed companies rather than farmers had asked for (40). Such schemes not only fail to respond to farmers' needs and preferences, they also flood the market with cheap seed, which curtails the development of a demand-led seed market.

The agricultural development sector often emphasizes the need to develop a commercial seed sector with the underlying purpose of stimulating supplies of staple foods. But more recent policy insights emphasize the need to stimulate crop diversity in response to nutritional needs (11, 41, 42). Outdated policy goals around staple crops, however, still permeate public sector efforts around seed system development. In contrast, commercial vegetable seed production is taking off in a number of developing countries, such as Kenya, India and Thailand, but often relies on exotic varieties of 'cosmopolitan' vegetables rather than native crops or locally bred varieties. Global seed companies tend to focus on major staple crops while regional companies are more likely to cover local crops, such as amaranth or cowpea (43). Working with farmers in an integrated way, combining nutritional information, improved horticultural practices, marketing and breeding, is one way to strengthen seed production and distribution of local crops (Box 4.5).

BOX 4.5 – Traditional leafy vegetables in Kenya

In the early 1990s, scientists in Kenya noticed that traditional African leafy vegetables were rapidly disappearing from farmers' fields and people's tables. Between 1996 and 2004, work was undertaken to collect, characterize and analyze the nutritional values of these leafy vegetables before identifying priority species, enhancing genetic material, and improving horticultural practices, marketing and processing. About 12 additional African leafy vegetable species were introduced into the formal market in Kenya. Seeds were made available and over 450 farmers were trained in good practices for growing African leafy vegetables. As a result, the area under African leafy vegetable cultivation increased by 69%. An impact assessment study in 2007 showed that nearly two-thirds of households growing African leafy vegetables had increased their income, with women being the main beneficiaries (44). In almost 80% of households surveyed, it was the women exclusively who kept the income from sales of the leafy greens. The percentage of farmers planting at least one species of African leafy vegetable increased by almost 23%, while nearly half of the households surveyed had increased their consumption of leafy vegetables. Today, farmers and local groups are continuing to spread knowledge of diversity and sharing seeds. The impact of this long-term programme is evident on farms, on tables and in markets, where production and use of African leafy vegetables has increased.

Even in the absence of specific seed sector development interventions or policies, seed production and distribution can either constrain or facilitate the availability of diverse seed in smallholder agriculture. In many cases, it is found that seed production in local exchange networks relies on a few individual seed-producing farmers every year. The structure of these networks – i.e. the distribution and proportion of farmers who provide seeds to other farmers – influences the total crop diversity that is accessible through such networks (45). These networks are generally not static and can be quite specialized in the sense that one farmer or family may produce only one variety and another one a different variety. A study in Nepal found that networks are often highly dynamic with a high turnover of farmers who supply seed to others from one year to another (46). As seed production was decimated by natural calamities and new varieties came into the villages, there was a shift in the farmers who supplied seed to others in the exchange network.

Farmers may not exercise choice if information about the differences between varieties is not available. Information is a crucial aspect of seed delivery. An especially well-documented study, covering 11 years of varietal choices in cotton cultivation in India, analyzed the extent to which farmers' seed choices reflected empirical learning about differences in the yield performance of different crop varieties (47). The researchers found that farmers' observations on performance influenced their seed choices in a very haphazard way. Farmers were eager to try new seeds, but had little information to objectively compare varieties. As a result, they engaged in herd behaviour, imitating others when they had a well-performing crop. This led to fads regularly sweeping through the seed system. Despite the availability of a large set of varieties, herd behaviour hindered the contribution from diverse seed access to sustainable production. The lack of learning precluded moving to better performing seeds over time. This case study illustrates how access to plant diversity does not only involve physical access to diverse seeds but also the ability to generate and exchange objective, empirical information about the different options available.

Limited demand for diverse seeds tends to limit crop diversity in seed production, even if access to these seeds is not a problem. For example, multi-resistant varieties of wheat are available in Belgium and France, but little used. An in-depth analysis based on interviews with relevant actors in the value chain identified reasons for this limited use. One major obstacle was the limited interest of input supply companies to reduce their fungicide sales. Also, different actors in the seed system favoured yield over profit, not taking into account the rising costs of chemical disease control. Farmers also reported having difficulties selling the grain of the multi-resistant varieties (48). Seed subsidies and other agricultural subsidies can also have an important effect on seed demand. Many subsidized financial products, such as credit and insurance, are crop-specific. Crop-specific seed and input policies often result in disincentives for farmers to cultivate other crops, including those that make important contributions to nutritious diets, such as vegetables, small grains, legumes and tubers (11).

Public policies which explicitly support diversity can go a long way to increasing diversity in seed systems. Diversity goals can be included in different ways, for instance, in restoration projects aiming to restore healthy, diverse landscapes. For example, the Brazilian state of São Paulo established a legal target of a minimum of 80 tree or shrub species at the end of the restoration process in areas where the goal was to restore high-diversity forest. Production of seedlings of native tree species grew from 13 million seedlings in 55 nurseries, primarily from 30 species in 2003, to 33 million seedlings in 114 nurseries, from more than 80 species in 2008 as a result of the policy (49).

Key function 2: Innovation

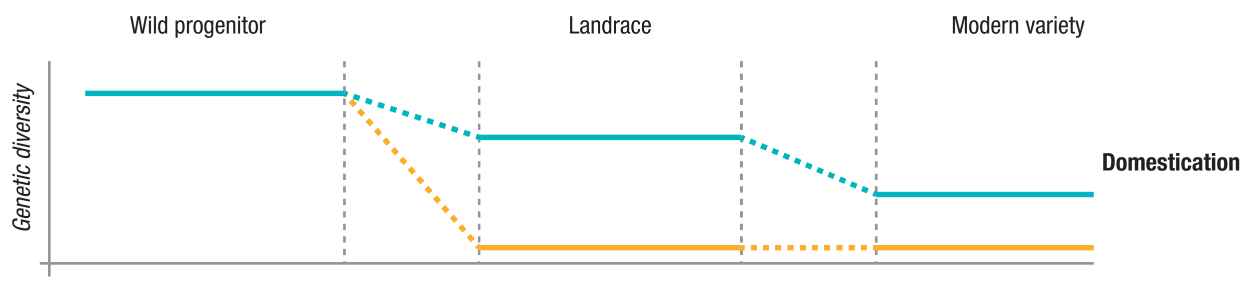
Innovation activities permit new genetic materials to be introduced into farmers' fields. Innovation may be the introduction of new species or seeds from alternative seed sources, farmer selection and plant breeding. While innovation is fundamental for crop diversity in sustainable food systems, depending on the form it takes, it can also contribute to a reduction in crop and variety diversity. Species introductions can diversify production systems, but can also replace traditionally grown crops or trees, with possible consequences for sustainable food systems. The extent to which introduction of varieties causes loss of crops and varieties is highly contested and possibly context related (16). For instance, the diffusion of improved varieties into traditional systems has been seen to cause "an accelerated loss of germplasm from the extant crop genepool" (50). This has been documented in a number of countries and crops, including pearl millet in India, rice in the Philippines, and wheat and barley in Ethiopia. However, other reports indicate that although improved varieties become predominant in a given production system, farmers still maintain traditional varieties and informal seed systems retain their function, as in other studies for rice in the Philippines (51).

Since pre-historic times people have prompted innovation in crop diversity, for example through migration. A community moving to another area would bring its seeds and crops and would exchange with the populations already in the new place. The Ancient Romans grew and ate rice, originally from Central Asia, and in some areas it replaced traditionally grown cereals. The so-called Columbian Exchange after the 'discovery' of the Americas by Christopher Columbus in 1492 fostered a 'homogenization' of agricultural systems around the world. A number of crops replaced their analogues on both sides of the Atlantic (52). For example, maize, a crop that originated in Mexico, has been an important contribution to African agriculture, but also has partially or wholly replaced sorghum, a crop that originated in Africa. With time, new crops are adopted and become part of the traditional food system. At times they add to what is already in the fields and at times they replace it. This is part of human cultural evolution and in the long term increases diversity. Most crops used in Mediterranean diets, for instance, originated outside the Mediterranean area and were brought in during ancient times from Asia and Africa, and more recently from the Americas. These innovations led to more diversified, healthier diets and farmers kept selecting varieties well adapted to local conditions and thus enhancing the diversity present in landscapes and countries.

Maize yields in the USA increased six-fold in the period 1940–2010; around 50% of this change is estimated to be due to the contribution of genetics (53). However, modern breeding over this same period also led to a considerable narrowing of the genetic base of US maize. Modern breeding has made an important, quantifiable contribution to productivity increases for more than a century, but has also affected genetic diversity on farm (Figure 4.3). Only a few of the thousands of varieties that existed around 1900 have contributed genetically to modern maize varieties. By 1970, virtually all varieties shared the same parent, which was used to make hybrid production more effective. This parent turned out be susceptible to the fungal disease southern corn leaf blight, resulting in an epidemic which wiped out maize production in a part of Florida. The disease was contained by identifying resistant material from other cultivated maize germplasm, which was quickly incorporated into modern varieties of maize. Low diversity of breeding materials can put a brake on the improvement of yield and grain quality as in this example (54).

FIGURE 4.3 – Expected loss of genetic diversity during crop evolution

The blue (upper) line represents expected loss of diversity through the domestication process, from being selected from the wild, to farmers' varieties (landraces), to modern varieties. The orange (lower) line depicts the relative change in genetic diversity in a specific part of the genome that affects functional traits, which are subject to strong and consistent selection during domestication and improvement.

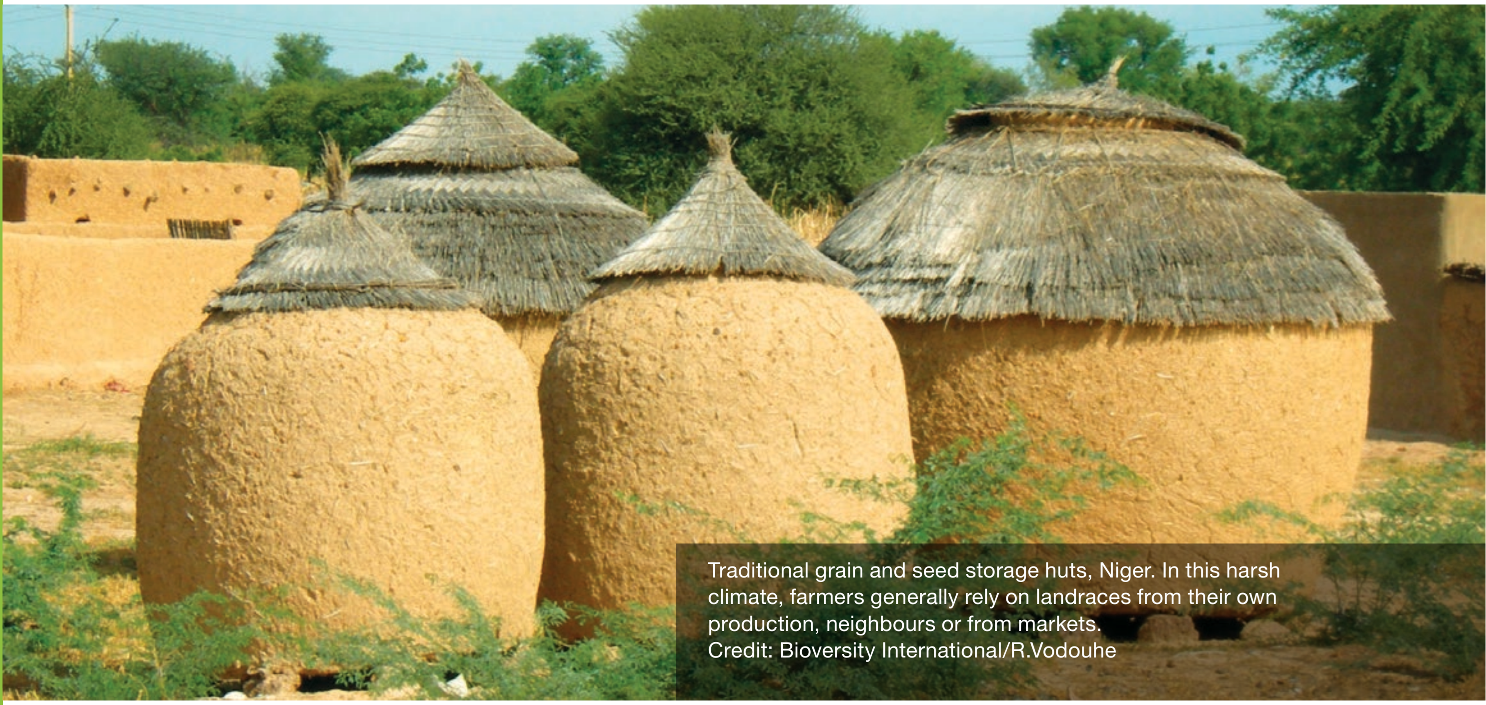


Adapted from (55).

Modern breeding tends to decrease the overall genetic diversity in improved varieties (Figure 4.3), but it can also increase diversity through 'base broadening'. Base broadening involves increasing the diversity of improved varieties by incorporating diversity from farmer varieties, the wild relatives of crops and related cultivated species. For example, the concerns about the narrow base of US maize led to genetic base broadening efforts. Researchers collected Latin American maize landraces and crossed them with US materials (54). Likewise, bean breeding is making use of crosses between different species of bean for biofortification, which aims to raise the nutrient content of crops through breeding. Crosses of common bean (*Phaseolus vulgaris*) with two cultivated species, runner bean (*P. coccineus*) and year-long bean (*P. dumosus/polyanthus*), have shown high levels of iron (56). If these, or similar interspecific crosses, become commercial biofortified varieties, they will contribute to increasing the overall genetic diversity of the cultivated crop genepool. Such use of different species or crop wild relatives is still rare and often relies on public investment. Another effective approach to managing much more diversity in breeding is 'evolutionary breeding'. This involves the maintenance of highly diverse populations that evolve with changing environmental conditions and supply genetic diversity for selection (27, 57).

The great decrease in crop diversity has had negative effects on nutrition. Farmers tend to keep a range of complementary varieties with diverse traits that correspond to different uses and needs (58, 59). For breeders, however, improvement has generally focused on yield improvement alone. This has negatively affected crop nutrient density, the nutrient content per unit of dry matter. A study comparing the nutrient content of the same 43 crops in 1950 and 1999 concluded that there was a statistically significant decline in the average content of protein, calcium, phosphorus, iron, riboflavin and ascorbic acid (60). The study explains these differences as the result of plant breeding, which focused on yield increases, but ignored nutritional content. A study on spring wheat varieties found a similar decline in the content of copper, iron, magnesium, manganese, phosphorus, selenium and zinc (61). This has negative consequences for human nutrition. For example, to reach their daily-required amount of zinc women aged 19–30 would have to eat 10 or 11 slices of wholegrain bread made with flour from historical cultivars, but would require about 15 slices of bread made with flour from modern cultivars. This is not true for all modern wheat varieties, however, which implies that this decline is not an unavoidable result of yield increases through breeding. In the case of tomato, the focus on yield and visual appearance has not only negatively affected nutrient content, but also taste (62). Compromised taste reduces consumers' appetite for these products and can lead them to include fewer fresh products in their diets; this is another pathway through which breeding affects nutrition (63). Better use of intraspecific genetic diversity and more careful analysis of trade-offs among different use traits (yield vs. nutrition value) would help avoid these negative impacts of breeding.

The reduction of crops grown and consumed is also partially due to the small range of species that are the focus of innovation efforts. Public breeding in poor countries has emphasized staple and horticultural crops at the expense of more nutrient-dense crops (11, 64). Relatively modest research investments can help to overcome obstacles in the use of currently neglected, yet highly nutritious, crops (see for example, (65) for African eggplant and (66) for minor millets in India).



Traditional grain and seed storage huts, Niger. In this harsh climate, farmers generally rely on landraces from their own production, neighbours or from markets.
Credit: Bioversity International/R.Vodouhe

For environmental sustainability too, the effect of innovation on plant diversity has important consequences. Modern breeding has usually taken place under high-input conditions, while landraces have generally evolved under low-input conditions. As a result, modern varieties tend to have lower nutrient use efficiency than landraces (67). Landraces are therefore an interesting source of diversity to reduce fertilizer use per unit of product.

An important element to create space for agricultural biodiversity in formal systems is client orientation in innovation. Bringing the diverse conditions, needs and preferences of clients into focus is important to ensure that innovation responds to the specific challenges of sustainable food systems. Four aspects determine if a plant breeding programme is client-oriented: goal-setting, parent population selection, environmental targeting and market targeting (68). This framework could be generalized to a broader area of innovation beyond plant breeding, including the introduction of new species or varieties or rediscovery of farmer varieties conserved in national or international genebanks, which can be an important source of innovation. Client-oriented innovation will tend to lead to a broader range of agricultural biodiversity being used to tailor to different production and consumption needs (Box 4.6).

BOX 4.6 – 'Seeds for Needs' in Ethiopia: an example of client-oriented innovation

The 'Seeds for Needs' initiative in Ethiopia[iv] involved wheat-growing farmers in two different areas, who evaluated 400 durum wheat samples from the national genebank and identified those that met their needs and expectations (client-oriented innovation). Farmers and scientists evaluated these varieties together and identified those that would better satisfy the farmer-clients. Agronomic and morphological data collected by scientists was linked to feedback from farmers.

Working with farmers allowed a better understanding of their priority traits, which can inform breeders so that they can take into account farmer preferences and identify suitable accessions for immediate distribution to farmers. Subsequently by matching farmers to varieties, the top 20 varieties were identified. Small amounts of these were then distributed to a large number of farmers to evaluate using a crowdsourcing approach. Different varieties have different features, as farmers use them to produce different types of products, e.g. local drinks, bread, enjera. They also have different agronomic performance and resistance to pests and diseases, so based on their climatic conditions and preferences, farmers can choose the best performing varieties. It was discovered that generally in marginal conditions, farmer varieties outperform formally improved varieties and are preferred by farmers.

If disruptive innovation is the aim, user feedback may have less value than for incremental innovations, as "existing users can be too tightly bound to existing products and use patterns to imagine radical alternatives" (69). Innovations towards sustainable food systems will often call for systemic changes, reconfiguring the systems themselves (42, 70). For example, the technological lock-in around chemical pest and disease control (the 'pesticide treadmill') will need disruptive innovation to bring systemic change (48, 70). Changes might involve farmers' choices, R&D investment and perhaps new market mechanisms, such as a premium for products produced with fewer pesticides.

Lock-in situations preventing innovation towards sustainable food systems are more likely to persist in the absence of institutional diversity. Different socio-technological configurations are easier to imagine and realize when institutional diversity is available in the form of proactive governments, vibrant businesses and engaged civil society actors, as well as diversity within each of the groups. There is a direct link between institutional diversity and innovation capacity (71). Institutional diversity, in the form of different breeding programmes or companies, has a direct positive effect on the range of crop diversity that is available (72).

Key function 3: Regulation

For farmers, it is important to know that the seed they obtain will grow into a healthy crop with expected characteristics. To ensure this, certain policies and regulations are needed, such as regulations on the market release of new crop varieties. Regulation in the context of formal seed systems covers seed quality control as well as variety registration and release (30). Regulation was generally designed to support the spread of improved varieties by creating a regulatory environment that recognized government institutions and companies that produce seeds. However, one result is that it has often ignored farmers' traditional seed production or even declared it illegal. This has created a playing field tilted against landraces or farmer-bred varieties. Regulation generally assumes, but does not necessarily verify, that modern varieties outperform landraces in farmers' fields. This assumption often does not hold, especially in marginal environments or in cases in which breeding has not been client-oriented (See Box 4.6). In the following, we will explore both positive and negative influences of regulation.

One influence of regulation on crop diversity comes from the variety release procedures of each country (30, 73). Variety release systems are a way to ensure that new varieties are of good quality. However, they can limit the number of varieties through excessive requirements on testing, with high costs and long procedures.

Also, variety release systems can discriminate against varieties bred for marginal environments or that do not comply with other characteristics, such as uniformity (landraces tend not to be uniform). In some countries, variety release systems require on-station testing or testing in the main production areas, even when varieties are developed for more marginal areas, which can make the results irrelevant or misleading. A survey on the variety release and registration systems of 30 African countries, using data provided by breeders working for the international agricultural research centre AfricaRice, found that of these 30 countries, only 13 had a functional variety release system and only eight recognize participatory field trial data in their variety release procedure (74).

Complicated and costly seed quality control or certification procedures can represent a limitation for the availability of crop and tree planting material coming from informal sources or produced by farmer organizations. A number of alternative mechanisms to seed quality certification are being tested around the world, including the Food and Agriculture Organization of the UN (FAO) Quality Declared Seed System, which relies on simplified, sometimes community-managed processes. The Seed Office of Costa Rica has made it possible for seed producers to become accredited to do their own seed quality control, replacing centralized seed quality control by the government (75). A simplification of variety release procedures, involving simple evaluations done by farmers, can take away the hurdles to make a larger range of varieties available to farmers. In Nepal, a simplified variety release procedure permits the use of data from participatory variety selection trials. This helped to fast-track the release or registration of new varieties of mung bean that are resistant to mung bean yellow mosaic virus (76). The disease had limited the use of mung bean, an important legume crop, so overcoming this constraint effectively added the crop back to local farming systems.

On the other hand, variety registration procedures may be too relaxed about distinctiveness, allowing the registration of an endless series of nearly equal varieties. In India, 1,128 Bt cotton hybrids (a genetically modified cotton) were approved between 2002 and 2012. A large number of these varieties are highly similar, which confuses farmers and prevents them from learning about crop performance, upsetting local knowledge systems that manage agricultural biodiversity (47). In this case, stricter rules would remove confusion and support local knowledge creation and exchange.

Intellectual property regimes are also a recurrent element in the discussions around seed systems and their capacity to contribute to agricultural biodiversity. Limitations on farmers to use, save, duplicate and exchange plant varieties protected by intellectual property rights; the lack of recognition or compensation for farmers when new products based on their traditional varieties and ancestral knowledge are subject to property rights; the incapacity of the current intellectual property system to adequately protect farmers' varieties and knowledge as well as innovations generated at the community level, are some of the issues that are commonly raised when identifying disincentives for community-based initiatives to engage in seed innovation for sustainable food systems (77).

Relationship with conservation

Conservation of crop and tree diversity is the foundation on which the three functions of seed systems rest. As a large subject in its own right, it is discussed in detail in Chapter 5. Conservation of the broadest genetic base possible provides a pool of resources to be used in innovation. As noted in Chapter 5, conservation of crop diversity takes place intentionally in genebanks, when materials are collected and safeguarded in long-term storage, and indirectly in fields and landscapes, when farmers and land managers make decisions about what to plant and how to use the land. The extent to which crop diversity is conserved emerges from the interactions of a host of policies and practices. Seed systems can support or hinder conservation through their formal and informal rules, regulations and exchanges.

In the field, introducing modern varieties may replace older crop genetic materials that farmers use (78). However, there is much scientific debate about the precise drivers for this replacement, including the availability of seed of modern varieties, pressures towards more intensive agriculture, the effects of subsidies and the demand for uniform products for markets.

The extent that displacement is going on is hotly contested. Various studies on genetic erosion of maize in Mexico have come to different conclusions depending on the methodologies used, and whether or not they focused on the household or the community (79, 80). In many cases, farmers add improved varieties to the pool of crop diversity they manage, without dropping existing varieties from their systems (Box 4.7). Farmers maintain portfolios of traditional, crossed and improved varieties as a pragmatic strategy to improve production in low-input conditions, and to manage different agro-ecological conditions, culinary traditions and changing climate patterns (81–84). Even where the use of creolized seeds has reduced the area cultivated with landraces, the overall diversity in the community increased due to the creolized varieties, which were genetically distinct from the traditional landraces. Case studies in South Asia show that rice variety introduction had mixed effects on varietal diversity, depending on the agricultural system and the existing diversity into which the new varieties were introduced (85). In none of the cases were existing varieties completely removed from the area; the 'reserve diversity' was not affected.

BOX 4.7 – Maize diversity in Yucatán, Mexico: an example of the coexistence of modern and traditional varieties

A 12-year longitudinal analysis found that, despite the increased introduction and supply of improved maize variety seeds in the Yucatán Peninsula, Mexico, farmers continue to maintain a substantial amount of traditional maize variety diversity.

Even with the increased availability of hybrid seeds, farmers in the community of Yaxcaba on average plant more than three-quarters of their *milpa* fields with traditional maize varieties, with the other one-quarter predominately planted with a locally improved variety *Nal Xoy*, a farm cross of a traditional variety and an improved variety. The research team observed a significant reduction in *X-nuuk* nal, a long-cycle traditional landrace, paralleled by an increase in short- and intermediate-cycle locally adapted improved maize varieties. Soil type accounts for great differences in the distribution of maize varieties, with modern varieties being targeted for the rarer, deeper and fine-grained soils, while traditional varieties predominate on the more prevalent stony and thin soils. The results provide a picture in which most traditional maize varieties in Yaxcaba continue to be maintained by farmers, coexisting with locally adapted improved varieties on the same landscape, and allowing the continued evolution of maize populations.

Adapted from (81)

Metrics to measure seed systems for sustainable food systems

Identifying metrics to measure the contribution of seed systems to sustainable food systems is a challenge. For the formal system, indicators tend to measure seed system performance in terms of seed production volumes and seed replacement rates, which are not helpful indicators for measuring the contribution to food system sustainability (86). Most indicators suggested stop short of establishing the contribution of seed systems to sustainable food systems. For example, they may measure the quality of seeds available to farmers, but not establish whether this makes any difference in terms of the sustainability of production or food and nutrition security. Such partial indicators may lead to seed policy recommendations that are at cross purposes with food policies, leading to policy fragmentation, the existence of ill-coordinated or contradictory, policies in related domains. Sustainable food systems simultaneously tackle productivity, environmental sustainability and food and nutrition security and therefore rely on policies that are well-coordinated across policy domains, or 'joined-up' in policy jargon. No comprehensive framework exists to assess seed system performance from the perspective of its contribution to sustainable food systems. No wide-scale monitoring exists also for the informal and intermediate systems, although at project scale methodologies have been developed which could, with appropriate support, be scaled up to global level.

We propose to take as a starting point the evidence outlined above of what is important for seed systems to contribute to crop diversity, which in turn contributes to sustainable food systems. We explore the available and potential indicators and data sources that can help monitor the aspects important for food system sustainability and recommend those which are most suitable under current circumstances. We consider the indicators for farmers' access to seeds (the overall goal of the system), and each of three key functions that underpin seed access.

Metrics for seed access

Seed access is the outcome of the three key functions of seed systems. Ideally, indicators on the contribution of seed access to agricultural biodiversity for food system sustainability should cover the following elements:

- Diversity of crops, trees and varieties available from the formal seed system
- Diversity of crops, trees and varieties available from the intermediate seed system
- Diversity of crops, trees and varieties of seed available from informal seed systems.

To obtain indicators, data need to be treated taking into account that: (1) species and varieties are not equivalent biological units and (2) they have different degrees of complementarity in their functional contribution to healthy food systems. Mathematical methods exist to convert such data into indicators of 'equivalent species' that would be comparable between countries (for example, 87).

The first indicator can be derived from several data sources. Important sources of data are large datasets with information about farmer access to seed of modern varieties (86), and modern variety adoption data, combining household survey data with existing data based on expert opinion of the adoption of modern varieties (88). Also, data on seed distribution (see next page) can be used as a proxy if other data are not available. For example, the Access to Seeds Index ranks how well seed companies are reaching small-scale farmers. The Regional Access to Seeds Index in particular is useful for assessing access to seeds of some local crops. At present the Regional Index has, however, been developed only for Eastern Africa (43).

Information on seed access from the intermediate seed system can be accessed from government records where there is involvement of public institutions in managing or supporting those institutions, or where some kind of seed quality control is in place. For example, information on community seedbanks can be obtained from public institutions in some countries, including Ethiopia and Uganda. This source can provide inputs on number of crops and varieties accessible to farmers and it is expected that it will provide information on a larger number of crops and varieties.

The third indicator, for informal seed systems, will require the collection of primary data, as it is difficult to know the volume and the diversity of seed exchanged by farmers and sold in local markets. Some examples are illustrated below on methods to collect such data (Box 4.8).

In conclusion, data on access to seeds is currently limited in coverage and biased in its orientation towards major crops and modern varieties, limiting its use for assessment of seed systems. Efforts should focus on improving datasets on seed access. Even so, many data are already available and can be used to assess farmers´ access to seeds.

BOX 4.8 – Data on farmers’ seed access: three examples

Example 1 – Seed security assessments.

McGuire and Sperling present a large dataset on seed security derived from seed security assessments that follow a novel, standardized approach (28). The dataset provides relevant insights into seed access patterns (e.g. Figure 4.2). For an agricultural biodiversity analysis the methods used still have important limitations. The survey questions focused on the “most important” crops only, but fruits and vegetables are absent from this group, even though there is evidence that production and consumption of this group of crops may decrease disproportionally in emergencies (see p. 84 above). Also, these data are collected in response to emergencies and not regularly with comprehensive coverage. These factors limit the use of these data for periodic monitoring, even though the methods are of interest.

Example 2 – Household surveys.

Spielman and Kennedy suggest using the Living Standards Measurement Study - Integrated Surveys on Agriculture (LSMS-ISA) data for seed system analyses (86, 89). LSMS-ISA includes data on seed use (seed quantities, prices and sources). Even though the data do not cover seed access specifically as a constraining factor for seed use, certain inferences can be made. LSMS-ISA provides georeferenced panel datasets which allow for analysis of potentially relevant spatial and temporal patterns. An analysis of the LSMS data on use of seeds and inputs for several African countries illustrates the types of analyses that are possible with these data (90). The LSMS only provides representative coverage for a number of countries, but as its coverage expands, it could provide relevant data for comparisons between countries. A specifically designed indicator on seed access is being included as an indicator in the Rural Household Multi-Indicator Survey (RHoMIS) framework (ongoing work by authors; for RHoMIS, see 91). This indicator covers seed sources, farmers’ possibilities to choose from a range of diversity and the information they have to make these choices. Like LSMS-ISA, RHoMIS includes a large number of other indicators, allowing for examination of relationships between seed access and indicators on food and nutrition security, environmental sustainability and poverty, among others. A distinguishing feature of RHoMIS is that its format is geared towards implementation in practical situations, such as development project baselines. However, although its use is increasing, at the moment RHoMIS only covers a number of sites, so its value for international comparisons is still limited.

Example 3 – Genetic fingerprinting.

Survey data is often the best evidence we have, but it has a high degree of inaccuracy when it comes to farmers reporting on modern variety names. Spielman and Kennedy suggest complementing survey-based variety diffusion studies with genotyping of a large number of seed samples to determine variety identity (along with biological analyses of other aspects, such as seed quality) (86). If such studies were to include landrace materials as well, periodic monitoring of crop diversity in seed production would become feasible. A promising first study that pilots varietal fingerprinting using leaf material is now available for sweetpotato (92).

Metrics for seed production and distribution

The evidence presented on seed production and distribution implies that the following aspects are relevant to be monitored:

- Diversity of species and varieties distributed by the commercial sector
- Diversity of species and varieties produced and distributed by farmer organizations and NGOs
- Degree of healthy market competition, number of seed suppliers for each species
- Supply of high-quality information on characteristics of seeds
- Degree of policy and institutional openness to the development of demand of diverse seeds (for example, absence of barriers, such as direct crop-specific subsidies, crop-specific subsidized financial products, crop-specific market development support).
- Presence of specific programmes with diversity goals supported by public policies (for example, support for farmer seed exchange, support for tree diversity in landscape restoration activities, seed security interventions with an explicit crop diversity focus).

Indicators on the informal sector for seed production and distribution are difficult to collect and already sufficiently covered if data on seed access are available. The focus should be on how the formal and semi-formal sectors support diverse seed availability.

Seed is an important commodity, but official data on seed production and distribution are very limited. Agricultural census data from FAOSTAT provide some information on seed production by crop, but the data are only partially complete, they often rely on estimates, do not distinguish between commercial and non-commercial seed production and do not cover seed price or total value (93). Data on seed exports and imports, however, are available and provide an indication of domestic seed production capacity. Countries that export have better capacity than countries that only import seeds of a specific category. The International Seed Association collates seed import and export data.[v] These data were available for 2014 for most countries at the time of writing and are updated periodically. They distinguish between cereal and vegetable crop seeds.

It may be difficult to provide good data on the number of seed suppliers for different species in each country, but it may be less difficult to assess if there is an oligopoly/monopoly or a healthy, competitive seed market for different species. This could be measured through comparative expert assessment.

The remaining indicators cover drivers that influence seed production and distribution related to the social organization and political economy of the formal seed sector. Good examples exist of comprehensive seed system studies with a focus on varietal diversity (48, 94). They are based on interviews with a comprehensive range of stakeholders.

Some other data sources provide data that can also support assessment of seed production and distribution:

- The Access to Seed Index provides an indication of production and distribution of seed in the formal system for a number of countries.
- The World Bank initiative 'Enabling the Business of Agriculture'[vi] collects data in 62 countries on the existence of policies, regulations or programmes that establish community seedbanks and diversity fairs, which are both mechanisms for seed distribution.

In summary, data to assess the production and distribution function are available and can be used to determine how the formal and semi-formal seed sectors contribute to seed access. However, simple exercises to retrieve expert opinion should complement these data sources in order to refine assessment.

Metrics for innovation

To cover the innovation key function, performance metrics will need to address the following aspects:

- Species and genetic diversity used in breeding efforts
- Degree of investment of seed R&D in nutritionally important species
- Degree of investment of seed R&D in environmental sustainability (for example, pesticide reduction)
- Degree of client-orientation and systemic innovation in seed-related R&D
- Institutional diversity of the seed-related innovation system.

To assess the species and genetic diversity used in breeding, bibliometric reviews would be possible, although they may miss some of the most recent developments and underestimate efforts when they are not published. Plant breeding takes generally from 7 to 17 crop cycles to produce a new variety (95), so there will be a significant time lag between innovation activities and publication. Other data that could be used are seed requests from international and national genebanks. At the moment, these are not collated periodically in a comprehensive way, but recent analyses show how these data can be used to reveal trends (96). These data could give indications of germplasm use, although use of germplasm sourced from within the same country would need to be assessed with other data that will often be more difficult to obtain.

Several data collection initiatives have tried to capture country-level investments in plant breeding, one component of seed-based innovation (97, 98). The only effort that has periodically collected new data, however, is the 'Agricultural Science and Technology Indicators' initiative, which collects data on agricultural research investments (99). The last update was done in 2011. Beginning in 2011, it also breaks down the number of researchers by crop categories: cereals, roots and tubers, pulses, oil-bearing, horticultural, other crops. Even though these are very broad categories, it allows for basic comparisons across countries if investments are proportional to what would be expected in a healthy diet.

It has been argued that a research investment gap cannot be deduced directly from current R&D investment data, as countries have very different needs for innovation (100). A new indicator of research intensity based on ASTI data that takes into account various factors, including the current size of the economy of each country and the need for agricultural diversification might be an effective way of assessing the gap (100). The resulting indicator appears to be an important step forwards, but it does not consider national food system health, and gives equal weight to export diversification as to national food supplies. The indicator could be further refined to better reflect policy goals associated with agricultural R&D investments.

Detailed data to measure the environmental focus, client orientation, or institutional diversity of innovation initiatives and systems are largely absent. Also, the highly aggregated existing data preclude any detailed analysis of the contribution of seed-based innovation to agricultural biodiversity and sustainable food systems. More detailed periodic inventories of seed-based innovation efforts would be needed to assess the precise contribution of these efforts to sustainable food systems. A number of country studies provide interesting models. For example, a Nepalese study of the agricultural innovation system lists plant traits and geographic areas that are being targeted (101).

Even though detailed information on these aspects is lacking, there are the data collected across 62 countries from the World Bank 'Enabling the Business of Agriculture' initiative for the following questions:

- Companies are obtaining access to germplasm preserved in publicly managed genebanks
- Existence of policies, regulations or programmes that establish participatory plant breeding.

Together with the ASTI data, these variables provide a good start for assessing the innovation key function.

Metrics for regulation

The evidence presented suggests that an evaluation of regulation in terms of agricultural biodiversity should cover the following aspects:

- Ability of the regulatory system to release varieties tailored to diverse conditions with reasonably simple requirements and to have provision for a register of farmer varieties with clear descriptors and procedures
- Limits on the release of varieties without clear, distinctive benefits for farmers and agriculture
- Seed quality control arrangements that make it feasible to produce quality seeds in remote regions for marginal conditions and that can cater for farmer varieties
- Policies that allow farmers to exchange and sell seeds legally
- Recognition of intellectual property rights for farmer varieties.

The World Bank 'Enabling the Business of Agriculture' initiative has a very rich dataset that includes many aspects of regulation relevant to crop diversity. Under the *Environmental Sustainability* topic of this initiative, there are many questions that have direct relevance for crop diversity. These include the following:

- Existence of an official registry that lists all local varieties that can be exchanged or commercialized
- Existence of laws or regulations that specifically regulate the commercialization of seeds of local varieties
- Legal exceptions for the legal commercialization of seeds of local varieties to:
  - registration/listing requirements
  - Value for Cultivation and Use testing requirements
  - Distinctness, Uniformity and Stability testing requirements
- Quantity restrictions applicable to the commercialization of seeds of local varieties
- Geographic restrictions applicable to the commercialization of seeds of local varieties
- Legal possibility of farmers to:
  - save and use on their property, seeds of varieties protected by plant breeders' rights
  - exchange seeds of varieties protected by Plant Breeders' rights
  - sell seeds of varieties protected by plant breeders' rights
- Laws establishing the procedural requirements to access plant genetic resources found in the country
- Whether the access to plant genetic resources for research, breeding and commercialization requires:
  - the use of a Material Transfer Agreement (MTA)
  - the use of a Standard Material Transfer Agreement (SMTA)
  - a government notification
  - a government permit
  - free prior informed consent of farmers or local communities.

Data are available for 62 countries. These data would need to be converted into indicators that correspond to the different aspects mentioned above.

Conclusions

In this chapter, we give conceptual form to the contribution of seed systems to crop diversity in sustainable food systems. This framework suggests a structure for indicator development to be able to measure this contribution. The evidence reviewed shows that the different characteristics of seed systems make a distinct contribution to the capacity of food systems to produce food in a sustainable way and provide healthy diets. Not only are changes in production systems and consumer demand important to explain changes in food systems, but also the specific ways in which the different functions of seed systems work together to provide specific types of crop and tree diversity. From a policy perspective it is therefore important to monitor seed systems in such a way that it is possible to manage their contribution to sustainable food systems.

Overall assessments of seed system functioning are currently still limited in scope and devote little attention to agricultural biodiversity, which involves important causal linkages between seed systems on the one hand, and sustainable food production and healthy diets on the other. These monitoring tools therefore risk reinforcing the current policy fragmentation, which is an obstacle to supporting sustainable food systems. Data collection efforts should focus especially on household data on seed access to be able to compare across different sources of seed. The current narrow focus on the formal sector precludes an objective comparison with the contribution of seeds from non-formal sources. Also, better data are needed on seed production and distribution, which currently do not figure in agricultural statistics. Agricultural innovation investments also lack more detailed data to assess the contribution of different investments to sustainable food systems, although it is possible to quantify the relative investment across crop groups. The area of regulation is perhaps best covered with current datasets. Investments in data collection in these areas will improve the ability of countries to compare themselves and to assess different policies and investments in a more objective way.

In spite of the data gaps, the chapter has also identified a number of important resources that can readily be used to compare different countries over time. Constructing indicators based on these data will already allow important comparisons to inform country-level decision-making and to continuously track progress in this area.

Seedlings of *Saba senegalensis* grown at the National Tree Seed Center of Ouagadougou (Burkina Faso). The fruit is highly prized and the species is considered to have medico-magical properties. It grows across most West African countries (from Senegal to Niger and Nigeria). The habit of the species varies according to where it grows: shrub-like in open, drier lands and a climbing liana when growing in forests, with a stem over 40 metres long.
Credit: Bioversity International/B.Vinceti

Notes

[i] For brevity, the term 'seeds' refers not only to seeds but to all planting materials. Planting materials include seeds, seedlings, stem cuttings, roots, tubers and leaf portions.

[ii] http://www.proinpa.org/VallesNorte/

[iii] Conservation and Use of Crop Genetic Diversity to Control Pests and Diseases - Phase 1 (2007-2011). UNEP GEF grant no. GFL/2328-2715-4983

[iv] http://www.bioversityinternational.org/seeds-for-needs/

[v] http://www.worldseed.org

[vi] http://eba.worldbank.org/

References

1. Evenson RE, Gollin D (2003) Assessing the impact of the green revolution, 1960 to 2000. *Science* 300(5620):758-62.
2. Piesse J, Thirtle C (2010) Agricultural R&D, technology and productivity. *Philosophical Transactions of the Royal Society B: Biological Sciences* 365(1554):3035–3047.
3. Coomes OT, et al. (2015) Farmer seed networks make a limited contribution to agriculture? Four common misconceptions. *Food Policy* 56:41–50.
4. Bishaw Z (2004) Wheat and barley seed systems in Ethiopia and Syria. PhD Dissertation (Wageningen University).
5. Kabore O (2000) Participatory plant breeding, seed networks and grassroot strengthening in Burkina Faso. In *Conserving Agricultural Biodiversity In Situ: A Scientific Basis for Sustainable Agriculture*, eds Jarvis DI, Sthapit BR, Sears L (IPGRI, Rome), pp 192–193.
6. Ndjeunga J, Anand Kumar K, Ntare BR (2000) *Comparative analysis of seed systems in Niger and Senegal* (ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), Patancheru).
7. Gauchan D, Thapa Magar DB, Gautam S, Singh S, Singh US (2014) *Strengthening Seed System for Rice Seed Production and Supply in Nepal* (IRRI-NARC collaborative EC-IFAD funded project on Seed Net Development. Socioeconomics and Agricultural Research Policy Division, Nepal Agricultural Research Council).
8. Almekinders CJM, Louwaars NP (2002) The importance of the farmers' seed systems in a functional national seed sector. *Journal of New Seeds* 4(1–2):15–33.
9. Sperling L, Boettiger S, Barker I (2013) Integrating Seed Systems. Planning for Scale Brief #3. Ag Partner XChange.
10. Ceccarelli S (1989) Wide adaptation: How wide? *Euphytica* 40(3):197–205.
11. Pingali P (2015) Agricultural policy and nutrition outcome – getting beyond preoccupation with staple grains. *Food Security* 7:583–591.
12. Louwaars NP (1994) *Seed Supply Systems in the Tropics* (International Agricultural College Larenstein, Deventer).
13. Maredia MK, Howard JA (1998) Facilitating seed sector transformation in Africa: key findings from the literature. Policy synthesis for USAID - Bureau for Africa, Office of Sustainable Development. Number 33.
14. Hirpa A, et al. (2010) Analysis of seed potato systems. *American Journal of Potato Research* 87:537–552.
15. Louwaars NP, de Boef WS (2012) Integrated seed sector development in Africa: a conceptual framework for creating coherence between practices, programs, and policies. *Journal of Crop Improvement* 26(1):39–59.
16. Thomas M, Dawson JC, Goldringer I, Bonneuil C (2011) Seed exchanges, a key to analyze crop diversity dynamics in farmer-led on-farm conservation. *Genetic Resources and Crop Evolution* 58(3):321–338.
17. Guhuray F, Ruiz B (1997) The effects of war on cropping systems: A study of two zones in Nicaragua. *War and Crop Diversity*, Sperling L ed. Agricultural Research and Extension Network Paper 75. (ODI, London) pp1–12.
18. de Barbentane Nagoda S, Fowler C (2003) Seed relief after Hurricane Mitch in Honduras: a critical analysis of institutional responses. *The Journal of Humanitarian Assistance* 6.
19. McGuire S, Sperling L (2011) The links between food security and seed security: facts and fiction that guide response. *Development in Practice* 21(4--5):493 -508.
20. Sperling L (1997) *War and Crop Diversity*. Agricultural Research and Extension Network Paper 75 (ODI, London), pp 1-54.
21. von Hertzen L, Hanski I, Haahtela T (2011) Natural immunity: Biodiversity loss and inflammatory diseases are two global megatrends that might be related. *EMBO Rep.* 12(11):1089-93
22. Khamsi R (2015) A gut feeling about immunity. *Nature Medicine* 21:674–676.
23. Mwongera C, Boyard-Michea J, Baron C, Leclerc C (2014) Social process of adaptation to environmental changes: How Eastern African societies intervene between crops and climate. *Weather, Climate, and Society* 6:341–356.
24. Singh S (2015) Crowdsourcing seed data in Nepal. *SciDevNet South Asia*. Available at: http://www.scidev.net/south-asia/food-security/news/crowdsourcing-seed-data-in-nepal.html [Accessed 4 May 2017].

25. Bezabih M (2008) Agrobiodiversity conservation under an imperfect seed system: the role of Community Seed Banking schemes. *Agricultural Economics* 38(1):77–87.
26. Ceccarelli S, Grando S (2007) Decentralized-participatory plant breeding: an example of demand driven research. *Euphytica* 155(3):349–360.
27. Rahmanian M, Salimi M, Razavi K, Haghparast R, Ceccarelli S (2016) Evolutionary populations: Living gene banks in farmers' fields in Iran. *Farming Matters*:24–29.
28. Lipper L, Winters P, Cavatassi R (2012) Seed supply in local markets: supporting sustainable use of crop genetic resources. *Environment and Development Economics* 17(5):507–521.
29. McGuire S, Sperling L (2016) Seed systems smallholder farmers use. *Food Security* 8(1):179–195.
30. Tripp R, et al. (1997) Alternatives for seed regulatory reform: An analysis of variety testing, variety regulation and seed quality control. Agricultural Research and Extension Network Paper 69 (ODI, London).
31. Ndjeunga J (2002) Local village seed systems and pearl millet seed quality in Niger. *Experimental Agriculture* 38:149–162.
32. Tripp R (2001) *Seed Provision and Agricultural Development* (ODI, London).
33. Tripp R, Pal S (2001) The private delivery of public crop varieties: Rice in Andhra Pradesh. *World Development* 29(1):103–117.
34. Lillesø JBL, Graudal L, Moestrup S (2011) Innovation in input supply systems in smallholder agroforestry: Seed sources, supply chains and support systems. *Agroforestry Systems* 83:347–359.
35. Nyoka BI, Roshetko J, Jamnadass R (2015) Tree seed and seedling supply systems: a review of the Asia, Africa and Latin America models. *Small-Scale Forestry* 14:171–191.
36. Gaudral, L, Lillesø JBL (2007) Experiences and future prospects for tree seed supply in agricultural development support (Working Paper) Copenhagen: Ministry of Foreign Affairs of Denmark.
37. Meinzen-Dick R, Eyzaguirre P (2009) Non-market institutions for agrobiodiversity conservation. In *Agrobiodiversity Conservation and Economic Development* Kontoleon A, Pascual W, Smale M Eds.(Routledge, London) pp 82–91.
38. Vernooy R, Sthrestha P, Sthapit B (2015) *Community Seed Banks: Origins, Evolution and Prospects* (Routledge, London).
39. Vernooy R, Sthapit B, Galluzzi G, Shrestha P (2014) The multiple functions and services of community seedbanks. *Resources* 3(4):636–656.
40. Chinsinga B (2011) Seeds and subsidies: The political economy of input programmes in Malawi. *IDS Bulletin* 42(4):59–68.
41. Global Panel on Agriculture and Food systems for Nutrition (2016) *Food Systems and Diets: Facing the Challenges of the 21st Century* (London).
42. IPES-Food (International Panel of Experts on Sustainable Food Systems) (2016) *From Uniformity to Diversity: A Paradigm Shift from Industrial Agriculture to Diversified Agroecological Systems.* (IPES-Food, Brussels)
43. Access to Seeds Foundation (2016) *Access to Seeds Index Report 2016* (Access to Seeds Foundation, Amsterdam).
44. Gotor E, Irungu C (2010) The impact of Bioversity International's African Leafy Vegetables programme in Kenya. *Impact Assessment and Project Appraisal* 28:41–55.
45. Pautasso M, et al. (2013) Seed exchange networks for agrobiodiversity conservation. A review. *Agronomy for Sustainable Development* 33(1):151–175.
46. Poudel D, Sthapit BR, Shrestha P, (2015) An analysis of social seed network and its contribution to on-farm conservation of crop genetic diversity in Nepal. *International Journal of Biodiversity* 2015:1—13.
47. Stone G, Flachs A, Diepenbrock C (2013) Rhythms of the herd: Long term dynamics in seed choice by Indian farmers. *Technology in Society* 36:26–38.
48. Vanloqueren G, Baret P (2008) Why are ecological, low-input, multi-resistant wheat cultivars slow to develop commercially? A Belgian agricultural "lock-in" case study. *Ecological Economics* 66(2):436–446.
49. Barbosa LM, et al. (2009) Diagnostico sobre producao de sementes e mudas de especies florestais nativas do Estado de Sao Paulo. *Informativo Abrates* 12(527).
50. Brush SB (1991) A farmer-based approach to conserving crop germplasm. *Economic Botany* 45(2):153–165.
51. Carpenter D (2005) The *in situ* conservation of rice plant genetic diversity: a case study from a Philippine Barangay. *Agriculture and Human Values* 22(4):421–434.
52. Williams DE (2004) Columbian exchange: the role of analogue crops in the adoption and dissemination of exotic cultigens. In *Encyclopedia of Plant and Crop Science* (Marcel Dekker Inc, New York), pp 292–296.
53. Duvick DN (2005) The contribution of breeding to yield advances in maize (Zea mays L.). *Advances in Agronomy*, 86:83–145.
54. Pollak LM, Salhuana W (2001) *The Germplasm Enhancement of Maize (GEM) Project: Private and Public Sector Collaboration. Broadening the Genetic Base of Crop Production* (CABI, Wallingford).
55. Burke J, Burger J, Chapman MA (2007) Crop evolution: from genetics to genomics. *Current Opinion in Genetics & Development* 17(6):525–532.
56. Blair M (2013) Mineral biofortification strategies for food staples: the example of common bean. *Journal of Agricultural and Food Chemistry* 61(35):8287–8294.
57. Ceccarelli S (2016) Increasing plant breeding efficiency through evolutionary-participatory programs. In *More Food: Road to Survival*, eds Gavazzi G, Pilu R (Bentham Science), pp 17–40.

58. Abay F, Waters-Bayer A, Bjørnstad A (2008) Farmers' seed management and innovation in varietal selection: implications for barley breeding in Tigray, northern Ethiopia. *Ambio* 37(4):312–20.
59. Zimmerer KS (1991) Managing diversity in potato and maize fields of the Peruvian Andes. *Journal of Ethnobiology* 11(1):23–49.
60. Davis D, Epp M, Riordan H (2004) Changes in USDA food composition data for 43 garden crops, 1950-1999. *Journal of the American College of Nutrition* 66:436–446.
61. Murphy KM, Reeves PG, Jones SS (2008) Relationship between yield and mineral nutrient concentrations in historical and modern spring wheat cultivars. *Euphytica* 163(3):381–390.
62. Klee HJ, Tieman DM (2013) Genetic challenges of flavor improvement in tomato. *Trends in Genetics* 29(4):257–262.
63. Provenza FD, Meuret M, Gregorini P (2015) Our landscapes, our livestock, ourselves: Restoring broken linkages among plants, herbivores, and humans with diets that nourish and satiate. *Appetite* 95:500–519.
64. Afari-Sefa V, Tenkouano A, Ojiewo CO, Keatinge JDH, Hughes Jd'A (2012) Vegetable breeding in Africa: constraints, complexity and contributions toward achieving food and nutritional security. *Food Security* 4(1):115–127.
65. Chadha ML, Mndiga HH (2007) African eggplant–from underutilized to a commercially profitable venture. *Acta Horticulturae* 752:521–523.
66. Bergamini N, Padulosi S, Ravi S, Yenagi N (2013) Minor millets in India: a neglected crop goes mainstream. In *Diversifying Food and Diets: Using Agricultural Biodiversity to Improve Nutrition and Health*, eds Fanzo J, Hunter D, Borelli T, Mattei F (Routledge, London), pp 313–325.
67. Newton AC, et al. (2010) Cereal landraces for sustainable agriculture. A review. *Agronomy for Sustainable Development* 30:237–269.
68. Witcombe JR, et al. (2005) Participatory plant breeding is better described as highly client-oriented plant breeding. I. Four indicators of client-orientation in plant breeding. *Experimental Agriculture* 41(3):299–319.
69. Sumberg J, Heirman J, Raboanarielina C, Kaboré A (2013) From agricultural research to product development: What role for user feedback and feedback loops? *Outlook on Agriculture* 42(4):233–242.
70. Spangenberg JH, Douguet J-M, Settele J, Heong KL (2015) Escaping the lock-in of continuous insecticide spraying in rice: Developing an integrated ecological and socio-political DPSIR analysis. *Ecological Modelling* 295:188–195.
71. Juma C (2011) *The New Harvest. Agricultural Innovation in Africa* (Oxford University Press, Oxford).
72. Nuijten E (2005) Farmer management of gene flow: the impact of gender and breeding system on genetic diversity and crop improvement in The Gambia. PhD Dissertation (Wageningen University).
73. Bishaw Z, van Gastel AJG (2009) Variety release and policy options. In *Plant Breeding and Farmer Participation*, eds Ceccarelli S, Bishaw Z, van Gastel AJG (FAO, Rome), pp 565–587.
74. Sanni KA, et al. (2013) Rice varietal release systems in Africa. In *Realizing Africa's Rice Promise*, eds Wopereis MCS, Johnson DE, Ahmadi N, Tollens E, Jalloh A (CABI, Wallingford), pp 79–86.
75. Elizondo Porras FI, Araya Villalobos R, Hernández Fonseca JC, Umaña Martínez K (2015) Costa Rica: Unión de Semilleros del Sur. *Community Seed Banks: Origins, Evolution and Prospects*, ed Vernooy R, Shrestha P, Sthapit BR (Routledge, London), 99–103.
76. Joshi K D et al. (2014) Regulatory reform of seed systems: benefits and impacts from a mung bean case study in Nepal. *Field Crops Research* 158:15–23.
77. Crucible Group (1994) *People, Plants and Patents* (International Development Research Centre, Ottawa).
78. van de Wouw M, Kik C, van Hintum T, van Treuren R, Visser B (2010) Genetic erosion in crops: concept, research results and challenges. *Plant Genetic Resources* 8(1):1–15.
79. Brush SB, et al. (2015) Assessing maize genetic erosion. *Proceedings of the National Academy of Science* 112(1):E1.
80. Dyer GA, López-Feldman A, Yúnez-Naude A, Taylor JE, Ross-Ibarra J (2015) Reply to Brush et al.: Wake-up call for crop conservation science. *Proceedings of the National Academy of Sciences of the United States of America* 112(1):E2–E2.
81. Fenzi M, Jarvis DI, Arias Reyes LM, Latournerie Moreno L, Tuxill J (2017) Longitudinal analysis of maize diversity in Yucatan, Mexico: influence of agro-ecological factors on landraces conservation and modern variety introduction. *Plant Genetic Resources* 15(1):51–63.
82. Giuliani A (2007) Developing Markets for Agrobiodiversity: *Securing Livelihoods in Dryland Areas* (Earthscan Research Editions, London).
83. Bellon M (2009) Do we need crop landraces for the future? Realizing the global option value of *in situ* conservation. In *Agrobiodiversity and Economic Development*, eds. Kontoleon A, Pascual U, Smale M (Routledge, London) pp 51-59.
84. Jarvis DI, et al. (2016) *Crop Genetic Diversity in the Field and on the Farm: Principles and Applications in Research Practices* (Yale University Press, New Haven and London).
85. Witcombe JR, Joshi KD, Sthapit BR, Virk DS (2011) Impact of introduction of modern varieties on crop diversity. In *Agrobiodiversity Management for Food Security*, eds Wood D, Lenné JM (CABI, Wallingford), pp 87–98.
86. Spielman DJ, Kennedy A (2016) Towards better metrics and policymaking for seed system development: Insights from Asia's seed industry. *Agricultural Systems* 147:111–122.

87. Pavoine S, Izsák J (2014) New biodiversity measure that includes consistent interspecific and intraspecific components. *Methods in Ecology and Evolution* 5(2):165–172.

88. Walker TS (2015) Validating adoption estimates generated by expert opinion and assessing the reliability of adoption estimates with different methods. In *Crop Improvement, Adoption and Impact of Improved Varieties in Food Crops in Sub-Saharan Africa*, eds Walker TS, Alwang J (CABI, Wallingford), pp 406–419.

89. World Bank (2016) Living Standards Measurement Study - Integrated Surveys on Agriculture (LSMS-ISA). Available at: http://go.worldbank.org/BCLXW38HY0.

90. Sheahan M, Barrett CB (2014) Understanding the agricultural input landscape in sub-Saharan Africa: Recent plot, household, and community-level evidence, World Bank Policy Research Working Paper WPS7014 (World Bank Group, Washington DC).

91. Hammond J, et al. (2017) The Rural Household Multi-Indicator Survey (RHoMIS) for rapid characterisation of households to inform climate smart agriculture interventions: description and applications in East Africa and Central America. *Agricultural Systems* 151:225–233.

92. Kosmowski F, et al. (2016) Varietal identification in household surveys: results from an experiment using DNA fingerprinting of sweet potato leaves in southern Ethiopia. World Bank Policy Research Working Paper. WPS 7812 (World Bank Group, Washington DC).

93. Whiteman A (2005) *Statistics on the Production and Trade of Forest Seeds and other Forest Plant Material* (FAO, Rome).

94. Okry F, et al. (2011) Organizational analysis of the seed sector of rice in Guinea: stakeholders, perception and institutional linkages. *Experimental Agriculture* 47(1):137–157.

95. Shimelis H, Laing M (2012) Timelines in conventional crop improvement: pre-breeding and breeding procedures. *Australian Journal of Crop Science* 6(11):1542–1549.

96. Galluzzi G, Halewood M, López Noriega I, Vernooy R (2016) Twenty-five years of international exchanges of plant genetic resources facilitated by the CGIAR genebanks: a case study on global interdependence. *Biodiversity and Conservation* 25(8):1421–1446.

97. Guimarães EP, Kueneman E, Carena MJ (2006) Assessment of national plant breeding and biotechnology capacity in Africa and recommendations for future capacity building. *HortScience* 41(1):50–52.

98. Walker TS, et al. (2015) *Crop Improvement, Adoption and Impact of Improved Varieties in Food Crops* (CABI, Wallingford).

99. ASTI (2016) Agricultural Science and Technology Indicators. Available at: http://asti.cgiar.org/ [Accessed 4 May 2017].

100. Nin-Pratt A (2016) Comparing apples to apples: A new indicator of research and development investment intensity in agriculture. Working Paper 1559 (IFPRI, Washington DC).

101. Chhetri N, Chaudhary P, Tiwari PR, Yadaw RB (2012) Institutional and technological innovation: Understanding agricultural adaptation to climate change in Nepal. *Applied Geography* 33:142–150.

Peninah Mwangangi holding some of the bean varieties the Kyanika women's group conserves in Kitui, Kenya, displayed in traditional gourd bowls.
Credit: Bioversity International/Y.Wachira