Mainstreaming Agrobiodiversity in Sustainable Food Systems

Scientific Foundations for an Agrobiodiversity Index

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Bioversity International is a global research-for-development organization. We have a vision – that agricultural biodiversity nourishes people and sustains the planet.

We deliver scientific evidence, management practices and policy options to use and safeguard agricultural and tree biodiversity to attain sustainable global food and nutrition security. We work with partners in low-income countries in different regions where agricultural and tree biodiversity can contribute to improved nutrition, resilience, productivity and climate change adaptation.

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In memory of

Dr Bhuwon Ratna Sthapit,

participatory plant breeder, community biodiversity management pioneer,
agrobiodiversity champion and friend to many.
May your work and passion continue to inspire us.

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Foreword

As the United Nations Decade on Biodiversity (2011–2020) reaches its mid-point, the UN Decade of Action on Nutrition has just begun (2016–2025). This five-year overlap of global action offers a rare opportunity to bring together biodiversity and nutrition in novel ways for positive benefits to both. When people think of good nutrition, and about the diverse food groups that should be in a balanced diet, they rarely think about where those foods come from. By the same token, when people think about biological diversity, they may think about our animals, plants and birds in the wild, but they may not make the link to the amazing diversity that contributes to our food systems – the awe-inspiring diversity of species and varieties of cereals, pulses, fruits, vegetables, animals and fish – which have been developed by farmers over millennia and which are adapted to local customs and to different environments. Those links between production and consumption are important to sustainable food systems in order to have the richest possible food diversity on plates, sustainably sourced from the biological diversity that underpins agricultural systems.

The Convention on Biological Diversity – with partners including Bioversity International – has spearheaded for ten years a Cross-cutting Initiative on Biodiversity for Food and Nutrition. Much progress has been made in bridging agricultural biodiversity and nutrition in these ten years, but more can be done to integrate these two agendas. Silo thinking still prevails in many cases, leaving nutrition practitioners and agricultural practitioners blind to the benefits of agricultural biodiversity to healthy, year-round diets and to resilient, adapted farming systems.

The Sustainable Development Goals provide a renewed impetus for a focus on using biodiversity for food and nutrition and linking that to the sustainability of farming systems. Mainstreaming biodiversity in sustainable food systems is vital if we are to achieve those Goals by 2030. Using biodiversity for sustainable farming systems that produce diverse, nutritious foods will contribute to the conservation of these precious resources; conserving biodiversity resources will make them available for future climate scenarios and today's nutrient needs.

For this reason, the creation of an Agrobiodiversity Index, which can help bring production and consumption together for sustainable biodiversity-based solutions could go a long way to raise awareness about the multiple links between biodiversity, healthy nutrition and sustainable food production and, thereby, help promote the multiple aspects of sustainable food systems.

Dr Braulio Ferreira de Souza Dias

Executive Secretary (2012–2016)
Convention on Biological Diversity

Preface

"In a true sense we have with us a treasure of valuable agrobiodiversity that we have not explored scientifically yet."
Narendra Modi, Prime Minister of India

The Delhi Declaration on Agrobiodiversity Management, adopted at the first International Agrobiodiversity Congress, held in November 2016, calls for "an agrobiodiversity index to help monitor conservation and use of agrobiodiversity."

The book is the first step in the process of creating such an index, which can measure agricultural biodiversity across different dimensions. The concept grew from the observation – based on a scientific paper on levels of crop diversity produced compared to levels of crop diversity imported – that juxtaposing data from very different fields connected with agricultural biodiversity can yield novel and practical insights. There is a need to measure and understand biodiversity in rapid, cost-efficient ways, going beyond just numbers, to connect also with policy decisions by countries and companies on best practices to foster diversity. Expected benefits are being able to identify and steer opportunities for change towards sustainable food systems, and being able to better measure and manage progress towards global targets such as the Sustainable Development Goals and the Aichi Biodiversity Targets of the Convention on Biological Diversity. Private companies and finance institutions are also interested in its applicability to measure the sustainability of investments, green bonds and company purchasing policies, while farmer organizations and consumer associations can use it to influence programmes and policies

There is no shortage of data. Indeed there is a huge, and growing, number of datasets on agricultural biodiversity, collected at different scales across different dimensions. The question is how to choose which to use in the Agrobiodiversity Index in order to draw insights for action. In this book, we summarize evidence on the contribution of agricultural biodiversity to four interconnected dimensions:

- Diverse, healthy diets
- Multiple benefits in sustainable farming systems
- Seed systems delivering crop diversity for sustainable food systems
- Conserving agricultural biodiversity for use in sustainable food systems

Within each dimension, agricultural biodiversity scientists reviewed the scientific literature to identify evidence for the most salient aspects of each dimension with respect to agricultural biodiversity. These aspects provide a starting point for identifying indicators for the Agrobiodiversity Index, which will be tested and validated in the months to come. The book provides an overview of evidence which scholars and practitioners alike will find useful in our joint quest to use agricultural biodiversity in food systems that are sustainable.

M. Ann Tutwiler

Director General
Bioversity International

Crop diversity on display at a market in Ecuador.
Credit: Bioversity International/F.Finocchio

1

Transformation

Agricultural biodiversity and food system sustainability

M. Ann Tutwiler, Arwen Bailey, Simon Attwood, Roseline Remans, Marleni Ramirez

KEY MESSAGES:

- Food systems need to be reformed so that they nourish people while nurturing the environment.
- Agricultural biodiversity is a source of nutritious foods which are culturally acceptable and often adapted to local and low-input agricultural systems. It is also a source of important traits for breeding resilient, nutritious crops and animal breeds.
- Agricultural biodiversity is already a key component of farming systems and breeding systems worldwide.
- The Agrobiodiversity Index will help policymakers and the private sector to assess dimensions of agricultural biodiversity to guide interventions and investments for sustainable food systems.

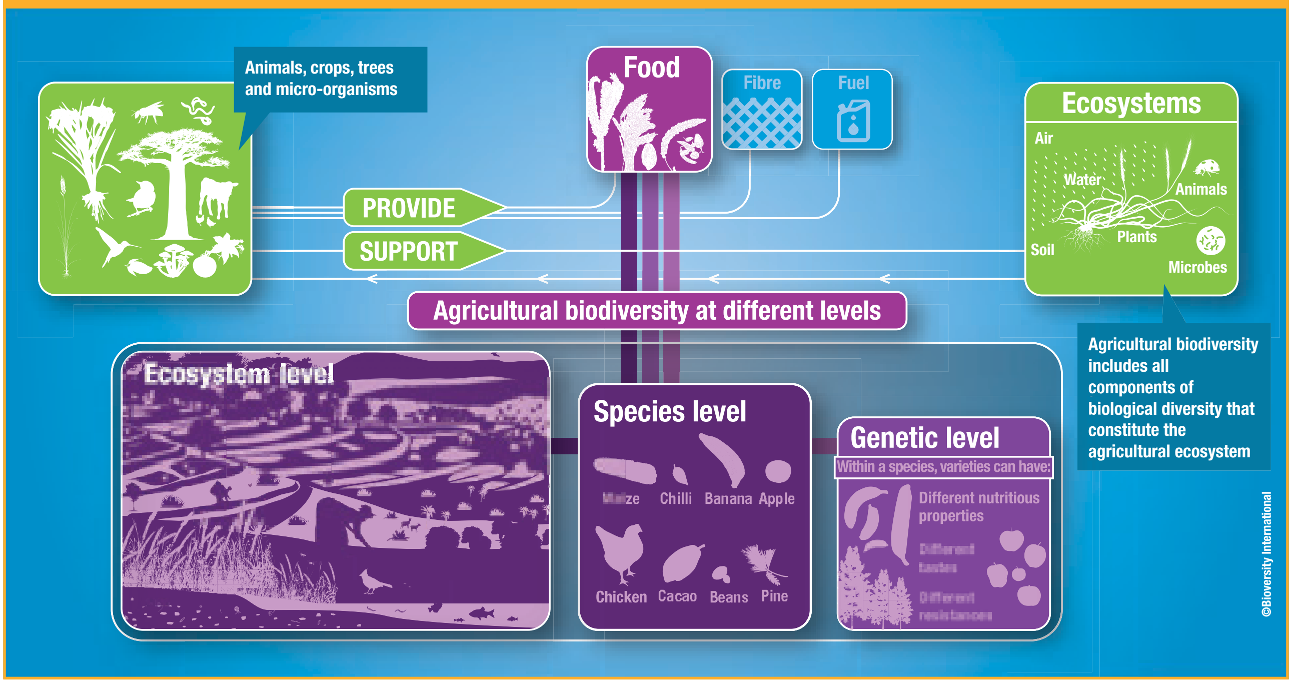
Introduction

In today's complex and interconnected world, what we eat and how we produce it are inextricably bound together. A focus on increasing food production without due concern for the environment is causing severe land and water degradation. A focus on addressing hunger without a focus on good nutrition is causing an epidemic of non-communicable diseases. A focus on increasing yields in a few staple food crops is contributing to loss of crop diversity. What we need is to be able to produce a wide variety of nutritious foods while having minimal impact on the environment – a sustainable food system. The Sustainable Development Goals, signed by 193 world leaders in 2015, recognize that these challenges are interconnected and multidimensional.

To address these complex and multifaceted problems, we need to transform our food systems both in the way we produce food and in what we choose to eat. Agricultural biodiversity (Figure 1.1) is an important resource for transforming agriculture. Agricultural biodiversity is the backbone of sustainable agricultural intensification (1, 2). For example, agroforestry, home gardens, integrated crop–livestock systems, mosaic land uses, intercropping, cover crops, integrated pest management and crop rotations all typically benefit from using agricultural biodiversity (Chapter 3). It is also a rich resource for year-round healthy, diverse diets by providing nutrient-rich species and varieties, which are often well adapted to local conditions. Increasing the number of food groups grown on farms is associated with greater diversity on the plate (Chapter 2). Households which grow a diverse set of crops are less likely to be poor than households that specialize in their crop production (3). Additionally, crop diversity reduces the probability that a non-poor household will fall into poverty and the probability that a poor household will remain in poverty (3). While agricultural biodiversity is by no means the only component needed in a sustainable food system, a sustainable food system cannot exist without agricultural biodiversity.

Using agricultural biodiversity in sustainable food systems can help to achieve multiple Sustainable Development Goals, and to meet several of the biodiversity targets set by the Convention on Biological Diversity (known as the Aichi Biodiversity Targets).[i] However, governments, the private sector and other decision-makers have no consistent way to assess and track agricultural biodiversity in sustainable food systems. Governments need to be able to identify opportunities for good investments and decisions, which satisfy human aspirations while protecting the natural resource base that underpins human well-being. Businesses too need "pragmatic but credible tools" in order to drive their practices towards sustainability (4). In short, we need metrics which can measure and compare key elements of food system sustainability. Measuring agricultural biodiversity is one powerful way to do this, since biodiversity is central to our agricultural systems, our diets, our environmental integrity and the livelihoods of farmers.

FIGURE 1.1 – What is agricultural biodiversity?



Credit: Bioversity International/P.Gallo

In this book, Bioversity International brings together scientific evidence of the role of agricultural biodiversity in creating a sustainable food system. Building on this evidence base, the book identifies a framework and candidate indicators for an 'Agrobiodiversity Index', a pragmatic and credible tool to measure and manage food system sustainability for the long term.

Drivers of change in our food systems

Recent assessments of trends and challenges driving change in food systems in the early 21st century agree that major drivers are climate change, depletion of natural resources, demographic changes and issues around food and nutrition security. These drivers – if no changes are made to our patterns of production and consumption – will increase the pressure on food systems beyond the capacity of the world to recover.

Demographic changes

The global population will grow from 7.4 billion now to about 9.3 billion people by 2050 (5). About a billion more people will live in Africa (6). The global middle class is expected to more than double in size to almost 5 billion by 2030, and two out of three people will live in a city (5). The world population is getting older; by 2100 young children will be 6% and older people 23% of the population (7).

Higher incomes, urbanization, a growing population and changing dietary patterns are driving intensified demand for increased production of food (7). This puts pressure on natural resources, and leads to high and volatile prices for commodities (rice, wheat, maize, soy, meat, oils, dairy and sugar), exacerbated by growing demand for more homogenous Western diets and for processed convenience foods (5). Both diets and agricultural systems have been greatly simplified over the past century. Within each individual country there has never been so much choice. For example, formal supermarkets in countries around the world offer avocado, quinoa and kiwi, which were not available 15 years ago. However, diets from one country to another are becoming more similar to each other, converging towards a Westernized diet based on major cereal crops, such as rice, wheat and maize, as well as sugar and oil (8). These crops increasingly dominate our agricultural production and therefore global food supplies (8). Sustained investment in producing more high-yielding starchy staples has led to a situation where of the 5,000–70,000 plant species documented as human food (Box 1.1), only three – rice, wheat and maize – provide half the world's plant-derived calories (10).

In much of the world, farmers are not benefiting from the growing demand for food. Within the agricultural sector, 800 million people live below the global poverty line (11).

BOX 1.1 – How many plant species are used for human food?

The exact number of plant species used for food is unknown and contested. The number depends on whether it includes both species found in the wild and those that are cultivated, which plant part is considered, potential and actual use, and whether species used for primarily medicinal purposes are counted. The Kew Royal Botanical Gardens *State of the World's Plants* report (9) summarizes data from 11 major databases and lists 'human food' (5,538 species) and 'medicines' (17,810 species) separately. Other authors suggest between 12,000 and 75,000 species (12, 13). A review in 2014 on 'plant diversity in addressing food, nutrition and medicinal needs' reported that "While the number of plant species used for food by pre-agricultural human societies is estimated at around 7,000 (14), another 70,000 are known to have edible parts (15). An estimated 50,000–70,000 plant species are used medicinally around the world (16, 17), of which relatively few are produced in cultivation (18)."(19, 20)

Climate change

The Intergovernmental Panel on Climate Change estimates total average global warming of over 1.3°C by 2040 (5). By 2100 it is expected to rise between 2.7°C and 3.7°C – far above the critical 2°C global target (11). Agriculture is not only affected by climate change, it is also a cause. Agriculture is responsible for about 21% of total global greenhouse gas emissions, mainly from changing land use, livestock production, and soil and nutrient management (7).

Climate change leads to changes in rainfall patterns and increases in extreme weather events across time and geography. In many of the poorest regions of the world, climate change will reduce crop yields and increase the incidence of animal diseases, leading to higher food prices (up to even 84% by 2050) (11), and insecurity for farmers, especially in low- and middle-income countries (5). In some areas – especially countries in tropical areas – rising temperatures can lead to some crops not being able to grow any more (7). Higher temperatures may affect the quality of food, with lower levels of zinc, iron and protein in some crops (7). They also lead to disruption in pollination and natural pest control, and degradation of soil and groundwater (7). Local extinctions of some fish species are expected near the equator (7, 21). In some areas, there will be new weather patterns, e.g. rains may be variable or late. Current yield-increasing methods such as using mineral fertilizers may be less effective under these new patterns (7). Climate change is expected to increase child malnutrition by 20% by 2050 (5). It will most affect rainfed smallholder farming systems in highlands and the tropics, i.e. 80% of the world's cropland and 60% of global agricultural output (7).

Depletion of natural resources

Natural resources include land, soil, water and biodiversity. Agriculture covers up to 38% of the Earth's surface (5) but 33% of the world's farmland is degraded (7). Agriculture accounts for 70% of all freshwater withdrawn (5, 7), and drives 80% of deforestation worldwide (7). The loss of forest and other wild biodiversity can lead to erosion of genetic diversity, which reduces options for breeding new plant varieties better adapted to climate change (7). The global food production system contributes around 24% of global greenhouse gas emissions (22, 23) and is the single largest user of fresh water on the planet (24). In addition, 62% of globally threatened species are negatively affected by agriculture (25). About 40% of the world's rural population lives in areas that are water scarce (7), yet demand for water is expected to rise by a further 40% by 2030. The effects of agriculture on natural resources are further exacerbated by climate change, changing diets, population growth and urbanization. Meat-rich diets drive depletion of natural resources through forest clearing for pastures and increasing methane emissions (7, 26).

Food and nutrition changes

Westernized diets put more pressure on natural resources; e.g. the production of 1kg of beef uses 12 times as much water as 1kg of wheat, and five times as much land (5, 27, 28). Modern diets are also linked to the triple burden of undernutrition, malnutrition and obesity (7). More than 2 billion people lack vital micronutrients (e.g. vitamins and minerals), and 2 billion are overweight or obese (5). Poor nutrition can lead to non-communicable diseases such as heart disease and type 2 diabetes, which are now the leading cause of death in all regions except Africa (11). In fact, 6 of the top 11 risk factors driving the global burden of disease are related to diet (6). This has real economic consequences: across Africa and Asia, the estimated impact of undernutrition on GDP is 11% a year (6). Intakes of pulses, fruits and vegetables are declining around the globe alongside a rising predominance of starches, meat and dairy (8). The supply of fruit and vegetables, nuts and seeds falls about 22% short of population requirements according to nutritional recommendations (29) with direct consequences for health.

Finding sustainable solutions

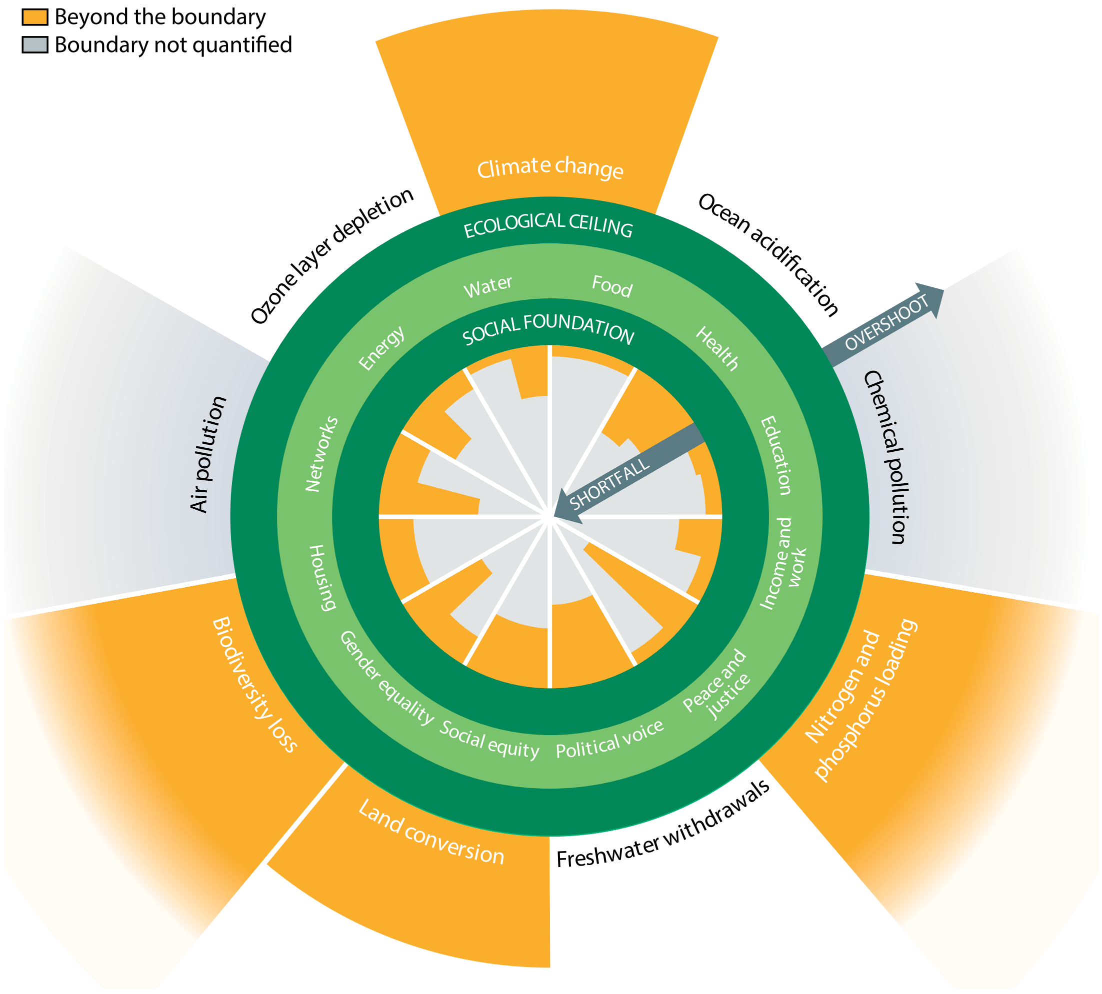
The global challenges related to the way we nourish a growing population while maintaining the health of our planet are intimately interconnected.

Sustainability is described in terms of accommodating three spheres: environmental integrity, social justice and economic growth. Addressing one or even two spheres alone often compromises the other sphere. For example, many of the great scientific strides to address food security in the 20th century, which have seen increases in the scale and short-term economic efficiencies of farming systems, did not take account of longer-term environmental or social concerns, leading to increased pressures on ecosystems and communities. Feeding the human population by improving the performance and yields of a limited number of staple crops and animal breeds, combined with intensive chemical inputs, is causing severe land degradation, air and water pollution (30, 31), and has led to a loss of biodiversity in supply chains and in farmers´ fields around the world (10, 32–34). Similarly, a focus on large-scale, intensive production of starchy crops for calories rather than for nutrition and healthy diets, has led to an epidemic of non-communicable diseases such as obesity and type 2 diabetes (35, 36). Moreover, although there has been a significant reduction of poverty globally, advances have been uneven. In many countries, even those that have reduced poverty at the national level, economic inequality is increasing and remains concentrated in rural areas (37).

To measure the environmental impacts of human activity on our planet, environmental scientists have developed the concept of 'planetary boundaries', which measure the boundaries for nine vital Earth system processes (e.g. biodiversity loss, climate change). We have to stay within those boundaries if the planet is to sustain human life in the long term (24, 38). For the social and economic spheres, social scientists have complemented these physical boundaries with social and economic boundaries – including decent jobs, access to education and gender equity – which also need to be respected for healthy societies (39). When both social foundations and environmental ceilings are respected, the world is in a "safe and just operating space for humanity to thrive" (39, Figure 1.2). We have already exceeded four planetary boundaries: biodiversity loss, climate change, land conversion and nitrogen and phosphorous loading (Box 1.2).

FIGURE 1.2 – A safe and just operating space for humanity

A safe and just operating space for humanity respects both planetary and social boundaries. The environmental ceiling consists of nine planetary boundaries, as set out by the Stockholm Resilience Centre. The social foundation consists of the eleven top social priorities identified by the world's governments in the run-up to Rio+20 (adapted from 39)



BOX 1.2 – What does it mean to exceed a planetary boundary?

The transgressing of planetary boundaries is far more than symbolic. The boundaries are scientifically derived levels of human-induced change, beyond which there is a risk of irreversible environmental change. This has serious implications for human society (38). Transgressing these boundaries creates considerable risk of moving planetary conditions outside of the relatively stable and benign conditions in which modern human civilization (including agriculture) developed and thrived. In the case of the planetary boundaries already shown to have been seriously (and potentially dangerously) transgressed, the risks and impacts include:

- Biodiversity loss: Reduction or loss of the many ecosystem services known to be generated from biological diversity, including future options for crop adaptation and collapse of pollination in some crop systems.
- Nitrogen loading: Increasing quantities of atmospheric nitrogen are converted into reactive nitrogen through human activities. Much of this reactive nitrogen is not taken up by plants, but leached into marine, aquatic and terrestrial systems as a pollutant, leading to potential and realized collapse of ecological systems (e.g. marine and coastal 'dead zones').

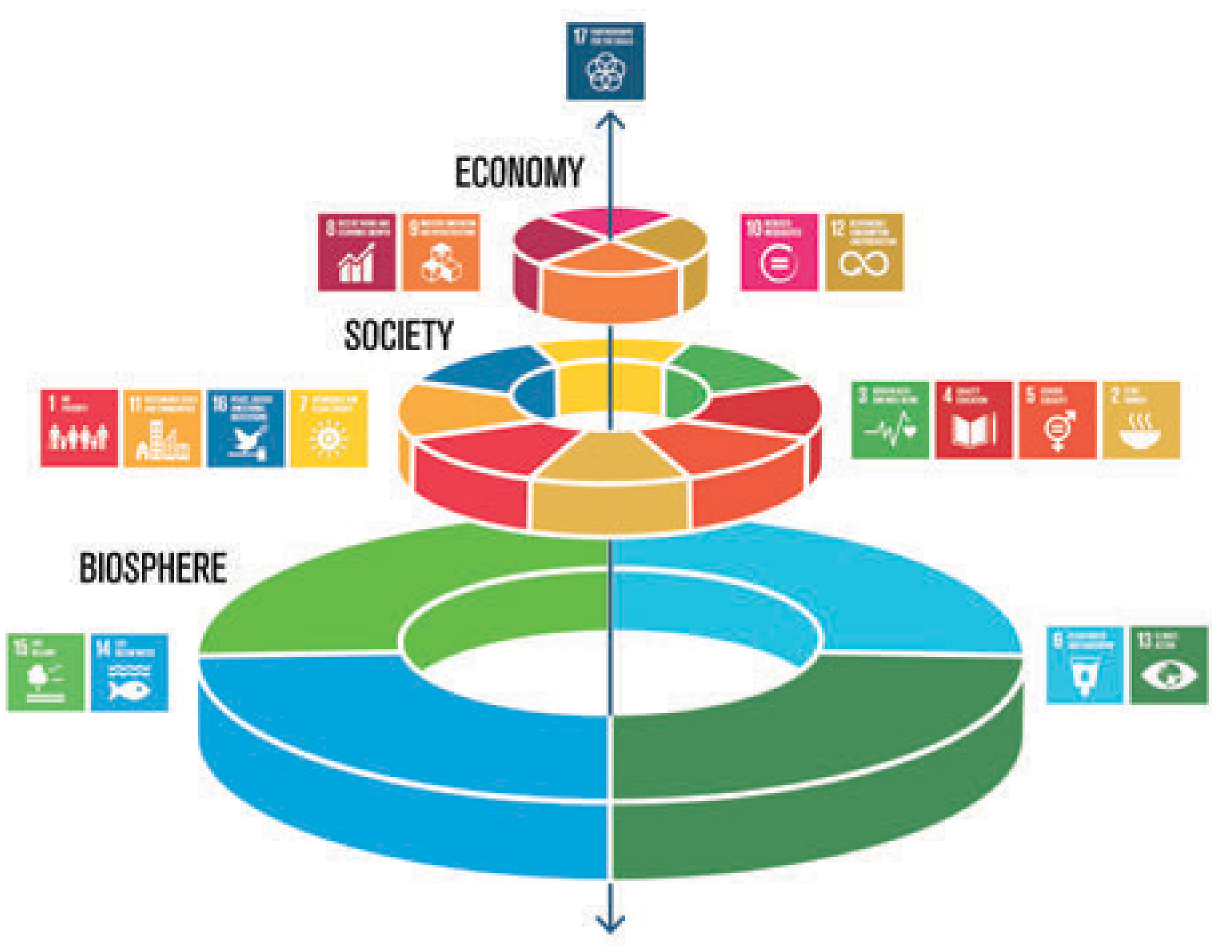
"What is required is a fundamentally different model of agriculture based on diversifying farms and farming landscapes."

International Panel of Experts on Sustainable Food Systems (40)

There is a global growing consensus that business as usual is not working, and it is time for a paradigm shift (6, 40). Solutions have to be as interconnected as the problems they seek to solve. The 2030 Agenda and its Sustainable Development Goals provide a framework for an 'integrated agenda', which means achieving multiple benefits at the same time – for example, including nutrition goals in farming systems; increasing yields without increasing the levels of inorganic and synthetic chemicals in the system; shaping landscapes which create positive synergies between wild and cultivated lands; improving environmental integrity while reducing poverty and gender inequality. The Sustainable Development Goals are indivisible and not hierarchical. However, none of the social and economic goals can be achieved if there is an inadequate natural physical resource base to sustain human life (Figure 1.3, 40, 42).

FIGURE 1.3 – A new way of picturing the Sustainable Development Goals: Linking the biosphere to sustainable and healthy food

In this representation of the Sustainable Development Goals, by the Stockholm Resilience Centre, the economy serves society, and both depend on the integrity of the biosphere. In this vision, all the Sustainable Development Goals are directly or indirectly connected to sustainable and healthy food.



Credit: Azote Images for Stockholm Resilience Centre

Rice terraces in Indonesia, a typical agricultural landscape of the region.
Credit: Bioversity International/M.Fancello

The contribution of agricultural biodiversity

One vital aspect of the biosphere resource base is agricultural biodiversity. Agricultural biodiversity is defined as "the variety and variability of animals, plants and micro-organisms that are used directly or indirectly for food and agriculture, including crops, livestock, forestry and fisheries. It comprises the diversity of genetic resources (varieties, breeds) and species used for food, fodder, fibre, fuel and pharmaceuticals. It also includes the diversity of non-harvested species that support production (soil micro-organisms, predators, pollinators), and those in the wider environment that support agro-ecosystems (agricultural, pastoral, forest and aquatic) as well as the diversity of the agro-ecosystems" (43, Figure 1.1).

Agricultural biodiversity is the result of natural selection processes (e.g. adapting to changing weather patterns or particular land characteristics) that have been interwoven with the careful selection and inventive developments of farmers, forest dwellers, hunter-gatherers, herders and fishers over millennia (e.g. selecting for taste, ease of processing or harvesting) (42, 43). Managed knowledgeably, agricultural biodiversity provides resources and processes embedded in farming systems, which allow these systems to meet current food and nutrition needs (Chapter 2), while having minimal negative impact on the environment and generating multiple ecosystem services (45, Box 1.3, Chapter 3).

BOX 1.3 – What are ecosystem services?

Ecosystem services are defined as "the benefits people obtain from ecosystems. These include services such as food, water, timber and fibre (provisioning); services that affect climate, floods, disease, wastes and water quality (regulating); services that provide recreational, aesthetic and spiritual benefits (cultural). The human species, while buffered against environmental changes by culture and technology, is fundamentally dependent on the flow of ecosystem services."

Adapted from (45) following the Common International Classification of Ecosystem Services (CICES) categorization (46)

Because agricultural biodiversity has co-evolved with farming systems and breeding systems, it is already deeply integrated within these systems. Increasing what we know about agricultural biodiversity, its components and the interactions among them can help countries to leverage their existing resources and knowledge for integrated nutrition and environmental outcomes.

Agricultural biodiversity is, however, under threat. Despite the many benefits it provides, agricultural biodiversity is being lost as:

- Farming production systems have shifted to more intensive production practices which rely on fewer varieties, genes or species (10, 31, 47, 48)
- Traditional agricultural practices and knowledge are displaced (by intensive, external input-based management practices) and undervalued
- Climate change and land-use changes accelerate land degradation
- Value chains are under pressure to provide standard products year round in any country and any season.

Conservation approaches have been developed to stem biodiversity loss (Chapter 5) and seed systems strengthened to make sure that biodiversity is not only conserved, but also available and accessible when and where it is needed by those who need it for different purposes (Chapter 4).

"At the World Health Organization, we are aware of the growing body of evidence that biodiversity loss is happening at unprecedented rates. There is increasing recognition that this is a fundamental risk to the healthy and stable ecosystems that sustain all aspects of our societies."

Dr Maria Neira, Director, Public Health, Environmental & Social Determinants of Health (49)

Using agricultural biodiversity in sustainable food systems

'Sustainable food systems' are a relatively recent concept with various definitions. In July 2014, the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security of the Food and Agriculture Organization of the UN (FAO) defined a sustainable food systems as "a food system that delivers food security and nutrition for all in such a way that the economic, social and environmental bases to generate food security and nutrition for future generations are not compromised" (50).

'Using agricultural biodiversity' is the act of intentionally taking advantage of the variety and variability of plants, animals, landscapes and even soil organisms, to achieve certain goals. Using agricultural biodiversity can take many forms. It can mean identifying which plant species or varieties contain important traits, such as salinity resistance or nutrient density, and using them to breed new varieties. At the farm level, it can refer to farming practices in which genetically distinct varieties of the same species are planted together as a mixture to increase resistance to diseases, or planting different varieties in different areas of the same farm to respond to different micro-environments. It can mean planting certain varieties of a crop because they have particular nutritional or cooking qualities. Using agricultural biodiversity might entail integrated farming systems where animals, crops and trees interact, with benefits of increased yields, lower fertilizer requirements and more food groups available for healthy diets. It can also involve adopting certain farming practices such as intercropping or crop rotations, which promote beneficial interactions among species, like the *milpa* system in Central America where beans are planted together with maize and squash, an ancient agricultural method which combines crops that are nutritionally and environmentally complementary.

At a landscape level, using agricultural biodiversity refers to creating a mosaic of different land uses – managed forest, cultivated fields, waterways, hedges and copses – to create beneficial synergies, such as water capture, pest control or pollinator habitat. It often involves matching land use to land form and soil type in order to tailor production to land capability, and in so doing reduce land degradation such as soil erosion. At the same time, diversity in the landscape can ensure that different food groups (vegetables, tree fruit, animals, staples) are produced all year round. Using agricultural biodiversity draws on the local agroecological knowledge of women and men, embodied in the development and use of certain varieties, species and landscape patterns, together with the scientific knowledge of biologists, ecologists, zoologists and agronomists, among others, to create innovation. Using agricultural biodiversity often means a focus on locally specific species, breeds and varieties, which are not well known on a global scale and are under-represented in formal research (neglected and underutilized species), because of the variety and variability that they represent in a system, and their suitability to local environmental conditions and cultural requirements.

Using agricultural biodiversity can contribute to many vital aspects of a sustainable food system, in turn contributing to realization of several interconnected Sustainable Development Goals and Aichi Biodiversity Targets (Figure 1.4).

Kyanika women's group cooking traditional food, Kitui, Kenya.
Credit: Bioversity International/P.Sands

FIGURE 1.4 – Agricultural biodiversity contributes to many aspects of a sustainable food system, in turn contributing to realization of Aichi Biodiversity Targets and Sustainable Development Goals

Aichi Biodiversity Target Icons Copyright BIP/SCB

Credit: Bioversity International/P.Gallo/A.Del Castello

Mainstreaming agricultural biodiversity in sustainable food systems

Knowledge of the value of using agricultural biodiversity is a useful first step towards food system sustainability, but to have impact, practices need to be 'mainstreamed' into other sectors.

Under the Convention on Biological Diversity, mainstreaming biodiversity is defined as: "the integration of the conservation and sustainable use of biodiversity in cross-sectoral plans such as poverty reduction, sustainable development, climate change adaptation/mitigation, trade and international cooperation, as well as in sector-specific plans such as agriculture, fisheries, forestry, mining, energy, tourism, transport and others." (51)

In practice, mainstreaming means that specific components of biodiversity (e.g. genetic, varietal, species, landscape) are integrated into other sectors for the generation of mutual benefits. Examples are: linking tourism to biodiversity for conservation and economic returns; or using diversity in agriculture to increase productivity and resilience while at the same time conserving biodiversity. Integration may be into the plans, policies and practices of natural resource sectors, such as agriculture or forestry, or other economic and social sectors, such as poverty alleviation or climate adaptation. Methods can comprise changes in policies, plans or laws, public–private partnerships or communication campaigns (See Table 1.1).

TABLE 1.1 – A framework for mainstreaming biodiversity

Integrating biodiversity…		
Integrate the components of biodiversity in order to achieve specific biodiversity goals…	**Specific components of biodiversity:** • Genetic diversity • Species and their habitats • Populations and communities • Ecological processes, functions • Landscapes, ecosystems • Ecosystem goods and services	**For specific goals:** • Minimize or mitigate risk • Restore, improve or maintain ecological integrity • Ensure ecological resilience and adaptation • Maintain ecosystem services • Improve diet diversity year round
	…into sectoral plans and policies…	
…into the plans, policies and practices of natural resource sectors, and economic/social development sectors at all levels…	**Natural resource sectors:** • Agriculture • Forestry • Fisheries, aquaculture, marine • Freshwater, rivers • Grazing, grassland	**Economic and social development sectors:** • Poverty alleviation • Health • Climate adaptation • Private businesses • Food and water security • Financial investments
		…using a variety of methods
…through approaches that rely on changes in policies and plans, on economic instruments and on education, among other methods.	**Policy and plans:** • Reform or create policies, plans, laws • Create protected areas, buffer zones, corridors • Modify management plans and practices • Incorporate into strategic environmental assessments • Incorporate into spatial and land-use planning • Public–private partnerships • Market-based certification • Voluntary best practice	**Economic instruments, education, incentives, partnerships:** • Economic valuation • Payments for ecosystem services • Communication, education • Biodiversity offsets

Adapted from (52)

Mainstreaming agricultural biodiversity in food systems contributes to their sustainability and enables policymakers to make progress toward their commitments to the Sustainable Development Goals and the Aichi Biodiversity Targets. Governments make a difference through the food and agricultural policies they adopt. Corporations make a difference through the business models they select. Given the right policy environment, together with appropriate management actions and information, from the same starting point, different results are possible (Box 1.4). Policies and actions matter.

BOX 1.4 – Illustration of the effects of policies and institutional arrangements on outcomes

An analysis of the nexus between food security and biodiversity conservation in two distinct agricultural systems in the same geographical area in Brazil (Mato Grosso) noted that the interplay between institutions and policies from household to global scale resulted in one system with a monoculture of soybean and both low food security and low biodiversity; the other with a vibrant patchwork of family farms with various land-use types, and higher food security and biodiversity.

Although the two landscapes shared the same climate conditions, regional and national governments and regulatory frameworks, what made a difference was how these interacted with global, landscape and household institutions. The interactions between different sets of policies and social institutions at different scales allowed the two different outcomes to emerge. At the global level, in the monoculture case, the forces of commodity markets and rise of meat and biofuels predominated; in the family farms, it was demand for sustainably produced and socially equitable foods. At a regional level, for the monoculture, policy drivers were public financing for export commodity production (e.g. land, credit, subsidies); for the family farms, main drivers were Brazil's 'Zero Hunger' policies and investment in family farming (e.g. credit and market access). At the landscape level, monocultures were shaped by a concentration of wealth among a few producers; the family farms were shaped by marketing cooperatives, access to inputs and local market development. Finally, institutional drivers at a household level for the monoculture were access to chemical inputs and markets, and increased household income; for the family farms, they were access to inputs, access to knowledge and more stable household incomes.

The case study highlights how the interplay of multiple scale policies and management actions can influence biodiversity and food security outcomes.

Challenges of mainstreaming agricultural biodiversity

While the potential benefits are multiple, mainstreaming agricultural biodiversity in food systems is easier said than done.

First, using agricultural biodiversity is not a 'one size fits all' solution. On the contrary, it is complex. It is about the diversity of varieties, species and systems, and how to manage such a range of options for multiple objectives – income generation, nutrition, sustainable natural resources and risk mitigation. Mainstreaming agricultural biodiversity therefore requires a systems approach, which recognizes the connectivity among elements, multiple viewpoints and the multi-functionality of food systems.

Second, there is a clear tension between specialization for increasing productivity, cost-efficiency and reaching economies of scale, and diversification for risk mitigation and stability (Box 1.4). Specialization, with intensified production geared towards local, national or international markets, can foster transitions out of poverty and boost local economic development. But important trade-offs may exist in terms of livelihood security, gender equity and landscape resilience. For example, what has been called the 'curse of the cash crops' (54) points to how specialization in high-value crops for sale (which has long been a major development strategy) can lead to negative effects on food and nutrition security, thereby limiting sustainable pathways out of poverty (54–57). In contrast, livelihood and landscape diversification help minimize production and commercial risks, and smooth out income flows throughout the year (58). Crop diversification has been found to decrease the likelihood of falling into or remaining in poverty (3). Balancing the continuum between diversification and specialization is a critical consideration in livelihoods and landscape development.

Third, mainstreaming diversity across the food system requires new ways of cross-sectoral working. While an increasing number of government and private sector departments are embracing multidisciplinary approaches (e.g. Mexico, see page 15), the successful coordination and implementation of such efforts remains a challenge. Sector accountability and reward lines may not favour them working together and there may be competition among sectors for influence and resources.

Additionally, the way different sectors approach problems may be incompatible. For example, nutritionists generally are trained in a clinical tradition, and nutrition is often housed with the Ministry of Health, so a purely health focus will lack integration with agriculture and tend to overlook the role of food diversity and agricultural biodiversity in combatting malnutrition. Another example is the jurisdiction between Ministries of Agriculture and Environment (and sometimes Forestry) for lands falling under them. Different ministries will see plant diversity (such as the wild relatives of crops) in very different ways, leading to different expectations about policies and management regimes.

A fourth challenge for policymakers is current common measures of success. Success is usually measured within sector (e.g. nutrition outcomes, production outcomes or environment outcomes) without considering negative effects (or indeed positive synergies) on other sectors. In reality, policymakers have to engage in trade-offs and balancing acts among sector goals. (59, Box 1.5)

BOX 1.5 – Worked example. The wins and losses en route to zero hunger

In sub-Saharan Africa, ending hunger (Goal 2) interacts positively with several other goals – including poverty eradication (Goal 1), health promotion (Goal 3) and achieving quality education for all (Goal 4). Addressing chronic malnourishment is ‘indivisible’ from addressing poverty. Tackling malnourishment reinforces educational efforts because children can concentrate and perform better in school. Not addressing food security would counteract education, when the poorest children have to help provide food for the day.

Food production interacts with climate-change mitigation (Goal 13) in several ways, because agriculture represents 20–35% of total anthropogenic greenhouse-gas emissions. Climate mitigation constrains some types of food production; in particular those related to meat (methane release from livestock constitutes nearly 40% of the global agricultural sector’s total emissions). Yet food production is reinforced by a stable climate. Securing food from fisheries is also reinforced by protecting the climate, because that limits ocean warming and acidification.

Finally, in some parts of sub-Saharan Africa, promoting food production can also constrain renewable-energy production (Goal 7) and terrestrial ecosystem protection (Goal 15) by competing for water and land. Conversely, limited land availability constrains agricultural production.

The difficulty is compounded by large evidence gaps on the dynamic links between elements of a food system and long-term nutrition and sustainability outcomes.

Examples of successful mainstreaming

Despite these challenges, however, mainstreaming of agricultural biodiversity (i.e. the integration of agricultural biodiversity in other sector-specific plans) can be done.

Mainstreaming agricultural biodiversity into nutrition programmes

Brazil has made progress in promoting agricultural biodiversity for improved nutrition by taking advantage of the horizontal and cross-sectoral governance mechanisms already in place under the Zero Hunger Strategy umbrella and strategically targeting relevant public policies and instruments that can facilitate agricultural biodiversity mainstreaming. Public policies – such as the National School Meals Programme and the Promotion of Socio-biodiversity Product Chains among several others – provide entry points for potentially improving nutrition or livelihoods with links to native agricultural biodiversity. Results include new dietary guidelines that take into account healthy diets derived from socially and environmentally sustainable food systems. The guidelines support multiple small retail channels, including those using organic and agroecological methods, and family farming. Further outcomes can be seen in the national budget for 2016–2019, which includes many objectives, targets and initiatives related to the sustainable use of biodiversity for food and nutrition (e.g. promoting biodiversity products in public purchases from family farming) (60).

Mainstreaming agricultural biodiversity into agricultural production

UN Environment from 2004 to 2014 assisted 47 countries in Africa, Asia and Latin America to mainstream agricultural biodiversity conservation and sustainable use in the agriculture production sector. The projects were implemented in biodiversity-rich areas with globally significant agricultural ecosystems and where agricultural biodiversity is central to the livelihood strategies of small-scale farmers, rural communities and indigenous peoples. Projects demonstrated sustainable agricultural management practices that directly contributed to the conservation and sustainable use of agricultural biodiversity on 1,254,564ha of land. As a result of the mainstreaming interventions, the governments of partner countries developed supportive strategies and policies and regulatory frameworks that address the mainstreaming of agricultural biodiversity in different ways (61). For success in integrating biodiversity in agricultural production systems, partnerships and community engagement have been found to be fundamental (62). Partnerships need to be between different institutions (e.g. private sector, research, national governments) and between different disciplines (e.g. ecology, conservation, breeding, human health). Community institutions, such as farmer organizations and women's associations, make sure that actions reflect local needs and are grounded in local context (62).

Mainstreaming conservation of agricultural biodiversity across sectors of national government

Mexico is a federal republic and most biodiversity issues are federal matters with regulations generated at the federal level but implemented and managed by the state and local governments. The Secretariat of Environment and Natural Resources is responsible for the conservation and sustainable use of biodiversity. The Secretariat of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA) has functions which influence the conservation of biodiversity at three levels: ecosystem, species and genetic diversity. To mainstream biodiversity into cross-sectoral policies, interdepartmental and crosscutting commissions for biodiversity and sustainable development were put into action with mostly different functions: one agency, the National Commission for Knowledge and Use of Biodiversity (CONABIO) charged with information and knowledge generation; one commission, chaired by the Head of SAGARPA and including representatives of the Secretaries of State to coordinate rural development interagency participation from the whole country and boost concurrent regional projects for rural development; and the third, a large, broad-based Mexican Council for Sustainable Rural Development, with representatives from most national sectors (including rural, agriculture and social) and private sectors, as well as academia and NGOs, charged with an advisory role to the federal government. These structures provide an important opportunity to internalize the value of the natural capital of Mexico in all activities of the public sector and of society at large (63).

Picking *Garcinia indica* from trees in the forest near a village of the Western Ghats, India. *G. indica* has a distinctive flavour and medicinal properties. Its dried rind is used as a flavouring agent, while the seeds are a rich source of an edible fat. As a wild tree, it has no need of irrigation, pesticides or fertilizers. Of the 35 species of *Garcinia* reported in India, seven are endemic to the Western Ghats region. However, unsustainable harvesting is common and causing rapid erosion of valuable types.
Credit: Bioversity International/E.Hermanowicz

The Agrobiodiversity Index

Governments, businesses and investors seeking to drive food system practices and policies towards sustainability need a way to visualize the links between different elements of a food system at various scales and time frames, in order to make decisions on ways to sustainably achieve nutrition and environmental goals. Bioversity International, with a wide range of partners, is developing an 'Agrobiodiversity Index' to help policymakers and other interested parties to assess dimensions of agricultural biodiversity in order to guide interventions and investments for food systems that are sustainable and nutritious. The Index will:

- Be actionable, helping different stakeholders understand where best to intervene for multiple outcomes, along a desired pathway towards sustainability
- Simplify complexity, guiding policymakers to balance long- and short-term goals in situations of multiple sectors and multiple stakeholders in order to see promising intervention points for sustainable and healthy outcomes
- Integrate multiple disciplines and sectors, and the needs of different stakeholders from farmers to economists, nutritionists and social development practitioners
- Be based on scientific principles and evidence to make sure that analyses are as robust and rigorous as possible
- Be subject to iterative improvements based on review, user feedback and scientific advancements.

This book outlines the proposed dimensions of the composite Agrobiodiversity Index:

- Healthy, diverse diets
- Sustainable farming systems
- Diversity-supplying seed systems
- Conservation of agricultural biodiversity

Each dimension represents well-researched systems in their own right – nutrition systems, production systems, seed systems and conservation systems – but which are: (1) rarely considered together and (2) often not considered in terms of the multiple roles of agricultural biodiversity. Agricultural biodiversity can be a potent way to link these systems and leverage synergies among them.

The first two dimensions address one key aspect of a sustainable food system: how to integrate issues of consumption and production. We take these as the starting point of this book. From the consumption side, our interest is in when and how agricultural biodiversity can contribute to attaining healthy and diverse diets, which provide the basis for good nutrition status. From the production side, the focus is on the role of agricultural biodiversity in supporting production systems that provide not only high yields, but also multiple benefits, such as cultural values, environmental integrity and human welfare (64). We also explore components, such as on-farm biodiversity, which can be sources simultaneously of healthy, diverse diets and multifunctional farming systems, not to mention often supporting sociocultural identity and heritage.

To support the coupled needs of diets and farming systems, agricultural biodiversity has to be made available and accessible to potential users and adequately conserved. From this, emerge the third and fourth dimensions of the Index: diversity-supplying seed systems and conservation of agricultural biodiversity. Seed systems address issues of how seeds and other planting materials get to where they are needed to support nutritious, healthy diets and multifunctional production landscapes in sufficient quantity, quality and diversity. For conservation, the focus is on what diversity needs to be conserved to support sustainable food systems, how and where it should be conserved, and who needs to play a role in conserving it.

The authors of the book take the country as the main unit of analysis.[ii] However, the vision of the Agrobiodiversity Index is that it be designed with the flexibility to be tailored to the needs of other stakeholders (such as the financial sector, businesses or companies) at different scales and levels.

Each of the following four chapters outlines evidence of the role of agricultural biodiversity in one dimension of the Index, and any existing evidence gaps that need to be filled. The intention is to draw on a wide range of literature to present the core ideas around each dimension rather than conduct and present a systematic review or meta-analysis. Given the different nature of each dimension, each chapter focuses on different components and scales of agricultural biodiversity (Table 1.2).

TABLE 1.2 – Summary of components of agricultural biodiversity covered in each chapter

Chapter focus	Components of agricultural biodiversity addressed	Key areas to consider
Healthy, diverse diets	All diversity used for food – cultivated plants, domesticated animals, aquatic species and foods from the wild. Both among-species and within-species diversity	Nutritional composition of food biodiversity Food biodiversity on farm Food biodiversity in the wild Food biodiversity in markets Market diversity
Multiple benefits from sustainable farming systems	The diversity among and within cultivated plants, and their interactions with other elements of biodiversity (e.g. pollinators, soil fauna), including interactions between cultivated and wild biodiversity. Levels of diversity from genetic and species to farm and ecosystem	Agricultural biodiversity and… - Soil erosion control - Pest and disease control - Pollination - Wild biodiversity conservation - Soil quality - Yield of crops for food - Resilient agricultural landscapes
Diversity-supplying seed systems	Crop and food tree diversity, among and within species	Seed access Seed production and distribution Seed innovation Seed regulation
Conservation of agricultural biodiversity	The major components of farming systems for food – food crops and their many varieties, and domesticated animals. Both among-species and within-species diversity	On-farm conservation *In situ* conservation in the wild *Ex situ* conservation

The authors lay out the evidence for the role of agricultural biodiversity in each dimension and describe evidence of key areas to consider. They also reflect on how to assess and track each of these essential areas, proposing a set of candidate indicators for the Agrobiodiversity Index, selected through application of the criteria developed by the Biodiversity Indicators Partnership (BIP) (65): [iii]

- Scientifically valid: (a) there is an accepted theory of the relationship between the indicator and its purpose, with agreement that change in the indicator does indicate change in the issue of concern; (b) the data used is reliable and verifiable
- Based on available data so that the indicator can be produced regularly over time
- Responsive to change in the issue of interest
- Easily understandable: (a) conceptually, how the measure relates to the purpose, (b) in its presentation, and (c) the interpretation of the data
- Relevant to users' needs
- 'Championed' by an institution responsible for the indicator's continued production and communication
- Used: for measuring progress, early warning of problems, understanding an issue, reporting, awareness raising, etc.

The final chapter draws on the evidence presented to propose a framework for the Agrobiodiversity Index and compile a first set of candidate indicators for discussion with stakeholders. This chapter outlines the processes and inputs, including stakeholder conversations, analyses and indicator refinement, followed to develop this cost-efficient, robust and usable tool for all those seeking increased food system sustainability.

Conclusions

"...we highlight the close link between climate change, sustainable agriculture and food and nutrition security with the message that 'The climate is changing. Food and agriculture must too.' Without concerted action, millions more people could fall into poverty and hunger, threatening to reverse hard-won gains and placing in jeopardy our ability to achieve the Sustainable Development Goals."

Ban Ki-moon, World Food Day statement, October 2016

It is imperative for the world to change practices to get on a more sustainable route. The 2030 Agenda for Sustainable Development recognizes this necessity and suggests integrated targets which bring together indivisible goals of economic, social and environmental progress. To tackle these, new approaches are needed. In the context of sustainable food systems – which deliver food security and nutrition for all in such a way that the economic, social and environmental bases to generate food security and nutrition for future generations are not compromised – agricultural biodiversity is a key resource. While agricultural biodiversity alone is not the sum and breadth of a sustainable food system – many other elements are needed, such as sustainable agronomic practices and socially just working conditions for agricultural workers – it is also true that it is impossible to have a sustainable food system without agricultural biodiversity, since it represents the foundations of agriculture.

Although there have been calls now for over a decade to mainstream biodiversity into nutrition, farming and forestry, policymakers often find it difficult to identify what that means in practice and how to intervene. Many indicators exist for individually or separately measuring biodiversity conservation, production system effectiveness, ecosystem health and human nutrition (66). The Agrobiodiversity Index is being developed as a tool for integrating an evidence-based selection of these indicators into one composite index which offers visualization and assessment across multiple aspects of a sustainable food system. No other index exists which integrates agricultural biodiversity issues across genetic resource management, production and consumption in food systems. It will combine large-scale quantitative data sources, with granular crowdsourced data, qualitative insights and assessments of policies and programmes in order to identify leverage points for action. The Agrobiodiversity Index will be designed to be flexible to the needs of different users. It will help countries to track progress towards several Sustainable Development Goals and Aichi Biodiversity Targets. It will also be designed for companies and for public and private investors interested in more sustainable practices in business and finance. The index can also provide information to farmer and consumer associations, to inform their decisions about sustainable practices or as a basis for a call to collective action.

Notes

[i] The Convention on Biological Diversity is one of three 'Rio Conventions' along with the United Nations Convention to Combat Desertification and the United Nations Framework Convention on Climate Change. The three conventions derive directly from the 1992 Earth Summit. Each instrument represents a way of contributing to the Sustainable Development Goals of Agenda 21 (the action plan of the United Nations with regard to sustainable development). The three conventions are intrinsically linked, operating in the same ecosystems and addressing interdependent issues. While not addressed directly in this book, agricultural biodiversity is also a component of efforts to combat desertification and tackle climate change challenges (through both mitigation and adaptation). See www.cbd.int/rio/

[ii] We recognize that environmental and agricultural issues are rarely confined to national borders – species populations can span many countries, environmental problems do not respect country borders, and countries are interdependent when it comes to sharing genetic resources. Furthermore differences in country size – e.g. between China and Costa Rica – can make country comparisons challenging. However, since most policy is taken at national level, we have selected this as the best unit for interventions.

[iii] The Biodiversity Indicators Partnership is a global initiative to promote and coordinate the development and delivery of biodiversity indicators for use by the Convention on Biological Diversity (CBD) and other biodiversity-related conventions, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), the Sustainable Development Goals (SDGs) and national and regional agencies. The Partnership currently brings together over 50 organizations working internationally on indicator development to provide the most comprehensive information on biodiversity trends. See www.bipindicators.net/.

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Traditional Sri Lankan dishes, paired with the vegetables used.
Credit: Bioversity International/S.Landersz

2

Food biodiversity for healthy, diverse diets

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Food

KEY MESSAGES:

→ Food biodiversity – the diversity of plants, animals and other organisms used for food, both cultivated and from the wild – is a critical element in response to global malnutrition, and it supports sustainable food systems.

→ Food biodiversity reaches consumers through two principal pathways: (1) consumption via own production or gathering from the wild and (2) purchase of wild or cultivated species.

→ The nutrient content between different species, or different varieties or breeds of the same species, can vary a thousandfold. This information can be used to maximize the nutritional adequacy of diets.

→ Improved availability, accessibility, affordability and acceptability of food biodiversity are key factors for achieving better diets.

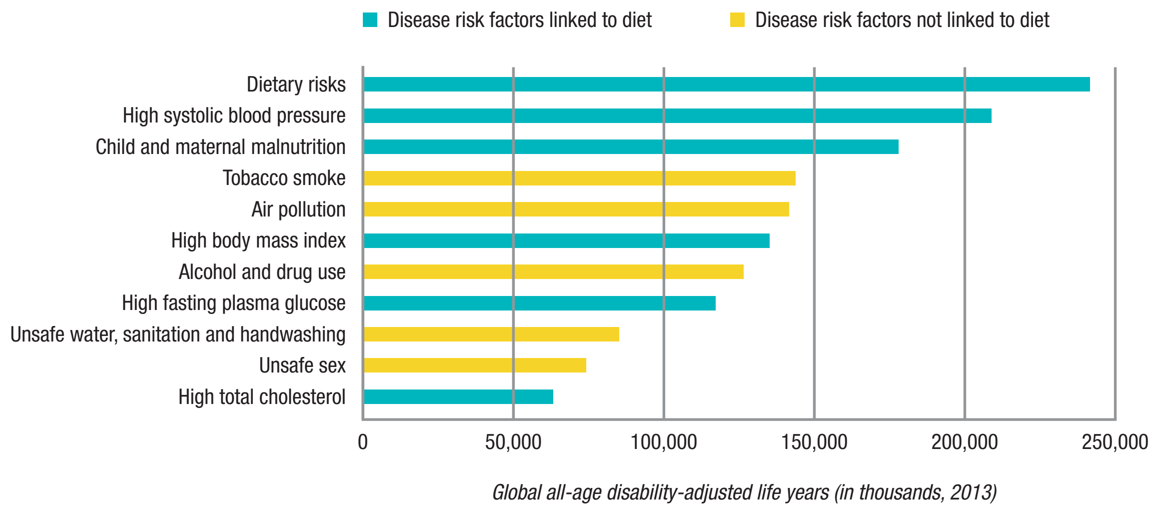
Introduction

One of the world's greatest challenges is to secure universal access to sufficient, healthy and affordable food that is produced sustainably. Current nutrition trends do not reveal a situation in which populations are well nourished, and the sustainability of how we produce, distribute and consume food is also a subject of concern. Serious levels of both undernutrition and overweight/obesity are reported for 57 out of 129 countries (1). Two billion people are overweight or obese, while two billion people lack essential vitamins and minerals needed for adequate nutrition. Malnutrition in children, which is in part linked to insufficient diets, is the underlying cause of half of all deaths among under-fives (2). Often malnutrition extremes, such as stunting in children and overweight adults, occur concurrently. Countries experiencing multiple forms of malnutrition, including under-five stunting, anaemia in women of reproductive age and adult overweight, are considered the new normal (3). At the same time there is an alarmingly fast-paced increase in non-communicable diet-related diseases (e.g. diabetes, hypertension) (4). One of the principal causes of these multiple burdens of malnutrition is poor diet. Diet-related factors are now the number one risk factor of morbidity and mortality globally (4) (Figure 2.1).

The economic toll of poor diets is also rising. The loss attributable to diet-related chronic disease has increased from 0.3–2.4% of gross domestic product (GDP) in Asia in the late 1990s to 11% in Africa and Asia in the 2010s (1). Improving diets is therefore an important health and economic goal for all countries.

Connected to the problem of addressing all forms of malnutrition is the issue of the environment. Sustainability issues within the food system relate to how we currently produce, transport, package, handle and consume food, including food waste. Our current food system is a major contributor to large environmental impacts, including biodiversity loss, greenhouse gas emissions, contamination and shortages of water, ecosystem pollution, and land degradation (6–9). Diets are influenced by the food system and its political, legal and institutional environment (10). When seeking to improve diets, a focus on food systems and the food environment is therefore key, particularly as regards the availability, accessibility, affordability and acceptability of healthy, sustainably produced food choices (3, 5). There is increasing evidence that both health and environmental benefits can be achieved by changing dietary patterns. Such a win–win is possible by transitioning toward more plant-based diets in line with standard dietary guidelines (11). Doing so could

FIGURE 2.1 – Diet-related risks are among the top eleven risks driving the global burden of disease



Source: Global burden of disease study 2013 adapted (5)
Note: The graph shows global disability-adjusted life years (DALYs) attribuited to level 2 risk factors in 2013 for both sexes combined.

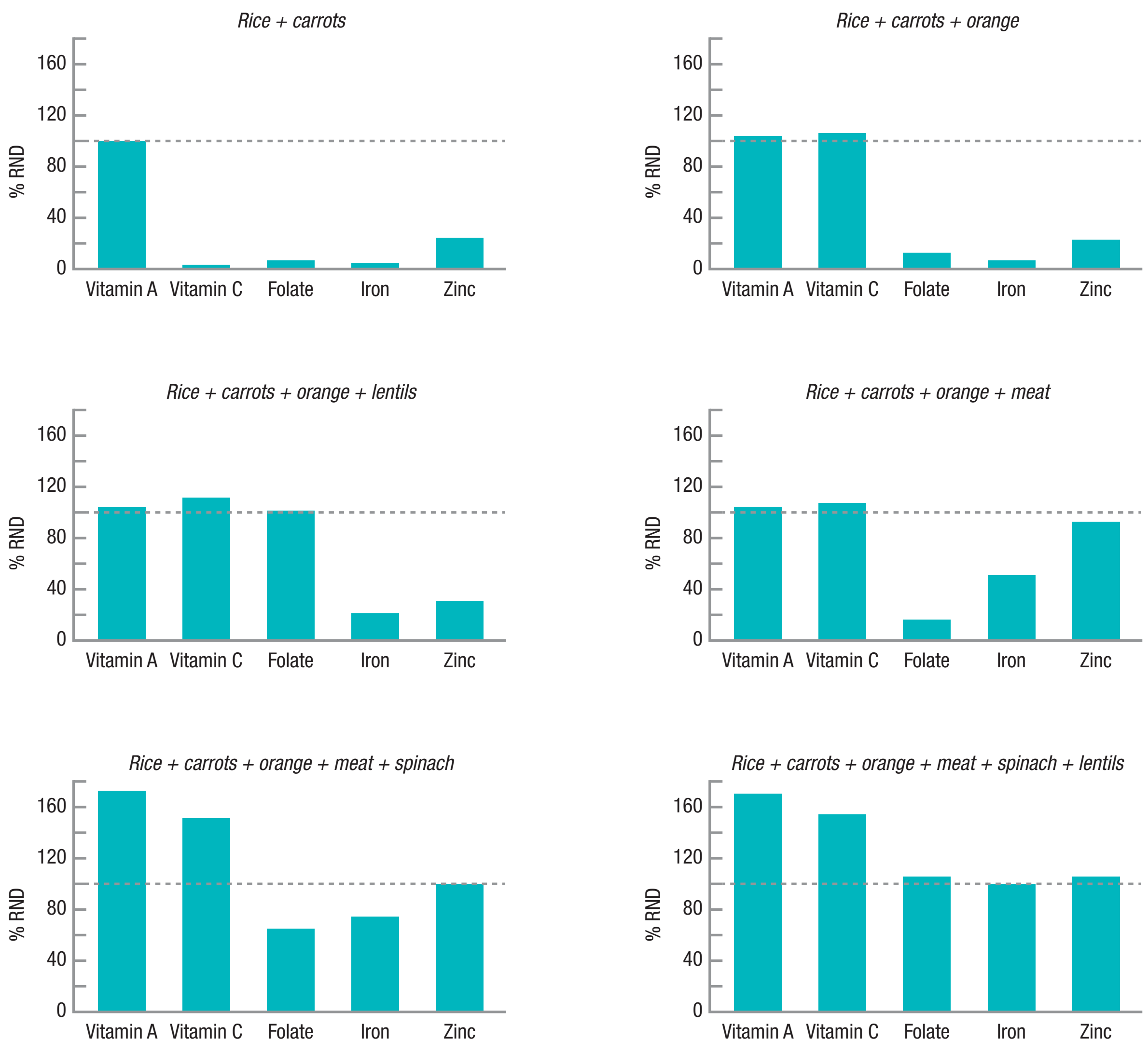
reduce both global mortality by 6–10% and food-related greenhouse gas emissions by 29–70% compared with a reference scenario in 2050 (11). Toward this end, recommended diets include a minimum of five portions of fruits and vegetables, less than 50g of sugar, a maximum of 43g of red meat, and an energy content of 2,200–2,300kcal per person per day, depending on the age and sex of the population. Tapping into the planetary wealth of diverse fruits, vegetables, pulses and grains, particularly nutrient-dense varieties among these food groups, holds the potential to generate the desired win–win scenario for people and the planet.

Food biodiversity and components of a healthy diet

In this chapter we use the term 'food biodiversity' as defined in a recent publication by FAO and Bioversity International (12) as "the diversity of plants, animals and other organisms used for food, covering the genetic resources within species, between species and provided by ecosystems". The contribution of food biodiversity to healthy and diverse diets can be measured at different levels. The highest level is food group diversity (e.g. cereals, dark green leafy vegetables and fruit), the next level is diversity within a food group (e.g. mango, banana and apple) and the lowest level considers diversity within a species (e.g. types of cultivated apple, such as Golden Delicious and Fuji, and also unnamed local and wild varieties).

Dietary guidelines around the world recommend a varied diet rich in fruits, vegetables, whole grains, nuts, seeds and legumes for optimal health (13). A diverse diet increases the likelihood of consuming adequate amounts of the full range of nutrients essential to human health (14). Figure 2.2 demonstrates this concept, showing how nutrient adequacy of the diet is improved as individual nutrient-dense foods are added to a meal.[i]

FIGURE 2.2 – Recommended nutrient density of a white rice diet improves with each addition of another type of food



Source: (15). RND = Recommended nutrient density

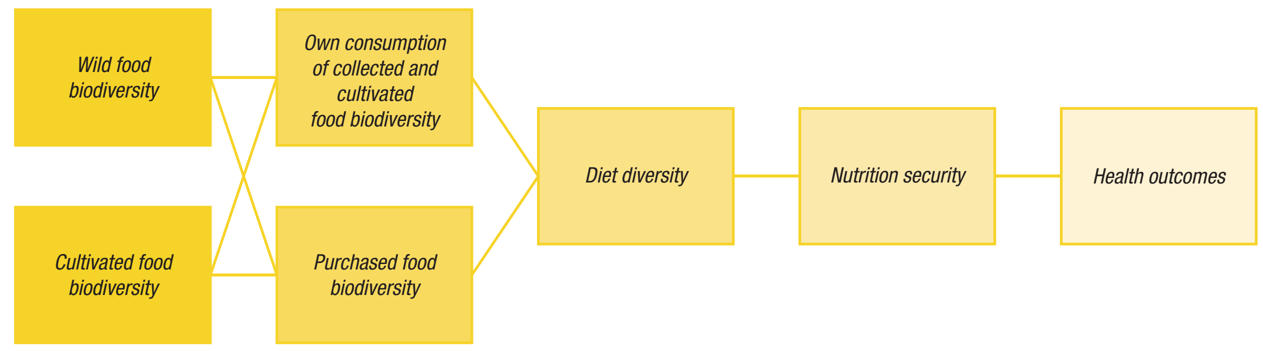
In the illustrative example in Figure 2.2, white rice is the first element of food biodiversity, carrot becomes the second food element, followed by orange, meat, spinach and lentils. Each of these foods represents one distinct element of food biodiversity. They are used collectively in the example to demonstrate how consumption of a diverse range of nutritionally distinct foods can fulfil nutrient needs. A common practice to simplify both measurement and messaging for consumers is to group foods with similar nutritional profiles into categories such as 'fruit', 'vegetables' or 'nuts and seeds'. The term 'diet diversity' is used in a general way to portray this concept. In many dietary guidelines, carrots and spinach might both be considered 'vegetables' Other definitions of food groups might categorize them in two different groups: vitamin A-rich vegetable (carrot) and dark green leafy vegetable (spinach). From the perspective of consumption of food biodiversity, they would be considered as two unique species in the diet.

Diet diversity is usually measured by counting food groups eaten in a certain time period. But this measure cannot provide a full picture of food biodiversity. For example, one can obtain information on the percentage of the target population that consumed 'fruit' in the previous 24 hours, but one would not necessarily know the intra-food group diversity consumed (e.g. banana, apple or orange) or how many species contribute to the food group and during which time periods of the year. It is even more difficult to gain information within the species, i.e. on the breeds, varieties or cultivars consumed.[ii] The implication of this is that most research uses dietary intake metrics based on diet diversity, which is not a perfect assessment of the full potential of food biodiversity, but does in an aggregate form represent consumption of diverse species.

This chapter will explore the evidence – as well as unmet potential for – food biodiversity, both cultivated and gathered from the wild, to improve healthy diet choices year round.

A balanced meal prepared during a cooking demonstration in Vihiga County, Kenya, by a group of caregivers trained in innovative dietary diversification. The meal consists of carbohydrate in the form of a rice–potato mixture, protein-rich beans, and a vitamin-rich mixture of vegetables (cowpea and amaranth leaves). Other ingredients used to enrich the meal are tomatoes, oil and iodized salt.
Credit: I.Otieno

FIGURE 2.3 – Two principal pathways leading from food biodiversity to diet diversity



Credit: Bioversity International

From food biodiversity to healthy, diverse diets: two principal pathways

Food biodiversity reaches consumers through two principal pathways: (1) consumption via own production or gathering from the wild, and (2) purchase of wild or cultivated biodiversity (Figure 2.3). We use these two principal pathways and the lenses of availability, accessibility, affordability, acceptability, gender and enabling environment to examine the contribution of food biodiversity to diet diversity.

The evidence for improving diets using food biodiversity

Food-based approaches to addressing malnutrition focus on food, rather than powders or pills, as the vehicle for supplying vital nutrients. Such approaches are considered among the most appropriate long-term and sustainable solutions to improving diets and nutrition (16). First, when we consume a food, we are consuming more than just the sum of its known nutrients, as foods may contain cancer-fighting antioxidants, fibre and many other beneficial substances that science is only beginning to discover. Second, there are important chemical interactions that occur when different food items are consumed together, such as the need for some fat in the diet to absorb vitamin A, or vitamin C-rich foods boosting the ability to absorb iron in foods. Synergistic interactions among nutrients and non-nutrient factors in different foods may convey further health and nutritional benefits (17–19). Third, certain foods, most notably fruits and vegetables, are now being promoted for intrinsic health benefits rather than focusing only on the known nutrients they provide (20). Last, a pure nutrient focus has led to some very misleading claims about 'healthy' foods (e.g. fortified breakfast cereals) and misguided messages to the public about the constituents of a healthy diet. For these reasons, a food-based rather than nutrient-driven approach is strongly advocated as an appropriate solution to alleviate the rise in diet-related non-communicable diseases, overweight and obesity (20).

Edible plant, animal and fish biodiversity can support nutrition through the availability and consumption of a wide variety of nutrient-rich foods (21, 22). Biodiversity has been explicitly recognized as a fundamental principle in recent versions of a number of national and regional dietary guidelines, including the Mediterranean Diet Pyramid (23), and the new Nordic (24) and Brazilian (25) dietary guidelines.

In addition to diversity across plant and animal species, there are important and significant nutritional differences within species. In the following sections, we first explore the evidence of the nutritional potential of within-species and between-species diversity for higher quality diets. We then discuss the linkages between cultivated and gathered diversity and diet diversity, and between food biodiversity in markets and diet diversity. We then summarize the evidence of policies and institutions that work to enhance the use of food biodiversity in food systems aimed at diet diversity and resilient production systems.

The nutritional value of food biodiversity

Food composition studies demonstrate that there can be important differences in nutrient content both between similar species (for example the difference in nutrient content of different kinds of fish in Figure 2.4) and within species (for example the difference between various varieties of banana or rice in Table 2.1). Knowing about nutrient content allows people to select and promote the most nutrient-dense species, varieties and breeds to use in farms, markets and public health campaigns in order to maximize the nutritional adequacy of diets.

Nutritional values between species

Research into fish consumption in Bangladesh provides a good example of the nutritional significance of these differences between species. In Bangladesh, although people had started eating more fish, there was a decline in intake of some essential nutrients. This was explained by the increase in production and consumption of farmed exotic fish species over non-farmed indigenous fish species, which contain higher levels of micronutrients (Box 2.1, 26).

Nutritional values within species

The nutrient content differences within crop varieties and animal breeds of the same species can sometimes be even greater than the differences between species (21, 27). For example, consumption of 200g of rice per day can represent from less than 25% to more than 65% of the recommended daily intake of protein, depending on the variety consumed (28). Table 2.1 shows the range of variation in some common species (rice, potato, banana) and some uncommon ones (pandanus, gac, breadfruit).

Significant nutrient content differences in meat and milk among different breeds of the same animal species have also been documented (29–31).

TABLE 2.1 – Examples of nutrient composition within varieties (per 100g edible portion, raw)

	Protein, g	Fibre, g	Iron, mg	Vitamin C, mg	Beta-carotene, mcg
Rice	5.6–14.6		0.7–6.4		
Cassava	0.7–6.4	0.9–1.5	0.9–2.5	25–34	<5–790
Potato	1.4–2.9	1–2.29	0.3–2.7	6.4–36.9	1–7.7
Sweet potato	1.3–2.1	0.7–3.9	0.6–14	2.4–35	100–23,100
Taro	1.1–3	2.1–3.8	0.6–3.6	0–15	5–2,040
Breadfruit	0.7–3.8	0.9	0.29–1.4	21–34.4	8–940
Eggplant		9–19		50–129	
Mango	0.3–1.0	1.3–3.8	0.4–2.8	22–110	20–4,320
Banana			0.1–1.6	2.5–17.5	<1–8,500
Pandanus			0.4	5–10	14–902
Gac					6,180–13,720
Apricot	0.8–1.4	1.7–2.5	0.3–0.85	3.5–16.5	200–6,939 (beta-carotene equivalent)

Source: (32)

BOX 2.1 – Nutritional value of small indigenous fish species

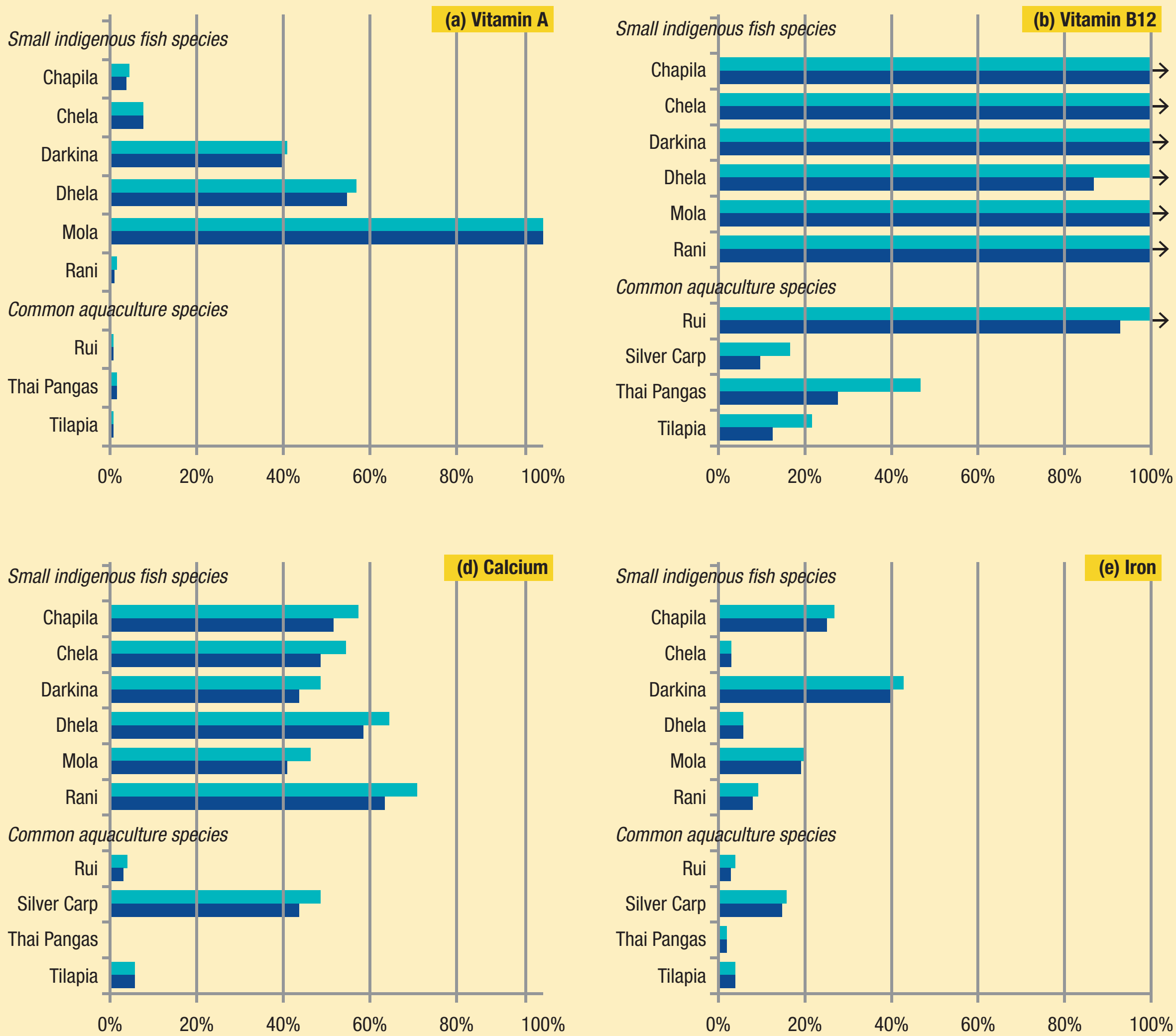
In many low-income countries, fish are an important animal-source food and means of dietary diversification, though the quantity and frequency of consumption can be low, especially among the poor. Fish are important not only for population groups who live close to water sources, such as marine coasts, lakes, rivers and wetlands, but also for those who live in areas far from water, as dried fish is commonly traded. The diversity of fish species found in water bodies can be great. For example, in Bangladesh, 267 freshwater fish species, 475 marine species and 24 introduced fish species have been recorded.

In Asia, led by China, aquaculture has expanded vastly in the last 30 years, with increasing fish production. However, the diversity of fish species used in aquaculture is small; in Bangladesh, species cultivated are mainly a few exotic carp species, tilapia and pangasius.

Using data from the Bangladesh Household and Income Expenditure Surveys from 1991, 2000 and 2010, it was shown that total mean fish consumption increased 30% over time, with the greatest relative increase (19%) among extremely poor households. Analyses of nutrient intake from fish showed increased intakes of animal protein and total fat, in parallel with increased fish consumption. However, the intake of iron and calcium decreased and intakes of zinc, vitamin A and vitamin B12 remained unchanged. These nutrient intake patterns over time reflect the shift to consuming a greater proportion of farmed fish and the lower nutritional quality of these farmed fish in comparison to non-farmed indigenous fish. Many small indigenous fish species have the potential to contribute significantly to micronutrient intakes of women and young children (Figure 2.4).

FIGURE 2.4 – Nutritional value of small indigenous fish species

Contribution (%) of selected fish species from Bangladesh to recommended nutrient intakes (RNIs) for pregnant and lactating women (light blue) and infants and young children (6–23 months, dark blue). Arrows represent contributions that exceed 100% of RNIs.
Standard fish portion sizes of 50g/day for women and of 25g/day for infants and children were used.



Source: (26)

The important finding is that differences in nutrient composition are statistically significant, sometimes with a thousandfold or greater nutrient content differences. For example, the content of beta-carotene (a precursor of vitamin A) in varieties of sweet potato can vary from 100mcg to 23,100mcg in 100g raw produce, and that of banana cultivars from 1mcg to up to 8,500mcg. Most notably, these differences can translate into meeting people's nutrient requirements, particularly for vulnerable individuals. For example, while the world's most commonly consumed banana, the Cavendish, contains almost no beta-carotene, the banana cultivar To'o, when ripe, contains 7,000mcg of beta-carotene equivalents (33), which meets the daily vitamin A requirement of both women and children.

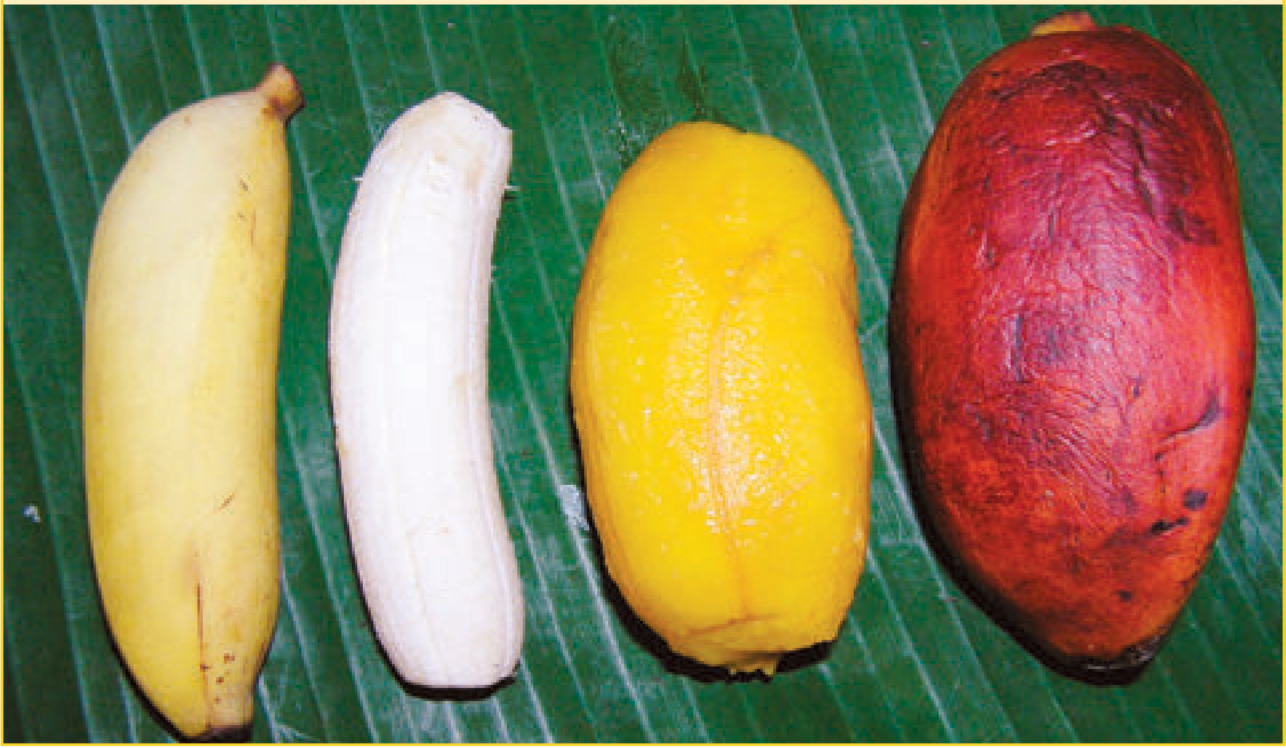
In some cases, the superior nutritional trait is visible. Figure 2.5 compares the Karat cultivar, one of a group of bananas commonly found in the Pacific known as the Fei group, with a white-fleshed banana. Another orange-fleshed banana, the Asupina had such high levels of carotenoids that a pre-school child could meet 50% of their vitamin A requirement by consuming one Asupina banana (c. 77g), whereas they would need to eat 1kg of Williams bananas to reach the equivalent amount of vitamin A (34). The nutritional distinction evident in the orange colour can be used by consumers to make better nutritional choices.

As yet we are only scratching the tip of the iceberg in relation to exploring the nutritional value of the world's food biodiversity. Despite many examples of within-species differences in nutrient composition, which could underpin successful food-based approaches, analyses often aggregate samples of the most commonly available cultivars and present them as mean values. This practice masks nutrient differences specific to the genetic diversity of a species and is a great handicap to researchers wanting to assess how food biodiversity can be used for better diets in countries around the world. However, increasing efforts are being made to disaggregate information to at least species level, including the definition of process indicators to measure progress in food composition and food consumption that measure the difference in composition between varieties of the same species (36, 37).

As more and better data become available, food biodiversity – covering thousands of varieties of fruits, vegetables, grains, legumes, animal breeds, fish, insects and fungi – is being recognized for its potential to improve the nutritional status of communities. The *Voluntary Guidelines for Mainstreaming Biodiversity into Policies, Programmes and National and Regional Plans of Action on Nutrition*, endorsed by the Commission on Genetic Resources for Food and Agriculture (CGRFA) in 2015, recognize that more data on composition and intake, for example on wild and underutilized species and animal breeds, are needed to determine the importance of food biodiversity in nutrition and food security (38).

FIGURE 2.5 – Comparing the nutritional composition of white and orange bananas

The orange Fei banana (right) known as Karat in the Micronesian island of Pohnpei contains 1000 times more provitamin A carotenoids than a white-fleshed banana (left).



Source: Musarama.org

Improving diet diversity through cultivated or gathered food biodiversity

How populations source food is complex and context-dependent. In particular, there are differences between urban and rural populations. Every individual household is likely to consume a varying mix of foods grown by themselves, gathered from the wild and procured from markets. Here, however, we separate out the evidence into the contribution to diet diversity of homegrown food biodiversity, wild food biodiversity and food biodiversity from markets.

On-farm food biodiversity and contribution to healthy, diverse diets

Food-based strategies can result in improvements in diet diversity (39–41). 'Nutrition-sensitive' agricultural interventions use food-based strategies to modify diets. Typical strategies include diversifying the household production system through home gardening, aquaculture and small-scale fisheries, small livestock rearing and dairy development programmes, as well as strategies to improve food processing, storage and preparation (42). Nutrition knowledge is key – strategies that are accompanied by a nutrition education component are more successful (39, 40). Many food-based strategies have the potential to diversify diets by promoting production of, and access to, a wider variety of food biodiversity.

Homestead food production in particular has been found to have a positive impact on nutritious diets. For example, a review of this production mode in four countries in Asia concluded that increasing the number of varieties of micronutrient-rich fruit and vegetables and animal-sourced foods available year round was one of the pathways that led to increased consumption of micronutrient-rich foods and improved micronutrient status (43).

Two recent reviews provide evidence of the positive link between biodiversity on farm or in the landscape and diet diversity (44, 45).[iii] The first review compared measures of agricultural biodiversity (crop species generally, sometimes also livestock species) to measures of diet diversity (counting food items or food groups over a certain time period). In five out of eight studies a positive association between farm diversity and diversity of the diet was reported; while in one study the relationship was positive for one country and not another (44). The second review, looking at the relationship between household-level food biodiversity and household- or individual-level diet diversity or quality, also found a positive correlation in 14 out of 15 studies (45). These associations were independent of household wealth or market access.

The significant peaks and troughs in household food availability are reduced when there is diversity in family farming activities. More biodiverse agricultural production systems (i.e. including more food groups in farming systems) (46) can enhance the availability of micronutrient-rich food varieties and improve nutritional outcomes all year round (47). In Malawi, researchers compared the strength of association between the number of food groups grown on farm and a diet diversity score for the entire household, for only children and for only women (all based on twelve food groups). Increasing the number of food groups grown was associated with a 0.12 increase in the number of food groups consumed by the farm household, 0.17 increase in food groups consumed by children and 0.11 increase in food groups consumed by mothers (48).

In another study from Malawi, the evidence suggests that more diversity grown on farms contributes to more diverse household diets, although the authors do highlight that the relationship is complex and may be influenced by a variety of socioeconomic factors. The specific nature of the farm diversity is also important. For example, a study in six districts of western Kenya found that on-farm production diversification correlates with household diet diversification, and also that livestock ownership, especially poultry, was more strongly correlated with diet diversity than crop production (49). Local initiatives that enhance traditional integrated livestock–crop systems of nutrient-rich vegetables and grains and the keeping of small animals (particularly indigenous chickens raised under extensive production systems) have been shown to have a positive impact on families' diet quality and consumption patterns, improving the diets of pregnant women and young children (Personal communication, Robyn Alders, Box 2.3).

Diversified farming systems, especially integrating small livestock such as poultry, sheep and goats, are sound interventions for enhancing diet diversity and nutrition for very poor, marginalized smallholders, as well as having added benefits as a risk management strategy against adverse shocks (49). Rural communities that rely on rain-fed crops often go through a hunger period or 'lean' season just before the major harvesting season, when their stored grains have been exhausted. Results from research in Zambia (Bioversity unpublished) found average diet diversity scores for both adults and children differed significantly across three seasons, and that average food group diversity was highest for adults in the middle of the identified hunger season. Similar findings of higher diet diversity scores – particularly of fruits and vegetables – during the lean season have been observed in rural Burkina Faso (50) and Kenya (51). Promoting fruit species which mature during periods of the year when other food supplies are limited can be a successful food and nutrition security strategy as well as a means to supply fresh fruit year round (Box 2.2). Similarly, integrated livestock–crop systems can be designed to maximize the availability of nutritious foods all year round especially during the lean seasons (Box 2.3).

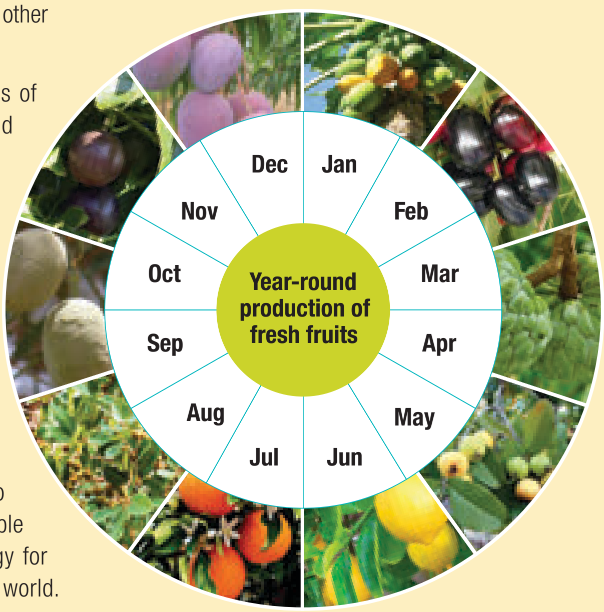
BOX 2.2 – The role of fruit tree portfolios in year-round access to fruit

Integrating fruit trees into mixed crop farming systems can provide year-round harvest of a variety of healthy, nutrient-dense foods. Fruits increase the nutritional quality of local diets, mostly due to their micronutrients (mineral and vitamins), but also macronutrients (protein, carbohydrates) and phytochemicals (e.g. antioxidants) (52). In addition, trees are resilient with regard to climate variability and their products can close hunger and nutrition gaps caused by the seasonality of common grain and pulse staples and other crops such as leafy vegetables.

'Fruit tree portfolios' are defined as location-specific combinations of indigenous and exotic fruit tree species that can provide year-round harvest of vitamin-rich fruits and, at the same time, fill 'hunger gaps' and specific 'nutrient gaps' when integrated into farming systems (53, 54). Fruit tree portfolios can enhance the diversity of fruits on farms and in food systems for increased consumption and better diets, while addressing seasonal fruit availability.

The fruit tree portfolio approach was piloted in two sites in Kenya: Machakos, Eastern Kenya and Kakamega and Siaya Counties, Western Kenya. The fruit tree portfolio for Machakos County is presented in Figure 2.6. Ten fruit species rich in pro-vitamin A and vitamin C were selected and combined in a portfolio for promotion in the county. The portfolio approach can be developed to include suitable, complementary vegetables, as well as annual, staple crops to provide for a 'diversified diet' approach. The methodology for developing fruit tree portfolios can be applied in any country in the world.

FIGURE 2.6 – Fruit tree portfolio for Machakos County, Kenya, showing year-round fruit harvest of vitamin A and C rich fruits



Contributing authors: Stepha McMullin and Ramni Jamnadass
Figure source: (54)

BOX 2.3 – Integrated livestock–crop systems are crucial to support balanced diverse diets throughout the year

Local initiatives, such as enhancing traditional village chicken–crop systems, can provide a sustainable solution to the ongoing nutritional challenges in Africa and Asia. Rural communities that rely on rain-fed crops often go through severe hunger periods just prior to the major harvesting season when their stored grains have been exhausted. By improving village poultry health and welfare, for example by vaccinating against widespread diseases, such as Newcastle disease, families have greater access to poultry meat and eggs, which are a source of high-quality protein, highly bioavailable micronutrients and income. Village poultry have the additional quality of being able to scavenge feedstuffs not typically consumed by humans. Poultry manure can contribute to increased soil fertility for the production of indigenous vegetables at the household level, further diversifying the range of foods eaten (55, 56).


Community vaccinators increase village chicken health and production by vaccinating them against Newcastle disease. Credit: R.Alders

Contributing author: Robyn Alders

Diverse, wild herbs for sale at the the 6th edition of the Alaçatı Herb Festival in Western Turkey.
Credit: Bioversity International/D.Hunter

Farm diversity is only one factor affecting diets. Data from Indonesia, Kenya, Malawi and Ethiopia found that the relationship between increasing production diversity and diet diversity is smaller compared with the effect of improving market access (57) (see Section on markets p36).

Wild food biodiversity and evidence of its contribution to healthy, diverse diets

The role of wild foods in diets has been explored at two levels: the first investigating the relationships between different landscape types and diet diversity; the second the relationships between wild food species and diet diversity.

At a landscape level, researchers, using remote sensing and satellite imaging, found an association between tree cover and diet diversity (44). Similarly, a significant positive relationship between tree cover and children's diet diversity was observed in 21 African countries, suggesting that children in Africa who live in areas with more tree cover have more diverse and nutritious diets (58). A similar approach in Malawi found that forest cover is associated with better health and nutrition outcomes in children and that children living in areas where there was a net loss of forest cover had less diet diversity and were less likely to consume vitamin A-rich foods (59). Ickowitz et al. (60) examined the relationship between different tree-dominated landscapes and consumption of micronutrient-rich foods in Indonesia and reported that areas of swidden/agroforestry, natural forest, timber and agricultural tree crop plantations were all associated with more frequent consumption of food groups rich in micronutrients, with swidden/agroforestry landscapes associated with the most frequent consumption of the largest number of micronutrient-rich food groups. As yet, the mechanisms behind these associations are unknown.

Recent reviews (27, 61) of the extent of wild biodiversity used as a food reveal the following highlights:

- Approximately 1 billion people around the world consume wild foods
- The mean use of wild foods by agricultural and forager communities in 22 countries of Asia and Africa (36 studies) is 90–100 species per location
- Aggregate country estimates can reach 300 to 800 wild edible species (e.g. India, Ethiopia, Kenya).

The extent to which this edible wild biodiversity contributes to diet diversity and nutrient intakes can vary considerably and, due to methodological limitations and differences across studies, is difficult to quantify. In some instances, wild foods can constitute a large portion of the diet. For example in Vietnam, wild vegetables contributed between 43% (Central Highland) and 75% (Mekong Delta, flood period) of the total weight of vegetables consumed (62). In other studies, despite documentation of an abundance of wild species traditionally used for food, dietary intake studies show actual consumption is limited (due to seasonality or small amounts of wild food consumed) (44). In Benin and the Democratic Republic of Congo, for example, a considerable number of wild edible plants were known by the local populations (61 and 77 species respectively), but the contribution to total dietary intake was relatively low due to low frequency of consumption (63, 64). A study conducted in rural South Africa found that not all of the available wild vegetables were consumed and, if they were consumed, the quantities were small (65).

Because of their resilience to harsh conditions, wild foods often act as safety nets or coping strategies in times of food shortage and famine. Studies have found that wild food consumption increases when stores of staple food crops decline (66, 67). For example, in the harsh lands of the Pamir Mountains, when the winter stores are dwindling and the new harvests are not yet ready, people collect and eat wild foods, such as wild rhubarb, purslane and mushrooms (68).

It is difficult to accurately assess the contributions of wild food biodiversity to diets and nutrition, due to the technical challenges of identifying the correct taxonomy of foods and measuring diet intake (22). The actual proportion of daily nutrient requirements supplied by wild foods relative to consumption of home-grown or purchased foods remains largely unknown (27). Information remains limited and fragmented (32) or of poor quality (69). Sometimes the challenge lies in the false dichotomy of distinguishing between wild and cultivated biodiversity, since many wild foods are actively managed in the wild, or introduced into gardens (61, 70).

Despite the methodological challenges in reviewing actual contributions of wild foods to diets, there is a huge potential for wild and neglected foods to contribute to diet diversity and nutrition. Many wild food species are richer in vitamins, minerals or macronutrients (fats and protein) than many conventional domesticated species that dominate agricultural or home-garden production (27, 61). For example, indigenous fruit trees (52), indigenous leafy vegetables (53, 71, 72) and wild plant and animal species (27) have higher nutrient content compared to their more widely cultivated exotic counterparts. In South Africa, for instance, four wild leafy vegetables (lambsquarters, sow thistle, black nightshade and nettles) were found to be good sources of protein, crude fibre, calcium, iron, manganese and phenolics (73). Nettles contained the highest concentrations of calcium, potassium, phosphorus and zinc, while a particularly high level of iron was observed in sow thistle.

A study in Baringo District, Kenya, demonstrated that wild foods have the potential to increase nutrient adequacy while reducing the cost of a nutritious diet, were they to be consumed in sufficient quantities to boost intakes of essential nutrients (74).

Many wild foods have been reported to have medicinal as well as nutritional uses. For example, the rare White *Garcinia* fruit, found in the forests of southern India, is highly valued in Ayurvedic medicine to treat severe gastric reflux (75). In the Pamir Mountains, safflower, purslane, black cumin, seabuckthorn and wild rose, among others, are used to treat common ailments (68). Wild foods often possess pharmacological substances that cultivated plants have lost during the process of domestication (70, 76).

Despite their value, the use of wild foods is declining (77). Increasing modernization and globalization are contributing to a loss of knowledge and decline in their use (77). The loss of indigenous knowledge has been recognized as one of the general factors negatively affecting biological diversity (78). Community health and extension workers tend not to have the necessary knowledge to promote the nutritional value of wild foods as a sustainable strategy to improve diet. Replacing traditional foods with a more homogenized range of species results in the loss of genetic diversity in traditional food species and a decline in cultural diversity. On the other hand, wild foods can represent an inextricable link between people and their lands, defining biocultural identity (61, 68, 76). It appears that cultural attachment to local culinary traditions and the appreciation of specific dishes in urban circuits can be, in some regions, sufficient to partially halt the erosion of traditional knowledge related to the use wild food biodiversity (78–80).

Wild foods are often excluded from official statistics on economic values of natural resources (61). A recent quantification of the economic contribution of wild foods, using data from almost 8,000 households in 24 developing countries across three continents found that 77% of households were engaged in wild food collection from forest and non-forest environments (81). The main role of wild food collection was found to be for household nutrition, with wild plant and animal foods contributing important sources of micro- and macronutrients. In addition to contributing directly to household consumption, wild foods are also traded in significant volumes around the globe. Households can use income from sale of wild food biodiversity to purchase nutritious foods (Figure 2.3). In southwest China, for example, over 280 species of edible vegetables are sold; trade in wild vegetables contributes 15–84% of cash income for certain groups, and the price for wild vegetables exceeds that of cultivated vegetables (27).

Introduced machines to ease the processing of quinoa and other traditional grains in Bolivia, a process that otherwise takes hours. Some highly nutritious grains are burdensome to prepare and so being abandoned in favour of easy-to-use crops. Reducing preparation times can put nutritious, traditional crops back on the plate.
Credit: Bioversity International/S.Padulosi

Considerations of gender in food biodiversity and nutrition

The role of women as custodians of food biodiversity is critical. In several regions and among different cultural groups, it is women who predominate as wild plant gatherers, home gardeners, plant domesticators, herbalists, seed custodians, informal plant breeders and farmers (82). By doing so, women are not only the main providers of household nutrition and health (83), but also managing and conserving most of the plant resources used by humans. Products from their gathering and gardening activities bring additional diversity to otherwise monotonous diets. Some experts consider women to be the nexus of the agriculture, health and nutrition sectors (84). Because of their domestic tasks (gardening, plant gathering, post-harvest preservation, storage and food processing), women maintain a close relationship with plants and have the greatest local plant knowledge (82). However, this knowledge is greatly undervalued as most of the activities occur within the domestic realm and the principal values of plant genetic resources are localized and non-monetary (82). Several studies (Southern Zimbabwe, Mexico) stress the important role of women and children in collection, processing and sales of edible insects (85, 86). The insects harvested by women or the income derived from insect sales tend to be used for household needs (87). Men and women also tend to have different knowledge about insects; for example in Niger women were able to name approximately ten more folk species of grasshoppers than men, as women play a larger role in collecting and preparing the insects (Groot 1995 in 87). While men are often more involved in hunting of game meat, in some cultures women are the primary retailers. A study in Kinshasa (DR Congo) found that 80% of bushmeat traders were women (88). One should not, however, make too many generalizations, as ecological and traditional knowledge and practices should be studied within their biocultural context.

Women's knowledge, education, social status, health and nutrition, and their control over resources are key factors that affect nutritional outcomes (77). Women's social and economic empowerment, often resulting from improved education or access to regular income, is key to addressing hunger and malnutrition (83). As early as 1999 it was shown that women's status and improvements in women's education are associated with positive impacts on child nutritional status (89). Different aspects of women's empowerment appear to have different effects on diet diversity and nutritional status for both mothers and children (90). For example, nutrition education interventions targeting caregivers with small children significantly increased caregivers' nutritional knowledge and improved diet diversity of the children involved (91).

Women also play a key role in food purchases. Their food choices take into account individual and household preferences and market factors, such as availability, accessibility and affordability. Interventions in the enabling environment need to account for this aspect, and targeted efforts to enhance nutrition knowledge and sensitize consumers regarding the importance of food biodiversity for diverse, healthy diets require a strong, albeit not exclusive, focus on women.

Considering the evidence above, a focus on the role of women in the production and use of food biodiversity is central for sustainable food systems as: (1) women are the main providers of household food and nutrition and have important, but undervalued, knowledge on agricultural biodiversity for food and nutrition, and (2) there is growing evidence that empowering women through education and/or income generation contributes to improving diets and nutrition. There is an important opportunity to document, validate, strengthen, share and transmit women's knowledge on agricultural biodiversity as a valid strategy to empower them to improve sustainability of diets, nutrition and health.

Improving diet diversity through food biodiversity purchased in markets

Rural households can meet a good part of their dietary needs through consumption of homegrown or gathered food biodiversity. Growing populations in urban and peri-urban areas, however, largely rely on purchased food. For this second pathway (Figure 2.3), they make use of a range of often informal market outlets, such as wet markets, street markets, traditional grocery stores and kiosks. At the same time, food is increasingly being purchased in supermarkets and hypermarkets, which are on the rise, particularly in Asia and Latin America (92). Along with the food environment around them, these market outlets drive food choice by signalling what is available, accessible, affordable and acceptable (1, 10). While the role of markets in improving diet diversity has not been empirically researched on a large scale (93), this section reviews existing evidence of diverse market outlets to make food biodiversity available, accessible, affordable and acceptable to low-income consumers in urban, peri-urban and rural areas.

Availability of food biodiversity in different markets

As an entry point to the food system, agricultural production and, to a lesser extent, food collected from the wild are key variables for determining how much food is available (volume, stability of production, seasonality), in what quality (nutritional value, food safety), and with what degree of diversity (food groups). Over the past four to five decades, profound changes have altered the global food system. World average availability of food energy (kilocalories) for direct human consumption reached 2,770kcal/person/day in 2005–2007, up from 2,411 kcal/person/day in 1969–1971 (94). While availability of food in general has increased, over the same period, the food offer in many countries has become more uniform. Lack of availability of food biodiversity is therefore the major factor that affects dietary choices (10). For instance, fruit and vegetable intakes do not reach the dietary recommended levels in many countries due to their limited availability in markets (95, 96). Availability of pulses, a nutritionally and culturally important diet component, has decreased globally (97). At the same time, the shares of meat, fish and eggs, in total protein availability per capita, have steadily increased over time (98). The expansion of supermarkets in Latin America and Asia and, to a lesser extent, Africa, has been a major factor driving availability of these foods (99, 100). In South Africa, for example, healthier food choices are available in supermarkets, but many towns only have small food stores with a limited selection of healthy foods (101). Food availability is also limited by seasonality, which proves particularly challenging for the most vulnerable populations (102). Even in emerging economies, such as Malaysia, seasonal household food shortages are due to unavailability of food in the market (103). Traditional, often informal and small-scale market outlets buffer such shortages and contribute to year-round availability of food biodiversity, but systematic evidence of the magnitude and quality of this buffering role across countries is lacking.

Relationship between market access and diet diversity

Availability of food biodiversity is closely linked to market access, both from a producer's and a consumer's perspective. Access to markets can be differentiated according to the type of market outlet (e.g. formal vs. informal, large-scale vs. small-scale). In addition, local, regional, national and international markets are increasingly connected, and changes in higher-level markets have repercussions on lower-level markets over the short and medium term. For example, while the share of imported foods (higher-level market) in many African countries is still fairly low, imports of fairly homogeneous foods in Asia and Latin America are growing rapidly, increasing the risk of crowding out producers and traders of locally produced, biodiverse foods in lower-level markets.

From an urban consumer's perspective, the informal sector plays an important role in many food retail markets and the diversity of informal market outlets allows for a diverse offer of food choices based on food biodiversity. In Kenya, for example, a country with a growing number of supermarkets and a relatively well developed formal food sector, high-income households may buy all types of food in a supermarket, while low- and middle-income households mostly use supermarkets to buy processed foods, but purchase fresh fruit, vegetables and other food from traditional *dukas*, followed by open markets, butcheries and kiosks (104). A similar preference has been observed for livestock products, such as milk, as Kenyan households prefer to buy unpasteurized raw milk from informal retailers, who sell raw milk at almost half the price of the formal retailers, rather than buying more expensive pasteurized milk (105).

From a rural producer's perspective, market access has been found to be positively correlated with diet diversity. In a comparative assessment across five studies, greater market access was associated with higher diet diversity or quality, with positive relationships for: selling higher share of production, devoting more land to market crops, and access to public or own transport; and negative relationships for: reliance on own production for consumption, distance to nearest road or market, and rural location (45). In Mexico, proximity to urban areas paired with opportunities to participate in larger and differentiated markets were found to be linked with higher on-farm diversity levels, reflecting that greater market opportunities can bring about diversification rather than specialization (106). In Benin, high diversity of markets increased the consumption of diversified diets among mothers, accounting for 65–80% of all the variation of foods consumed by mothers (106). As a result, mothers consumed more than the threshold amount of grains, roots and tubers, as well as meats, fish and seafood (106). In Malawi and Ethiopia, better market access by producers increased the level of purchased food diversity (107).

These examples show that a positive relationship can exist between market access and diet diversity – from a consumer's perspective in terms of having physical access to food biodiversity and, from a producer's perspective, through opportunities for generating income that can be used for food purchases, complementing the consumption of self-produced food. In a study from Malawi, it was concluded that improving access to markets, along with productivity-enhancing inputs and technologies, is a more promising strategy to improve diets in smallholder farm households than further increasing production diversity (48).

Affordability of a more diversified diet

In addition to availability and access, affordability of healthy food is a key determinant for achieving better diet quality. While in theory healthy eating does not need to be more expensive than unhealthy food habits, there is evidence from various countries that moving towards healthier diets comes at a price (see Box 2.4). In rural South Africa, for example, a typical 5-member household would need to increase food expenditures by more than 30% of the total household income to eat a healthier diet (101). In South Asia, when the price of staple foods goes up, poor consumers are more likely to consume less of the heathier dietary components and tend to consume cheaper and lower-quality foods (108).

BOX 2.4 – Cost of a healthy diet

In most rich countries, the mean cost difference between healthy and unhealthy diets is about US$10.50/week (109). Other studies show that in the UK the cost of a healthier diet is double that of the least healthy one (110). In Ethiopia, Myanmar, Tanzania and Bangladesh, the average minimum cost of a healthy diet ranges from US$0.72 to US$1.27/day (111), and in South Africa a healthier diet costs 69% more than an unhealthy one (101). A 10% increase in price of fruits, vegetables and pulses has been predicted to result in 7.2% lower consumption in poor countries, 6.5% lower in middle-income countries and 5.3% lower in rich countries (112).

Evidence on affordability of healthy food suggests that a principal way to increase consumption of diversified diets is to lower their relative price (10), particularly as regards fruit and vegetables (113, 114). While this sounds like a straightforward solution, there are some caveats to this: (1) if consumer prices are to be lowered, farm-gate prices for food biodiversity might be put under further pressure, crowding out poor smallholder households, (2) strong collaboration is needed among various stakeholders in value chains for biodiverse products to ensure higher efficiencies, and (3) significant public and private investments in infrastructure (e.g. road network, storage facilities, cold chain) are needed to reduce post-harvest losses.

Acceptability of a more diversified diet

Even if healthy food is readily available, accessible and affordable, there may be social and cultural reasons for low-income consumers to prefer less diverse or less healthy diets. Evolutions in diets are influenced by higher income per capita, food prices, individual and sociocultural preferences, and the development of the cold chain (98). Acceptability is linked to perceptions of taste, palatability, prestige, convenience and cultural factors, among others. For example, there is a striking increase in demand for convenience, often highly processed foods. In East and Southern Africa, the market share of such foods has risen to one-third of the purchased food market, with little differentiation between rural and urban areas (31% vs 35%) (115). Acceptability of food biodiversity can be shaped by sensitization, education and capacity building. For example, 45.2% of households in Kenya who had participated in awareness-raising activities about the nutrient content of some 40 different species of traditional leafy vegetables still reported increased consumption ten years later (116).

The types of foods that urban and rural dwellers consume often differ significantly. While it is difficult to determine the role of preference relative to that of access and affordability, urban and rural food preferences are not alike. In Mozambique, for example, urban and rural dwellers consume comparable amounts of maize flour, but urban dwellers consume three times as much rice, much less cassava flour, and negligible amounts of sorghum flour compared with rural dwellers. Urban dwellers also consume more meat, chicken and fish, especially fresh fish. The types of vegetables and pulses they consume also differ significantly: urban consumers prefer butter beans, tomatoes and Portuguese spring greens, while rural consumers purchase more peas and cassava leaves (117). Similar differences in preferences have been observed elsewhere in Africa, for example in Niger, Mali and Burkina Faso (118), Burundi and South Africa.

In addition to rural–urban differences in food preferences, the transformation of the food system in many countries is likely to have important implications for food biodiversity in markets and produced on farms. In India, for example, during a first stage of food system transformation (income-induced diet diversification), consumers replace inferior goods with superior foods, for example by substituting traditional staples, such as rice. In a second stage (diet globalization), there is a much more marked increase in the consumption of proteins, sugars and fats (119). These transformations may have significant implications for food biodiversity in markets, since foods rich in proteins, sugar and fat can be efficiently produced by larger farms and food processors without requiring high diversity of animal and plant species or varieties. Such agri-food value chain actors also rely on a limited number of retail outlets, particularly supermarkets or hypermarkets.

Maintaining or expanding market diversity is therefore critical for linking food biodiversity with the diversity that ends up in people's diets. Factors which mediate between market and diet diversity include the status of food, norms, advertising, food quality and perceived value (price–quality relationship, convenience). People in urban areas tend to eat more fast, street and highly processed foods because they are convenient, affordable and tasty (120). Advertising increases the desirability of foods, and hence influences food choices (10). Consumers' knowledge, through educational campaigns, influences their attitudes towards consuming food types. African traditional vegetables, for example, have been marketed with emphasis on their nutrition qualities which helped change consumers' perception that such crops are low-status (121). Quinoa, an American native crop with high nutritional qualities (122) that provides reliable yields also under extreme growth conditions (123), has long been consumed by the rural Andean population, while the region's urban consumers took it as a low-status food. When consumers in the global North, stimulated by promotional campaigns, started to increasingly consume quinoa in the 1990s, local producers received positive price signals. With growing demand in North America and Europe, along with the consumers' willingness to pay premium prices, quinoa production became more prestigious. Not only is it now consumed in many parts of the world, but there is also growing awareness in its centres of origin, like Bolivia, regarding the value of the Andean crops both for local uses and for marketing in global value chains (124). Increasing the visibility of and adding value to local food biodiversity have proven to be instrumental for boosting its consumption. In combination with added value, the enhanced use of food biodiversity through improved practices is expected to increase food supply and make countries like Nigeria less dependent on food imports (125). This calls for integrated approaches that combine agronomic and market interventions, with the aim of boosting the availability, accessibility, affordability and acceptability of food biodiversity.

Creating enabling environments for healthy diets based on food biodiversity

Recent high profile reports starkly remind us that our agriculture and food systems are not delivering optimal nutritional outcomes, and draw attention to a number of key opportunities and recommendations necessary for the transformations required to reverse this (5, 7). Current production sector policies, public and private investments and related programmes all too often focus on maximizing productivity and income-generating potential, but give little consideration to how each sector might contribute to improved diets and nutrition (126). As a consequence, agricultural and food investment policies have become divorced from nutrition policies, a disconnect that needs to be urgently corrected (127). Agricultural and food policies have proven resistant to change due to a number of reasons including silo and short-term thinking (128). The development of better food planning processes and joined-up food policies at multiple levels have been identified as two recommendations to break down this resistance (7). Though still few, there are a growing number of instances where cross-sectoral approaches are contributing to joined-up policies that are effectively linking agriculture with steps to tackle malnutrition and the impacts of unhealthy diets. An area of considerable convergence in terms of recommendations and opportunities to transform agriculture and food systems for improved diets, identified in three recent, high level reports (5, 7, 129) addresses a group of common and related themes: sustainable and healthy food sourcing, institutionalizing high-quality diets through public sector purchasing power, public procurement to support local agroecological produce, and the development of short supply chains. In each case agricultural biodiversity can be used to support the desired transformation. Already there are useful examples that can be replicated and scaled up.

For example, the *2014 State of Food Insecurity in the World* highlights the significant strides that some countries, such as Brazil, have made in reducing hunger and strengthening food security (130). The policy and governance frameworks in which this is happening can provide strategic opportunities to mainstream agricultural biodiversity for diverse, healthier and more sustainable diets. Brazil has recently strategically targeted several of its policies to promote local and indigenous biodiversity for food and nutrition (131). Actions taken in Brazil include promoting diverse, healthy native foods in dietary guidelines; supporting production of food biodiversity through public procurement strategies (e.g. for foods in schools); and prioritizing food biodiversity in relevant national strategies/action plans and agriculture and nutrition policies (see Box 2.5).

BOX 2.5 – Brazil's policies that strengthen food and nutrition security through use of food biodiversity

Fome Zero (Zero Hunger) has been Brazil's foremost campaign against hunger and food insecurity since 2003. It takes a multisectoral approach, contributing to family farming, inclusive rural development and improved accessibility to food through various social protection options. Brazil has made progress in promoting agricultural biodiversity for improved nutrition by taking advantage of the horizontal and cross-sectoral governance mechanisms already in place under the *Fome Zero* umbrella and strategically targeting relevant public policies and instruments that can mainstream agricultural biodiversity. Public policies – such as the Food Acquisition Programme, National School Meals Programme, the National Food and Nutrition Policy, Minimum Price Guarantee Policy for Biodiversity Products and the National Plan for Agroecology and Organic Production – all provide suitable opportunities and entry points for potentially improving nutrition or livelihoods with links to native agricultural biodiversity.

For example, in 2009, the **National School Meals Programme** decreed that at least 30% of the food purchased through its programme must be bought directly from family farmers, who manage and conserve high levels of agricultural biodiversity. **The Food Acquisition Programme** also pays 30% more for organic and agroecological food from family farmers, thus encouraging local, diversified procurement (132).

The realization of improved diversification of food procurement and school feeding has been further enhanced by the 2016 endorsement of a new public policy, Ordinance No.163 **Brazilian Sociobiodiversity Native Food Species of Nutritional Value**, which for the first time officially defines and recognizes 64 nutritionally valuable species and provides incentives for these species to be better integrated into food procurement and other initiatives. Most of the species on the ordinance are nutrient-rich fruits. It is anticipated that the ordinance will contribute greatly to better understanding and dissemination of knowledge on these species and will ultimately enhance their promotion and sustainable use across a broad range of relevant public and private policies and related initiatives. In particular, the species on the ordinance will now be more attractive for family farmers not only to grow and conserve, but also to use and commercialize, since they now have greater recognition by public initiatives especially the Food Acquisition Programme, the National School Feeding Programme and the Minimum Price Guarantee Policy for Biodiversity Products.

The Brazilian **National Plan for Agroecology and Organic Production** (PLANAPO) involves numerous ministries and is focused on promoting and supporting organic and agroecological production of healthy food. It aims to achieve this through the conservation and use of agricultural biodiversity (7). The first phase (2013–2015) of PLANAPO is estimated to have benefited more than 60,000 families and 23,000 young farmers through the implementation of credit schemes, insurance provision and capacity building for agroecological food production. In PLANAPO's second phase (2016–2019) the aim is to have 1 million family farmers producing food using agroecological approaches. PLANAPO's second phase includes targets to determine the nutritional value of 70 native species and the publication of four books documenting the nutritional and other values of regional Brazilian flora.

The **National Council for Food and Nutrition Security** (CONSEA) is an advisory body to the Brazilian presidency, which facilitates the participation and coordination of a wide range of public, private and civil actors to inform food policies and the promotion of healthy diets through provision of incentives to family-based and agroecological production (133). A National Conference on Food and Nutrition Security (CNSAN) is held every four years to set guidelines and priorities for food and nutrition security actions to inform policymaking at CONSEA. The fifth CNSAN, in November 2015, incorporated biodiversity as one of the main aspects related to food and nutrition security.

Food Fair in Mongu (Barotse floodplain), Zambia, to raise awareness of how to prepare delicious recipes from locally available, traditional foods, many of which are nutrient dense. Zambia is home to rich biodiversity, with about 100 cultivated plant species, including cowpea, sorghum, Bambara groundnuts, beans, maize and 16 species of domesticated animals (mainly cattle and chicken), which can be used to improve diets and nutrition and address micronutrient deficiencies.
Credit: Bioversity International/E.Hermanowicz

School feeding programmes

The majority of countries around the world already provide school meals of one kind or another, feeding an estimated 368 million children daily and representing an annual investment of roughly US$75 billion (134). While there is growing recognition of the potential for schools to provide and promote the consumption of healthy, diversified foods by increasing the demand for local farm products, and supporting more efficient local food procurement and delivery systems, the actual integration of underutilized, nutrient-rich food biodiversity to date has been limited and therein lies an opportunity (135).

The *2016 Global Nutrition Report* (1) highlights that “schools provide a huge opportunity to reset norms about healthful diets and good nutrition practices” (p5). The same report provides guidance on realizing diverse diets and healthy eating environments in school settings as well as how school feeding can support agricultural development, such as through the reorienting of school feeding and public procurement in Brazil (1, panels 1.4, 6.2 and 6.6).

Homegrown school feeding programmes actively seek to procure food locally and provide opportunities to encourage sustainable and healthy sourcing while promoting short supply chains. Pilot approaches have demonstrated that underutilized, nutrient-rich African leafy vegetables can play a role in linking local farmer groups to school markets at the county and district level in Kenya (136). Underutilized minor millets incorporated in school feeding programmes have enhanced the nutritional status of school children in certain areas of Karnataka state, India (137). With the inclusion of minor millets in the Public Distribution System through the 2013 National Food Security Act (138), India has created an unprecedented opportunity to promote these highly nutritious and climate resilient crops for the benefit of millions of school children and the population at large.[iv] Greater efforts are needed though if this policy is to have major impact, as most states in the country lack a suitable implementation framework that would set adequate levels of subsidies for growers, procurement rules (including minimum price) and promote best agronomic and technological practices (i.e. production of good quality seed, reduction of drudgery in cultivation, harvest and post-harvest operations) (139).

Dietary guidelines

Ensuring that food-based dietary guidelines – which are largely absent in low-income countries and limited in lower and middle-income countries – guide policy decisions to reshape food systems is one of ten specific priorities for action recommended by the Global Panel on Agriculture and Food Systems for Nutrition (5). National dietary guidelines aligned to local food cultures and local biodiversity are an example of how to improve the sustainability of food systems while encouraging healthy eating. In a recent review of food-based dietary guidelines, four countries – Brazil, Germany, Qatar and Sweden – were singled out for progressive guidelines that encompass both concepts of sustainability and healthy eating (13). Some specific advice where food biodiversity can support sustainable healthy eating includes: eat seasonal and locally grown produce (Brazil), use fresh ingredients whenever possible (Germany) and chose high-fibre vegetables (Sweden).

Social and cultural attitudes

Supporting positive perceptions and norms regarding biodiverse diets, for example by celebrating food biodiversity at food fairs, such as the Alaçatı Herb Festival and the Urla Artichoke Festival in Turkey (140) and the Barotse food fair in Zambia, and collaborations with celebrity chefs, are another means to create an enabling environment with consumers. Many chefs are now popularizing neglected and underutilized biodiversity through restaurants and related food activities (141) and the potential to mainstream food biodiversity into initiatives such as Chefs for Development and Slow Food's Chefs' Alliance and Earth Markets is considerable. The substantial growth in 'culinary tourism' and the financial resources this attracts present unique opportunities for food biodiversity. Finally, the various beneficial facets of producing and consuming food biodiversity should be integrated into the curricula of schools, universities and other education institutions for broader action and uptake.

International policies and guidelines

Countries can use their National Biodiversity Strategy and Action Plans (NBSAPs), guided by an international obligation and framework through the Convention on Biological Diversity (CBD), to mainstream food biodiversity across multiple production sectors. However, to date this policy instrument has been poorly used for this purpose (142). Those countries who are signatories to the CBD are required to develop NBSAPs to mobilize resources and promote actions to achieve their commitments to the Strategic Plan and associated Aichi Biodiversity Targets. During the recent NBSAP revision process in Brazil, a broad policy consultation was carried out to reach collective agreement on the approach and definition of the new National Biodiversity Targets for 2011–2020. During the revision process the "limited appreciation of the use of biodiversity for food and nutrition" was identified as one of a number of causes for biodiversity loss in the country, resulting in the inclusion of nutrition-related objectives, targets and indicators (143).

The FAO Commission on Genetic Resources for Food and Agriculture, at its 15th session in 2015 formally adopted *Voluntary Guidelines for Mainstreaming Biodiversity into Policies, Programmes and National and Regional Plans of Action on Nutrition* (38). The guidelines support countries in the integration of food biodiversity into relevant policies and actions to help address malnutrition in all its forms, and to promote knowledge, conservation, development and use of varieties and breeds of plants and animals used as food, as well as wild, neglected and underutilized species contributing to health and nutrition.

Metrics to measure food biodiversity for healthy, diverse diets

Transformative change to sustainable food systems delivering healthy diets will require significant commitment by diverse stakeholders at a global level. Toward this end, indicators and metrics are needed which track progress towards broader nutrition outcomes such as reduced micronutrient malnutrition, rather than our current fixation on calorie adequacy (144). In addition, we need to better understand how the quality and diversity of production supports smallholder households in consuming healthy diets and diversifying income opportunities, while also ensuring affordable market-based choices for peri-urban and urban consumers. At present, the importance of agricultural biodiversity for healthy diets is not adequately measured or valued in prevailing metrics systems (3, 7). Beyond conventional measures of agricultural production and yield, such metrics systems need to integrate indicators that measure nutritional quality, nutritional diversity of food systems and diet diversity (143). This section focuses on metrics and proxies for: (1) consumption of food biodiversity, (2) food biodiversity in markets and (3) the enabling environment for enhanced use of food biodiversity.

Metrics and proxies for consumption of food biodiversity

Measuring the actual food biodiversity that people eat

One of the most accurate measures of dietary intake of individuals is the quantitative 24-hour recall method. Data collected using this method can be used to create several indicators that relate to intake of biodiverse foods (145). Metrics of individual dietary intake that collect information at species or subspecies level would measure in the most accurate way possible the contribution of food biodiversity to dietary intake and overall diet quality. These metrics include species richness in the diet or even intraspecies diversity consumed (146). Indicators not in widespread use, but that are currently being tested, include species diversity scores or richness of species by food group consumed. One drawback of methods that use a 24-hour recall period is that seasonal usage of food biodiversity in diets is not measured unless the data are collected over several distinct seasons throughout the year. A second drawback is that few countries routinely use this method for national-level data collection, therefore data availability is patchy and most often representative of subnational areas within a country. However, the Food and Agriculture Organization with the World Health Organization are piloting a platform called the Global Individual Food consumption data Tool (GIFT) which is intended to provide open access to individual level 24-hour recall data. Several indicators that could help link the role of food biodiversity to healthy diets have been proposed in the GIFT pilot phase, including:

- Main food sources of vitamin A in the diet
- Main food sources of iron in the diet
- Main food sources of zinc in the diet
- Intake in grams/day OR g/kg of body weight/day of healthy (fruits, vegetables, whole grains, nut/seeds) and unhealthy (processed meat, sugar-sweetened beverages) food items.

Measuring diet diversity by food groups

In the current absence of a tool for measuring actual food biodiversity in diets, diet diversity scores can be used as a proxy. Diet diversity scores are relatively simple, practical tools for assessing the micronutrient adequacy of the diet in low-resource settings and in situations in which more in-depth dietary assessment is not feasible (147). There are two internationally recognized and validated standardized diet diversity scores currently available and becoming more frequent in use: Minimum diet diversity (MDD) for children 6–23 months of age and minimum diet diversity of women 15–49 years of age (MDD-W). The definitions of these indicators are presented in Box 2.6. Data for children are being routinely collected by Demographic and Health Surveys (DHS).[v] Data for women are not routinely being collected at a nationally representative scale, however MDD-W is widely used in programmes including the United States' programme Feed the Future and Germany's One World No Hunger. With promotion and recognition of the need to collect more information on diets globally, the MDD-W could be an indicator of choice for informing policymakers at international and national level of dietary patterns for this vulnerable population group. In addition to looking at percent of population achieving MDD-W the percent of populations consuming individual food groups can be analyzed. This does not alter the data collection tool, but emphasizes the different ways that the data can be analyzed to provide a much more robust indication of the level of diversity of consumption across food groups.

The World Food Programme collects another composite indicator, the Food Consumption Score (FCS), which is considered more of a food security indicator. Data collected are representative of a household, rather than an individual. From the point of view of measuring food biodiversity, FCS has similar drawbacks to the two diet diversity scores described. The Food Frequency Questionnaire (FFQ) is another tool that is used to directly assess the dietary intake of individuals, and food biodiversity metrics could potentially be constructed from these FFQ data. However, similar to the 24-hour recall method, the food frequency questionnaire method is not routinely used on a widespread basis to collect information on dietary intake.

BOX 2.6 – Definitions of minimum diet diversity

Minimum diet diversity scores are based on recall of the previous 24-hour period,

Minimum diet diversity in children 6–23 months is defined as: *the proportion of infants and young children 6–23 months of age who consumed food items from at least four of the seven defined food groups the previous day or night.*

The seven food groups used to calculate the indicator are: (1) grains, roots and tubers; (2) legumes and nuts; (3) dairy products (milk, yoghurt, cheese); (4) flesh foods (meat, fish, poultry and liver/organ meats); (5) eggs; (6) vitamin A-rich fruits and vegetables; and (7) other fruits and vegetables.

Minimum diet diversity for women is defined as: *the proportion of women 15–49 years of age who consumed food items from at least five out of ten defined food groups the previous day or night.*

The ten food groups used to calculate the indicator are: (1) all starchy staple foods, (2) beans and peas, (3) nuts and seeds, (4) dairy, (5) flesh foods, (6) eggs, (7) vitamin A-rich dark green leafy vegetables, (8) other vitamin A-rich vegetables and fruits, (9) other vegetables, and (10) other fruits.

Source: (148, 149)

Measuring food biodiversity in the national or global food system indirectly

An indirect but comprehensive way to measure food diversity at national or global level is through use of the FAO statistical database (FAOSTAT). FAOSTAT collects information worldwide on agricultural production, imports and exports, and uses of production including food and animal feed. The information generated on food available for human consumption is calculated to per capita figures based on national level population and demographics. These data provide a proxy for national level consumption, but cannot supply a direct measurement of dietary intakes. This database can be used to construct novel measures of production and consumption diversity (150). Potential indicators that can be calculated using the FAOSTAT data for tracking consumption diversity include 'Shannon entropy diversity', using the diversity of food items produced and supplied; Nutritional Functional Attribute Diversity describing the diversity in nutritional composition of food items produced and supplied; and percent of dietary energy supply per capita from non-staples. Additional alternative indicators based on use of FAOSTAT that could relate to food biodiversity include g/capita of foods recommended in food-based dietary guidelines, such as fruits, vegetables, legumes, nuts and seeds.

Finally, open-access Living Standards Measurement Study data are housed at the World Bank and can be used to provide an indication of the amount of food biodiversity (only species or more aggregated level, e.g. oil) purchased for consumption by household members.

Proposed indicators to assess food biodiversity in consumption

Adequate measures of overall diet quality are needed that include more specificity both of within-food group consumption (e.g. not just a fruit was consumed, but which fruit species) as well as contributing factors to diet-related non-communicable disease and obesity, such as consumption of highly processed food and sugar-sweetened beverages (151–154). Additional important indicators of individual level diet quality are species richness in the diet and proportion of calories of ultra-processed food and sugar-sweetened beverages consumed (10, 25, 146).

Ideal indicators for measuring consumption of food biodiversity do not yet exist in a systematically tested and validated way. However, the GIFT database of FAO/WHO is a promising future platform where species specific indicators could be derived.

In the absence of a validated metric of food biodiversity and lacking a comprehensive, accessible database of 24-hour dietary intake or food frequency questionnaire data for most countries, minimum diet diversity for children 6–23 months of age and minimum diet diversity of women 15–49 years of age are the most widely used and openly accessible indicators of diet.

Metrics and proxies for food biodiversity in markets

Diverse stakeholders representing the public and private sector and civil society, both within and outside of agri-food value chains, manage different types of information – a good entry point for a joint metrics system that helps measure progress towards healthy diets and sustainable food systems from a market perspective.

Measuring food biodiversity in markets for sustainable food systems

As a point of departure, diversity of local markets and food outlets is an important indicator for estimating the availability of food biodiversity in the market. The presence of local markets in diverse environments (city centres, suburbs, peri-urban and rural areas), for example, is a good proxy for diet variety as, from both a producer and consumer perspective, better market access increases diet diversity through increased levels of purchased food diversity (107). At present, the quality and quantity of data on market diversity vary widely from country to country and from region to region. Additional data will need to be collected for given countries and regions, but probably on a case-by-case rather than a regular basis.

Similar to the indicators on consumption, metrics and proxies for food biodiversity purchased in markets tend to focus on food groups. The share of each category (grains, vegetables, fruits, meat/poultry/seafood, dairy, beans/eggs/nuts) as part of total consumption (in terms of item counts) has been proposed (154), with higher values of the generated consumption index indicating higher diversity. In addition to volume-based metrics, prices of different food species and varieties sold in the market indicate consumption trends and can be linked to the different degrees to which certain species and varieties contribute to healthy diets. Higher consumer prices signal increased difficulties for low-income groups to diversify their diet in terms of both the total counts and the balancing of the varieties consumed (see examples from China, 154). Rather than monitoring prices of numerous individual foods, the focus should be on principal foods that are representative of different food groups. This also accounts for the fact that price information is available at species rather than variety level.

Food choice trends can also be captured by monitoring import and export data of key food groups and highly processed foods that move through more formal market channels. Equally important, but less readily available, are data on post-harvest losses. While they are critical to understand efficiencies in agri-food value chains and the overall move to sustainable food systems, they are usually based on case studies rather than being collected on a regular basis.

Finally, a market lens for assessing the progress towards sustainable food systems means looking into the environmental performance of principal agri-food chains. This is an important indicator complementary to the quality of the foods offered. Data are available for principal food companies committed to reporting according to the *Guidelines for Sustainability Reporting* at company level, within the framework of the Global Reporting Initiative (155) as described by Hoekstra et al. (156).

Proposed indicators to assess availability, affordability, accessibility and acceptability of food biodiversity in markets

In the absence of existing metrics systems that routinely measure several of the above indicators at national level and subnational levels, we recommend a focus initially on the following indicators for which data are more readily available:

- Diversity of retail outlets – with data from national governments (e.g. National Statistics Institutes, Ministries of Economy)
- Prices of principal foods representative of different food groups – with data from national governments (e.g. National Statistics Institutes, Ministries of Agriculture) and regional organizations (e.g. Agrimonitor tool of the Inter-American Development Bank)
- Trends in the diversity of nutritious ingredients in the packaged food industry, with standardized and cross-comparable statistics including total market sizes, market share, distribution and industry trends – with data from Euromonitor International
- Import/export of key food groups and highly processed foods – with data from FAOSTAT and national governments (e.g. National Statistics Institutes)
- Environmental performance of principal agri-food companies – with data from the Global Reporting Initiative.

Metrics to assess enabling environments for using food biodiversity

As highlighted earlier there are a breadth of policies and other elements of an enabling environment which could be used in a scorecard for countries to assess how well agricultural biodiversity is being mainstreamed for healthier eating environments and improved nutrition. This is also an area of increasing global interest and action and there are already ongoing initiatives underway to foster healthy eating environments or promote 'nutrition-sensitivity' of policies and programmes into which food biodiversity mainstreaming can readily tap.

A starting point could be an assessment of a country's current policies and enabling environment context, targeting private and public policies, other relevant national instruments (e.g. National Biodiversity Strategies and Action Plans and national food-based dietary guidelines) and ongoing nutrition-sensitive programmes and actions (e.g. food procurement and school feeding), to identify those which support or provide incentives for mainstreaming food biodiversity. Such an approach is similar to a 'policy portfolio' review of the food and agriculture sector to determine the impact of the existing policy portfolio on food environments and diets as well as identifying where opportunities might lie for improving impact through a new policy or revision of existing policies (129), but which is specific to mainstreaming agricultural biodiversity.

Hand-in-hand with measuring the opportunities for mainstreaming biodiversity is the need for countries to reduce the impact of those prevailing policies and actions, including subsidies and incentives, which work against the promotion of healthy food and agricultural biodiversity including unhealthy food promotion and advertising.

Assessing policies and an enabling environment is important to support the use of food biodiversity in sustainable food systems for healthy, diverse diets. It does not, however, measure actual changes in levels of agricultural biodiversity, nor can it be linked directly to outcomes such as improved nutritional status.

A scorecard approach to relevant public and private policies and other instruments could quickly reveal whether those policies already in place promote or incentivize food biodiversity for improving healthy diets and nutrition, and may simply be a matter of assessing yes or no. Example questions might be:

- Does a country mainstream agricultural biodiversity to improve healthy diets and nutrition outcomes in its National Biodiversity Strategic Action Plan (NBSAP)?
- Does a country have a national multisectoral strategy and action plan for tackling nutrition or national dietary guidelines?
- Do current policies influencing food composition, labelling, marketing, pricing and provision consider agricultural biodiversity for improving healthy diets and nutrition outcomes?
- Does research on food composition and food consumption at national level use a sufficiently detailed description to identify genus, species, subspecies, variety/cultivar/breed, and local name?
- Are there policies in place which provide subsidies/incentives for producing healthy agricultural biodiversity foods?
- Are there policies in place which support food biodiversity food choices in schools and other public settings?

Probably the most important and overarching of all of these questions is:

- Does a country have in place national food-based dietary guidelines which highlight the importance of food biodiversity not only for healthy diets and nutrition outcomes but also the many other multiple benefits including environmental sustainability and social equity?

Conclusions

Food biodiversity, or the diversity of plants, animals and other organisms used for food, covering the genetic resources within species, between species and provided by ecosystems, contributes to healthy and diverse diets in various ways. It reaches consumers through two principal pathways: (1) consumption via own production or gathering from the wild, and (2) purchase of wild or cultivated biodiversity. There is strong evidence of the importance of variation in nutrient content within and between species for addressing micronutrient deficiencies, as illustrated by the striking difference in nutrient content among different cultivars of the same species, and the superior nutrient content of several wild species when compared to domesticated types. From the perspective of the first pathway, production diversity is associated with improved diet diversity in most cases. Both on-farm and wild food biodiversity provide an important seasonal food and nutrition security buffer, particularly in the leaner months of agricultural cycles that affect rural populations, but also as a strategy to provide diversity in diets of both urban and rural populations all year round.

Women play a key role in both pathways, either as primary cultivators of food biodiversity that can diversify the household diet and as keepers of the traditional knowledge related to the wealth of plants, animals, insects and fungi that can be used as food, or as key actors making food choices when purchasing food in markets. Key factors influencing food choice are availability, accessibility, affordability and acceptability. Along with political-legal and institutional factors they make up the food environment that shapes consumer choice, particularly as populations urbanize, retail options expand to include supermarkets and fast food outlets, and convenience becomes ever more important. A particular challenge for the second pathway is to ensure healthy, diverse and affordable food options among low-income consumers who constitute the bulk of malnourished people, while offering attractive farm-gate prices to producers who supply these in a sustainable fashion. This will require multisector collaboration, involving stakeholders in agri-food value chains, service providers from outside of the chain, regulatory bodies and the media.

Public and private policies and programmes at the interface between agriculture and nutrition can help create an enabling environment for promoting healthy diets. With the appropriate regulations and incentives, they can have a profound influence on the types of food (fruits, vegetables, nuts, pulses) produced and can boost the consumption of healthy diets based on food biodiversity through public procurement programmes, such as school feeding and other social protection programmes.

Progress toward healthy diets as a critical element of sustainable food systems requires appropriate indicators and metrics systems for monitoring and learning. However, an important outcome of this review is to highlight that many of the indicators in current use are not well aligned with the measurement of food biodiversity. From a pure biodiversity lens for healthier diets, for example, reliable data for many fruits and vegetables – key elements of healthy diets – are not readily available at species, let alone subspecies, level. We therefore propose a pragmatic set of indicators that build on existing metrics and proxies to measure how food biodiversity contributes to diet diversity, and how market diversity and the enabling environment can boost these contributions. For example, FAO and national governments' statistics are a huge resource that can be used to understand trends in national food production and consumption. More granularity will need to come from additional data collection at national and company level. Towards this end, the Agrobiodiversity Index can be an important catalyst for researchers, policymakers and practitioners to better leverage the nutritional and productive potential of the food biodiversity existing on the planet.

Notes

[i] Vitamin A is fat soluble so, in order to fully utilize the vitamin A present in the foods, a small amount of fat needs to be added to the meal.

[ii] Bioversity International and FAO have developed guidance on the assessment of food biodiversity in dietary assessment surveys (12).

[iii] Five of the studies were included in both reviews. In the studies included in the reviews, on-farm diversity is most commonly measured as number of crop species grown (crop count). Some but not all studies include livestock. In both reviews, these farm-level indicators of production diversity are considered measures of agricultural biodiversity. Diet diversity scores of individuals or households were the most common nutrition indicator applied in the studies reviewed. Diet diversity was mostly defined as a count of the number of food groups consumed by a household or individual over a reference period, but in some studies a count of food items (rather than food groups) was measured. The number of food groups used to construct the diet diversity scores as well as the length of the reference period (previous 24 hours, previous 7 days) varied across the studies.

[iv] https://ccafs.cgiar.org/research/results/india-promotes-climate-resilience-through-its-food-security-bill#.WMGCqU0zXrc

[v] All DHS data are open access and can be obtained from http://dhsprogram.com/data/available-datasets.cfm.

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Rice terraces growing the improved Biramphul-3 variety of rice. This variety was developed together with farmers, using a participatory plant breeding methodology. Begnas Village, Kaski District, Nepal.
Credit: Bioversity International/J.Zucker

3

Using biodiversity to provide multiple services in sustainable farming systems

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Sustainability

KEY MESSAGES:

- Managing farming systems sustainably means that agriculture needs to be about much more than yields of commodity crops in highly simplified and specialized landscapes.
- Agricultural biodiversity provides variety and variability within and among species, fields, farms and landscapes. This diversity helps drive critical ecological processes (e.g. soil structure maintenance) and allows a landscape to provide multiple, simultaneous benefits to people (e.g. nutritious foods, income, natural pest control, pollination, water quality).
- Agricultural biodiversity is used by rural communities worldwide in many time-tested practices that can confer increased resilience to farms, communities and landscapes. Using it more effectively and more sustainably can help to maintain and increase the flow of services and benefits agricultural biodiversity provides to communities.

Introduction

Agriculture dominates global land use. Over 38% of the world's land is used for agriculture, with 11% under arable production (1). With the human population projected to reach up to 9 billion by 2050, there are increasing pressures to produce greater quantities of food. It is unlikely, however, that significantly more land can be converted from native vegetation and brought into production; most of the land potentially suitable for agriculture is already being used for that purpose and agricultural expansion is already noted as having caused significant negative environmental effects, such as deforestation and desertification. To exacerbate this situation, climate change projections indicate that every decade until 2050 food demand will increase by 14% globally but agricultural production will decrease on average by 1% (2), threatening in particular regions that are already food insecure, such as sub-Saharan Africa and South Asia (3, 4). In these two regions, major crop yields will face an estimated average decline of at least 8% by 2050 (4, 5).

Before the 1950s, farmers often increased agricultural production by increasing the area they cultivated. As human populations increased and the availability of land suitable for agriculture dwindled, the approach for increasing food production has more frequently been to raise yields per unit area of existing agricultural land through a range of management activities and processes collectively known as agricultural intensification (6). The approaches associated with agricultural intensification, such as increased use of inorganic fertilizers and synthetic pesticides, increased mechanization, irrigation and increased use of monocultures, have been very effective in terms of raising gross yields. In the period from 1961 to 2007 total global agricultural production tripled (7). However, levels of intensification (and hence yields) differ greatly around the world, leading to significant 'yield gaps' in some countries and regions, while yield increases appear to have plateaued in others despite increasing levels of external inputs (8).

These widely adopted intensification practices have contributed to altering earth system biophysical processes to the extent that today genetic diversity loss (biosphere integrity) is the most surpassed of the nine 'planetary boundaries', which should not be transgressed if humanity wishes to remain within a "safe operating space" (9, 10). The extinction rate for biodiversity has reached 1,000 times that suggested by the fossil records before humans. One of the key areas of biodiversity loss is the shrinking diversity of agricultural crops grown and consumed. Of the 150 or so species that make up the vast majority of our plant-based food, a mere three crops (rice, wheat and maize) supply more than 50% of the world's plant-derived calories, and only 12 crop and five animal species provide 75% of the world's food (11), illustrating a gradual homogenization of global food production (12). The simplification of the world's farming and food systems leaves farmers with fewer resources to draw upon to manage the risks of crop failure due to pests and diseases, or the impacts associated with increasing climatic variability (13–15). Together, agricultural intensification and the simplified food value chains that accompany it, affect both environmental and human health. Agricultural intensification contributes directly to environmental degradation through loss of biodiversity, pesticide impacts, soil degradation and negative effects on native vegetation remnants. For example, the excessive use of inorganic fertilizer has caused harm to a number of critical areas, including climate change, water pollution, loss of aquatic

BOX 3.1 – Definitions of common agroecological practices based on agricultural biodiversity

Agroforestry: A production system in which trees are integrated with crops, thus providing many synergistic relationships, such as shade or nutrients.

Cover crops: Crops which are sown for agroecological purposes, such as containing soil erosion, controlling pests or enriching the soil with nutrients. Green manure is one specific instance of a cover crop. Nutrient-rich plants (usually legumes) are planted and then ploughed into the earth to improve soil quality.

Crop rotations: Different crops grown in succession in the same field (e.g. cereal followed by legume), often to reduce risks of pests and diseases or to add nitrogen to the soil.

Intercropping: A mixture of crop species in the same field at the same time, often with synergistic effects, such as pest suppression.

Live fences: Fences of herbs, shrubs or trees (e.g. hedgerows), either retained from existing native vegetation or deliberately planted.

Non-cropped vegetation: This can be fields left fallow or patches of natural vegetation, such as forest patches, which are left on farm.

Riparian buffers: vegetation planted or retained on river banks to protect river systems from adjacent agriculture.

Farmers on a Sri Lankan farm where crop rotations of chilli, rice and other crops are practised, here harvesting chilli peppers. Credit: Bioversity International/S.Landersz

biodiversity and function, pollution of drinking water and impacts upon water-based industries and recreation (16). Simplification of cultivated crop diversity and increasing crop specialization may contribute to decreased dietary and nutritional diversity (17, Chapter 2 this publication). The adoption of new agricultural practices has also had profound negative social effects within farming households and communities, such as increased gender inequalities due to women's limited access to labour, land, inputs and assets (18, 19).

Agriculture and food systems are not only an important driver in pushing past several planetary boundaries, they are also a casualty of this transgression of biosphere integrity. Agricultural intensification needs to be made sustainable to rein in genetic diversity loss while providing a safe space for conservation within agricultural landscapes. Ecological approaches to agriculture are our best bet for reining in this boundary (20). 'Agroecological' intensification is a means by which farmers can simultaneously increase yields and reduce negative environmental impacts, through the use of biodiversity-based approaches and the production and mobilization of ecosystem services. Agroecological intensification encompasses diverse farming systems, all of which use the integration of ecological principles and biodiversity management to increase farm productivity, reduce dependency on external inputs, and sustain or enhance ecosystem services. Common practices based on agricultural biodiversity include intercropping, crop rotation, riparian buffers, non-cropped vegetation and diversified intensification (Box 3.1). Other management practices, such as conservation or no-tillage agriculture, are also common (21).[i] Here we focus on practices based on agricultural biodiversity.

All ecosystems provide a number of services to humankind (22). These services are generally categorized into groups (23):

- Provisioning: which includes aspects such as plant- or animal-based food, water, genetic material
- Regulation and Maintenance: which includes services such as disease and pest control, pollination and seed dispersal, storm or flood protection, climate regulation, soil formation and composition, to name a few
- Cultural: which includes benefits such as physical, intellectual, experiential, spiritual or symbolic interactions with biota, ecosystems and landscapes.

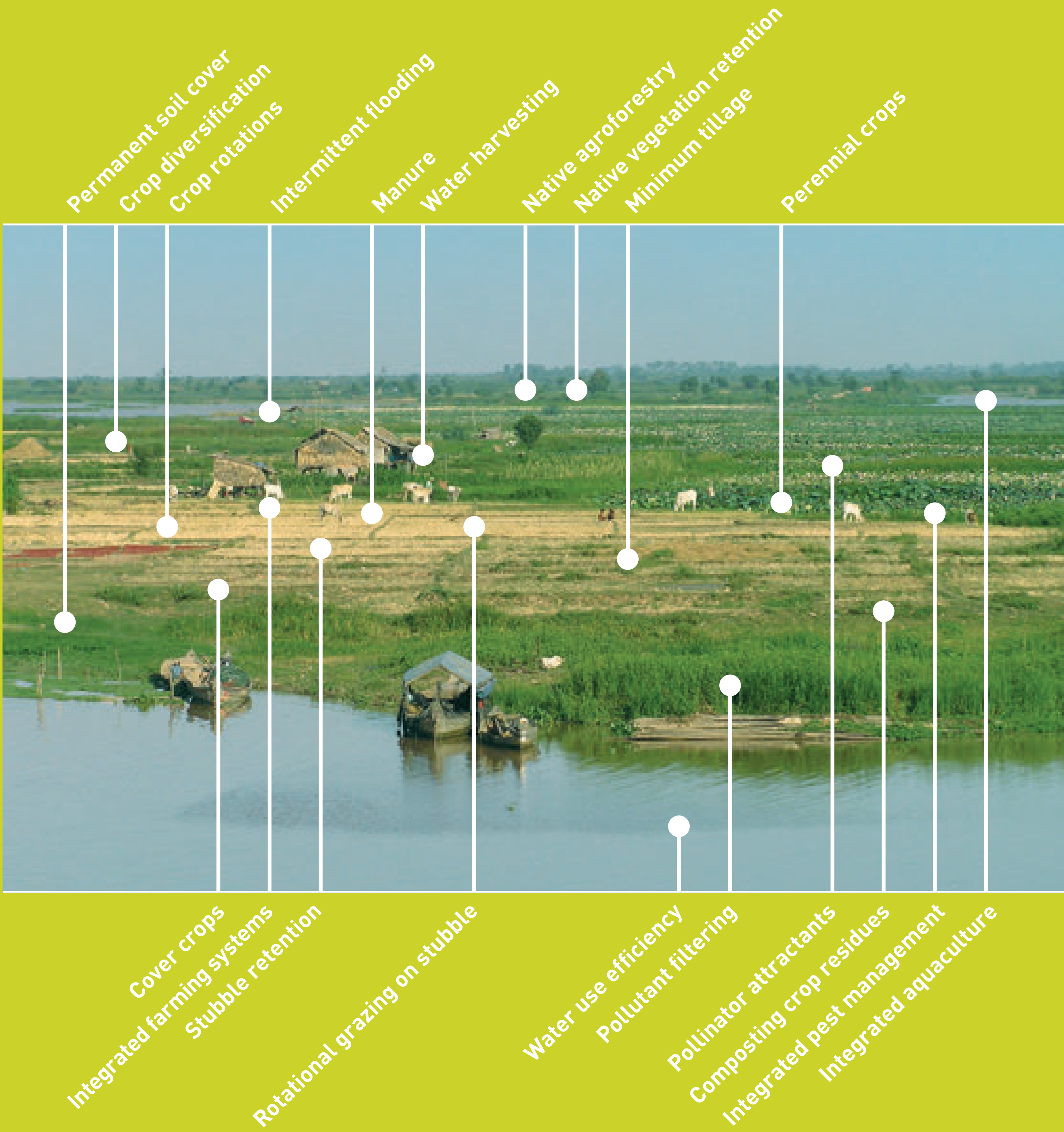
Agroecological intensification aims to widen the number of ecosystem services an agricultural landscape provides (21, 24, 25). So, while a highly industrial farming system may provide very well the service of 'yield', agroecological-based farming systems, regardless of the kind of farm or study sites, contribute to multifunctional farms that provide yield and diverse ecosystem services, in particular soil and water related benefits (26–28) (Figure 3.1).

This relationship between agroecological approaches on the one hand, and what is frequently termed conventional agriculture on the other, is frequently viewed in a binary way and can be highly adversarial and segregated. For example, using synthetic pesticides to control pests or encouraging the proliferation of the pest's natural enemies are often presented as being mutually exclusive approaches. The real challenge is to integrate the best elements of 'alternative' farming systems, in particular those related to ecological and social aspects (25), into high-tech agriculture, such as precision farming and more efficient use of inorganic agrochemicals (rather than a cessation of their use), for a more holistic approach.

Figure 3.1 depicts an example of a multifunctional landscape in which multiple components of an aquatic agricultural system are managed to provide diverse ecosystem services.

FIGURE 3.1 – Agricultural biodiversity is used for sustainable intensification

Examples of how different land and water uses can be integrated (e.g. grazing rice paddy stubble, integrating aquaculture into water bodies), as well as combining semi-natural elements such as vegetated field margins into the production system in order to provide ecosystem services (e.g. pest control) from wild biodiversity.
Kampong Chhnang floodplain, Cambodia. Original image © E. Baran



Credit: Bioversity International

The roles of agricultural biodiversity in agroecological intensification

Sustainable agriculture and agricultural biodiversity feature in both the Sustainable Development Goals (SDGs) and the Aichi Biodiversity Targets of the Convention on Biological Diversity (29), to differing extents, as a means to address environmental and social challenges (Box 3.2). While Aichi Biodiversity Target 13 specifically focuses on agricultural biodiversity, in the SDGs, there are two targets promoting such measures (Target 2.4 on area of land under sustainable agriculture and Target 2.5 on protecting levels of agricultural biodiversity in crops and livestock), with links and contributions mapped out to many of the other 16 goals, particularly goals 13 and 15 (30). Despite these calls for action, the role of agricultural biodiversity in sustainable food systems is still not well understood. A systematic review of over 300 peer-reviewed papers providing a definition of sustainable and/or ecological intensification mentioned nutrition and crop diversification in only 1.4% and 2.7% of papers respectively, whereas yield was mentioned in 91.7% of papers (31). Reducing environmental impacts, such as soil erosion and reduction in water quality, both of which can be biodiversity-linked, was mentioned in 67% of papers. This review highlights the limited scope of the current discourse on sustainable intensification (32).

BOX 3.2 – Selected global goals and targets where agricultural biodiversity can contribute

Sustainable Development Goals

Goal 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture

Target 2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality.

Target 2.5 By 2020, maintain the genetic diversity of seeds, cultivated plants and farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed.

Goal 13: Take urgent action to combat climate change and its impacts

Target 13.1 Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries.

Goal 15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss

Target 15.3 By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world.

Target 15.9 By 2020, integrate ecosystem and biodiversity values into national and local planning, development processes, poverty reduction strategies and accounts.

Convention on Biological Diversity Aichi Biodiversity Targets

Strategic Goal B: Reduce the direct pressures on biodiversity and promote sustainable use

Target 7 By 2020, areas under agriculture, aquaculture and forestry are managed sustainably, ensuring conservation of biodiversity.

Target 8 By 2020, pollution, including from excess nutrients, has been brought to levels that are not detrimental to ecosystem function and biodiversity.

Strategic Goal C: Improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity

Target 13 By 2020, the genetic diversity of cultivated plants and farmed and domesticated animals and of wild relatives, including other socio-economically as well as culturally valuable species, is maintained, and strategies have been developed and implemented for minimizing genetic erosion and safeguarding their genetic diversity.

Strategic Goal D: Enhance the benefits to all from biodiversity and ecosystem services

Target 14 By 2020, ecosystems that provide essential services, including services related to water, and contribute to health, livelihoods and well-being, are restored and safeguarded, taking into account the needs of women, indigenous and local communities, and the poor and vulnerable.

Agricultural biodiversity contributes to sustainable food systems by providing a set of resources that help "meet current food needs while maintaining healthy ecosystems that can also provide food for generations to come, with minimal negative impact to the environment" (33). The resources include cultivated biodiversity and also wild biodiversity, which plays an important role in agriculture, by cross-pollinating with cultivated crops to generate new sources of novel and adaptive traits, or by providing nutrient cycling, pollination, pest control and/or climate mitigation services to crops. Agricultural biodiversity's contribution to sustainable food systems occurs at four interacting scales: (i) within species (e.g. different varieties of bean or wheat), (ii) between species (e.g. wheat, beans, ginger, pears), (iii) field and farm (e.g. farming decisions such as the location and timing of different crops) and (iv) land use and landscape (e.g. cultivated fields, fallow, waterways, groves, hedges) (31). Understanding how the four scales of diversity interact to provide numerous ecosystem services, plus the added complication of considering both cultivated and relevant wild biodiversity, is challenging. Equally demanding is understanding what the actual ecological processes are that link agricultural biodiversity and ecosystem services (i.e. how they work). Despite the difficulty, scientific evidence and long-term experiments are revealing the complex dynamics of diversified systems and the multiple benefits both from biodiversity to agriculture and from agriculture to biodiversity (Figure 3.2). Although agricultural biodiversity includes animals, fish, microbes, soil fauna and fungi, to simplify the explanations that follow, we focus primarily on crop diversity, and its interactions with these other levels of biodiversity.

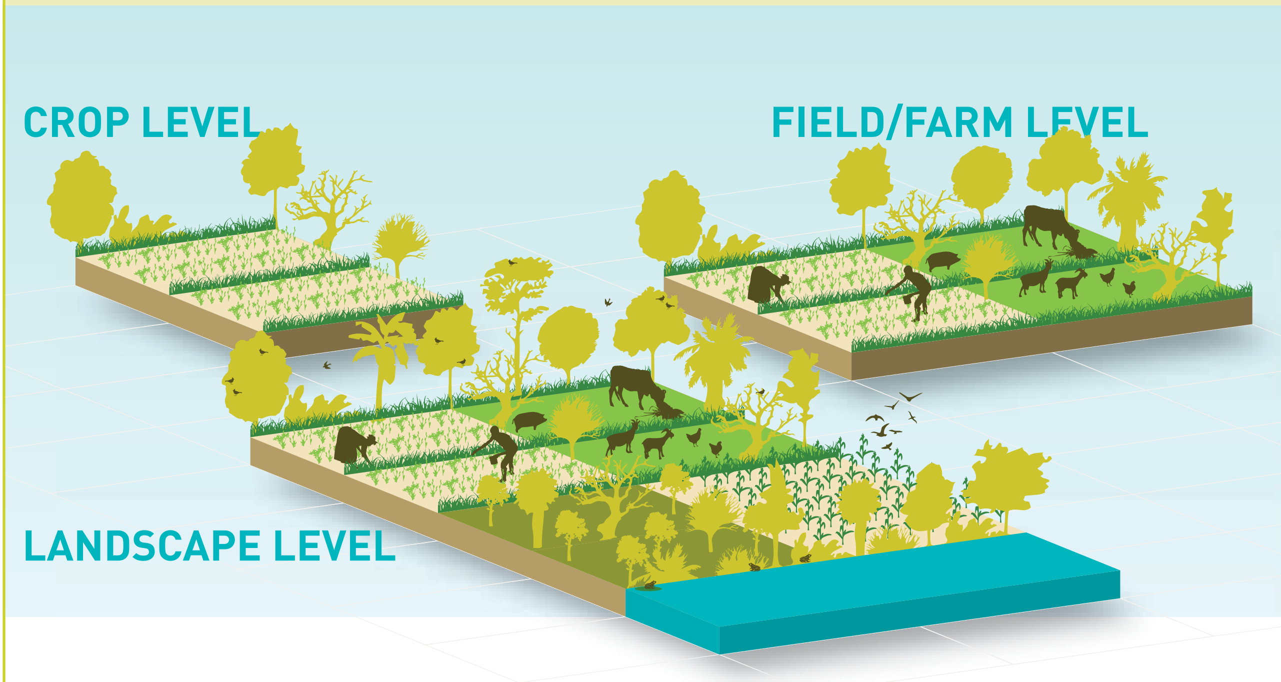
FIGURE 3.2 – Agricultural biodiversity at different levels contributes to healthy farming landscapes

Genetic diversity at crop level allows farmers to grow different varieties to suit different environmental conditions (e.g. poor soils) and resist different weather conditions (e.g. frost, unpredictable rainfall). Planting different varieties of the same crop can decrease pest and disease damage (7) and facilitate staggered flowering times to attract diverse pollinators (11).

At farm and field level, selecting different species with different growth forms, leaf size and shape, plant heights, rooting depth and nutrient uptake strategies, provides farms with more ways to respond to disturbances and shocks (12). Integrating livestock and crops reduces the need for synthetic inputs while facilitating more efficient nutrient cycling and availability.

At landscape level, complex landscapes have multiple benefits, e.g. forest remnants can reduce pests borne by the wind, and reduce soil erosion; patches of non-cropped vegetation also support beneficial plant and insect diversity, like pest enemies and pollinators (14,15).

Farmers manage trade-offs among benefits at many scales and across all levels, e.g. more biodiversity can lead to lower greenhouse gases and better pest control, but may reduce gross yields in the short term (16–18).



The relationship between biodiversity and ecosystem services is most often positive, but rarely linear (34–37). For many systems, it has been found that each additional species initially makes large contributions to improving any given ecosystem service. However, as more species are added, their marginal benefit declines because of redundancy (i.e. they perform the same function as another species in the system). Redundancy is important, because it offers resilience to the ecosystem service if other species are lost (i.e. different species with similar traits 'replace' lost species and therefore maintain important functions in the agroecosystem). Functional approaches to managing diversity in agricultural landscapes recognize that species richness or diversity may be less important than functional richness or diversity (38). Functional diversity acknowledges that species traits determine which services are provided or absent in a farming system. Example traits include nitrogen-fixing ability; stem density; rooting depth, form and density; or tolerance to cold and drought. Conventional cropping systems focus on single trait approaches where yield of the primary crop is often the only trait managed. Agroecological approaches to agriculture recognize that yield is the result of multiple ecological functions, including restoration and maintenance of soil carbon, pollination, pest control and nutrient cycling. Supporting these functions requires managing multiple species with different functional traits. A practical example of this approach is illustrated for soil management (Box 3.3).

The following pages outline the role of agricultural biodiversity in several important ecosystem services.

BOX 3.3 – Improving soil through managing functional biodiversity: an example from France

A farmer in Southern France, Yézid Allaya, manages an organic farm with primary crop production occurring between May and October. During the fallow months (November to April), he plants a mixture of four species: two grasses and two legumes. The specific trait desired of the legumes is nitrogen-fixing ability, whereas the grass species are selected for variable rooting depths and high root-to-shoot ratios. All four species have high cold tolerance, which permits them to grow through the winter. Finally, all four species are palatable and used as forage for the farm poultry. When planted in combination, the four species provide total soil cover, which reduces the risk of weed infestation. The farmer has several functions in mind: to build organic matter to increase nutrient- and water-holding capacity (high root biomass), to sequester nitrogen to make it available for the principal cropping season (nitrogen fixation); reduce weed cover and soil erosion (complementary plant heights for total soil cover); and poultry forage (palatability). The farmer obtains these functions through the careful selection of species with specific and complementary functional traits.

Yézid Allaya manages a 6ha organic farm north of Montpellier France. Biodiversity provides many functions on his farm, including reducing food waste, soil nutrient cycling and fertilization, carbon capture, pollination and pest control. More than 200 families benefit from the farm's produce and share the risk of crop failure. Credit: Lutin Jardin

Soil erosion control

Soil erosion is a natural process currently accelerated to extremely high rates in some agricultural landscapes. It becomes problematic from a productivity perspective when rates of soil formation are slower than soil loss rate. Increases in erosion are due in part to the over-simplification of vegetation, particularly in areas cleared for agriculture, which reduces soil protection from external forces such as wind or water. Retaining soil on farm benefits not only the farmer but also downstream users of clean water and healthy aquatic systems. Abiotic factors, such as slope steepness, slope length, soil condition or type, determine which parts of the landscape are more prone to erosion and, for instance, where vegetation should play a vital role in protecting this precious resource.

Agricultural biodiversity management strategies to reduce soil erosion include hedgerows (which help reduce runoff speed, facilitate infiltration and reduce wind erosion), cover crops (which protect soil from impacts of raindrops or wind erosion), agroforestry (which increases infiltration, produces mulching material, and the canopy reduces the speed of raindrops or wind), riparian buffer protection (which increases infiltration, retains sediment and reduces runoff speed), intercropping (which reduces exposed bare soil and optimizes nutrient cycling), non-cropped vegetation, and rotational livestock grazing regimes.

The capacity of biodiversity to control soil erosion depends on combinations of functional traits of the species included in the farming system (e.g. high root density, deep roots and dense vegetative structure), their location within the landscape, and the growth stage of the main crop. Practices such as hedgerows and mulching or grass strips are very effective strategies for keeping soil erosion at sustainable rates on steep slopes (39, 40), even if they can cause a dip in yields in the short term (40, 41). For example, adding a hedge of calliandra-Napier grass was found to significantly reduce runoff and soil loss, and boost other positive effects, such as biomass production and retention of nitrogen and phosphorous (42). Intercropping coffee trees with vegetables in hilly areas led to a soil erosion reduction of 64% with no decrease in coffee yield, compared to monocropped coffee (43). In a hardwood plantation, cover crops efficiently reduced erosion rates from 64% to 37%, particularly in the early stages of growth (44).

Pest and disease control

Crop losses to weeds, animal pests and pathogens are a significant source of food loss and must be reduced in order to support food security (45). Agricultural biodiversity can play an important role in plant protection through 'natural pest control', enhancing natural enemies, using pest-resistant crops and crop combinations, adapting cultural management, and judicious use of pesticides (45). Reducing the use of synthetic pesticides reduces the negative effects that they have on associated biodiversity, such as pollinators and soil biodiversity (46).

Farmers and plant breeders select and use varieties with genes that are resistant to pathogens and pests of their crops, and have developed farming systems that reduce the damage these cause (47, 48). Diversity employed over different seasons and across different parts of the farm, in the form of crop genetic diversity, polycultures and landscape heterogeneity, has been effectively used to control the damage caused by pests and diseases in agroecosystems (13). At the field scale, mixing varieties or species reduces the risk of pest epidemics (49, 50). Many farmers worldwide maintain a diversity of traditional crop varieties as part of disease management strategies (51, 52). Loss of local crops, which narrows down genetic options, reduces farmers' capacity to cope with changes in pest and disease infestations and leads to yield instability. Studies in Uganda have shown that increased common bean diversity results in reduced risks of anthracnose and angular leaf spot damage in crops (50).

The higher the number of species and varieties, the greater the structural diversity of a habitat or ecosystem. Greater habitat diversity in turn often supports greater abundance and diversity of beneficial predators such as spiders (53). For instance, a meta-analysis of multiple studies examining populations of many insect and other invertebrate groups in monocropped compared to diverse, multi-species systems found reduced numbers of plant-eating pests (23%) and increased natural enemy abundance (44%) in mixed plant associations, and found increased pest predation (54%) in diverse compared to monocropped systems (54). Complex landscapes tend to have more natural pest enemies (55), fewer pests (e.g. aphids) and often greater yields (56, 57). Patchy and diversified landscapes provide a habitat for natural pest enemies. For instance, non-crop habitats, such as fallows, field margins and wooded habitats, intermixed with cropping systems, lead to larger natural enemy populations (by up to 74%) and lower landscape pest pressure (by up to 45%) than simpler landscapes (58).

In addition, mosaic landscapes can reduce damage by pests, such as the coffee borer, which are mainly dispersed by wind, by disrupting their movement between fields in the agricultural landscape (59). The role of agricultural landscapes in pest control depends on a number of conditions, such as the presence of natural enemies in the region, the relative number of pests and natural enemies, the size and composition of the natural habitats, and lack of counteracting agricultural practices which eliminate enemies (60).

Large expanses of single species croplands are a high risk for losses to pest outbreaks, and are fully dependent on chemical and mechanical controls or genetic modification to keep losses down. As a general tendency, increasing diversity at each scale, from within-species diversity to landscape diversity, reduces risk of large crop losses.

Pollination

Pollination is a critical ecosystem service supporting 75% of the 115 major crop species grown globally, and up to 35% of global annual agricultural production by weight (61, 62). Pollination services, like the pest control services previously discussed, operate at many levels. Of practical importance to farmers and farming communities are the pollination services provided by native and imported pollinators to the 75% of crops requiring pollination to produce yield. Pollinators provide 10% of the economic value of world agricultural production (63), a value which might be even higher if the value to human nutrition is considered, since crops requiring pollination are largely fruit and vegetables, which are important sources of human nutrition. As much as 50% of plant-derived sources of vitamin A require pollination throughout much of Southeast Asia (64). One novel economic analysis of the value of pollination services is highlighted in Box 3.4.

BOX 3.4 – Assessing the value of pollination services: the case of Californian agriculture

Californian agriculture receives between US$937 million and $2.4 billion per year in pollination services from wild bee species. One-third of crops in California are pollinator dependent; the net worth of these crops is $11.7 billion per year. While many farmers rent honeybees to pollinate these crops at a cost of US$400 million per year, between 35% and 40% of all pollination services are provided by wild species. In 2012, bee keepers in the US earned more from pollination services provided by honey bees, than from honey itself: earning $283 million from honey, versus an estimated $656 million from pollination.

Source: (65) and US Agricultural Statistics Board[ii]

Hummingbirds are important pollinators in the Americas. This species is also one of 120 bird species that were analyzed to see whether they might be natural predators of the coffee berry borer (*hypothenemus hampei*), a devastating coffee pest.
Credit: PMA

The latest evidence indicates high seasonal bee hive colony loss, and declines in the abundance, occurrence and diversity of wild bees and butterflies (62). The *Pollination Assessment* by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (62) highlights the importance of this service and recommends actions to support the persistence of wild pollinators, which could reduce farmers' dependence on rented honeybee populations, while increasing contributions of local bee populations. Other actions to ameliorate the negative impact on pollinators of reduced landscape complexity, connectivity, nesting and foraging resources include practices such as fallow, border planting and semi-natural habitat conservation (66). Other practices, such as intercropping, agroforestry, targeted flower strips, crop rotation and cover crops, also mitigate those impacts, although their effects are context dependent (66).

Pollinators also play a critical role in maintaining plant genetic diversity, which is essential for the long-term survival and adaptation of crops (67). The random exchange of pollination between individual plants facilitated by animal pollinators ensures genetic mixing, the basis of natural selection and the development of novel genotypes.

In turn, crop genetic and species diversity are beneficial to pollinators (68). Genetic diversity can increase pollinators by ensuring the availability of nectar resources over a prolonged time period. This is an example of where functional diversity is more important than species diversity – if the functional trait is 'flowering', we would seek to enrich agricultural landscapes (fields, fallows and margins) with higher 'flowering period functional diversity' to ensure the stability of pollinator populations, particularly those serving agricultural crops requiring pollination for fruit set and productivity (13).

Greater diversity in landscapes leads to increased pollinator abundance and diversity (67). Bee diversity and abundance are greater in diversified fields (69) or in field margins, where they can spill over into fields or orchards requiring pollination services. For example, organic fields across biomes (tropical/subtropical, Mediterranean, temperate) hosted on average 50% greater richness and 70% more abundance of wild bees than conventional fields (69). High-quality, dense floral strips in large-scale agricultural landscapes support bee and wasp diversity by providing habitat (70). Pollinators consistently benefited from strips of trees and other wild vegetation in tropical farming landscapes, for connectivity (71) and habitat for nesting and overwintering (72). Similarly, small increases in bee habitat quality (e.g. nesting and floral resources) at the landscape level can lead to significant increases in total bee diversity (69). In Mexico, structurally and floristically complex shaded coffee systems hosted larger pollinator diversity than simpler systems, leading to greater fruit-per-flower ratios (up to 20% larger) (73). Greater amounts of semi-natural vegetation in the vicinity of almond orchards in California were also found to increase both wild pollinator visitation and fruit set (74).

Wild biodiversity conservation

As seen in the examples above, for pollinators and pest control, habitat diversity is an important component of a healthy agroecological system. Habitats may be the crops themselves, or they may be native vegetation. Maintaining connectivity among natural habitats is important to facilitate healthy populations of wild biodiversity and protect them at different life cycle stages (e.g. migration, dispersion, reproduction) (75).

Agriculture is often a threat to wild biodiversity, with considerable losses of biodiversity frequently resulting from the expansion of agriculture at the expense of native systems (34, 53, 76–78), or from intensifying the management of land that is already being cultivated. Wild biodiversity suffers from: the loss of habitat features, such as hedgerows, field margins and scattered trees; the application of agrochemicals, such as inorganic fertilizers or synthetic pesticides; and disturbances of soil through various tillage practices (79, 80).

But agriculture does not necessarily have to be a threat. Agricultural systems, from fields to landscapes, can support very high levels of wild biodiversity, including species of conservation concern (81). This places agriculture at the core of wild biodiversity conservation, in terms of: (i) addressing multiple on- and off-site threats, (ii) managing agriculture in order to provide improved habitat and resources for wild biodiversity, and (iii) ensuring sustained delivery of ecosystem services both to and from agriculture. Wild biodiversity can be enhanced through increased crop diversity (82–85), increased vegetation diversity (86) and the implementation of various agroecological management actions on farm (87). Complex landscapes (i.e. landscapes consisting of a mosaic of numerous land-use types and elements) contribute greatly to the conservation of wild biodiversity and therefore help maintain the ecological functions and services that they provide. A study in Costa Rica looked at the responses of numerous groups (e.g. mammals, moths, birds) in relation to landscape complexity and intensity of management. The researchers found that the number of mammal species was approximately the same, on average, in small forest remnants embedded in a complex coffee landscape as in natural forest (eight species on average). Meanwhile, the number of mammal species in small forest remnants surrounded by pasture (less structurally diverse and more structurally and compositionally different from forest) was much lower (4.5 species on average) (88). Also in Costa Rica, twice as many species and individual birds were found in complex coffee and cacao agroforests than in simpler and more homogenous pasture lands and sugarcane fields (89).

Natural vegetation embedded in agricultural landscapes can also help with connectivity. Tree cover (e.g. agroforestry, live fences) is critical for bird conservation, bird diversity and mobility (90–92). Other biodiversity, such as bats, butterflies and dung beetles, also benefit from tree cover and natural habitat in agricultural landscapes (93, 94). Woodland areas are important for deer dispersal (95) and moths and butterflies (96), whereas river bank areas increase the connectivity for carnivores between protected areas (97). Including live fences in low-diversity pasture lands can provide corridors which allow forest-dependent species to cross agricultural lands and reach forest patches (98). Hedges, field margins and road verges were shown to be important (although neglected) habitats and refuges for crop wild relatives in the UK (99). Both pest (aphid) predation and pollination were increased in homogenous cropping systems when hedgerows were present (100). These agricultural management practices can facilitate movement and provide shelter, habitat or foraging resources, particularly when the fields they surround do not provide the needed habitat and mobility.

Finally, the fields themselves can be managed to support biodiversity. Small changes to conventional crop management can have important impacts on wildlife and ecosystem services (Box 3.5).

Soil quality

Soil quality is "the capacity of soil to function" (102). This concept of soil quality is a balance of three major goals: sustained biological productivity, environmental quality, and plant and animal health. Critically, soil quality recognizes that soil is a living surface rather than an inanimate surface. While forests are well recognized for their role in climate regulation, soil biodiversity also plays an equally important role in regulating global metabolic processes (103). A healthy soil is formed by the balance between its physical properties, its biology and its chemical state. Healthy soils function as vital living ecosystems, sustaining plants, animals and humans.

Soil provides functions such as litter decomposition and carbon cycling, nutrient cycling, soil structure formation and maintenance, and biological population regulation (pest suppression by predatory species) (103). Soil biodiversity regulates biological processes that underpin long-term agriculture sustainability and crop health. Soil biodiversity includes complex relationships among diverse taxa from millipedes (nutrient cycling) and centipedes (pest predation), earthworms (soil structure, water infiltration), and springtails (organic matter decomposition), to spiders (predation) and millions of microbes in the soil (104). Three broad areas where soil biodiversity has the potential to be highly influential are: (i) soil nutrient cycling, (ii) soil physical structure and (iii) food web interactions, with benefits at farm and landscape scale (103).

BOX 3.5 – California rice

While integrated biodiversity in agriculture is often portrayed as pertaining to diversified smallholder systems, small changes in conventional crop management can have important impacts. California rice is a US$5 billion industry encompassing 220,000ha of land, primarily around the city of Sacramento, at the confluence of the American, Sacramento and San Joaquin rivers. It is highly productive, producing 2,270 tonnes per year, with some of the highest yields worldwide, averaging 8t/ha. While California rice is an intensively managed monoculture crop, with seedlings sown by airplane, several adaptations to management practices have helped make this landscape an important contributor to conservation and to reducing flood risk for the city of Sacramento.

This was not always the case however. Up until 1990, rice fields were burnt in the autumn, following the rice harvest. This practice reduced the risk of disease and helped to eliminate the silica-rich rice straw, facilitating spring planting. As the urban population of the city of Sacramento grew, however, pressure was placed on rice farmers to halt the autumn burning because of the negative impacts of the air quality on respiratory ailments. A burning ban was enacted in the 1990s. While farmers initially resisted the ban, collaboration with researchers found that winter flooding of rice fields was an effective means of eliminating the rice straw. An unintended benefit of this practice was the doubling of winter wetland habitat at the peak of the waterfowl migration. A change in agricultural management, driven by air quality rather than yield, has now been recognized for its tremendous conservation value, providing habitat resources for 203 species of wildlife and 9 million migratory waterfowl. The US Fish and Wildlife Service estimates that purchasing an equivalent amount of wetland would have cost $2 billion, with a management cost of $35 million per year. In addition to the habitat value, many of these farms serve as the first line of defence of the city of Sacramento against periodic flooding. The estimates of this service range between $8 million and $80 million per flood event.

Source: (101)

Various levels of biodiversity, combined with certain farming practices, interact to form healthy soils: soil biodiversity, aboveground plant species diversity and functional diversity. Soil biodiversity correlates with aboveground biodiversity across the world (105). It largely determines how productive agricultural land is (106, 107) and increases resilience of soil against climate change. The relationship between aboveground plant diversity and the belowground microbial and invertebrate communities that drive soil fertility is complex. Underground biodiversity can have a positive effect on aboveground plant diversity. However, the soil organisms can also produce negative effects by competing with plants for nutrients or by hosting pests and diseases, thus reducing plant productivity (108).

Ficus sycomorus, a desert tree widely distributed in Africa and parts of Asia, showing both the extent of soil erosion and the species' ability to tolerate such changes.
Credit: Bioversity International/R.Khalil

An array of processes associated with agricultural land-use changes and management threaten soil biodiversity, and therefore have the potential to impair ecosystem services: use of genetically modified organisms, habitat fragmentation, introduction of invasive species, climate change, soil erosion, soil compaction and organic matter decline (109). The more intensively managed the land, the fewer species and individuals of decomposer taxa (e.g. millipedes, springtails) (53). Specific agricultural management actions can also impact upon soil fauna, including soil tillage and insecticides. Tillage is generally negative for soil biodiversity, although it depends on soil texture and depth (110). In a study in Zimbabwe, soil tillage reduced the abundance of several groups of soil macrofauna (ants, termites, beetles, centipedes) that perform a range of ecosystem services (e.g. increased water infiltration, pest predation) in agricultural systems (111). Regarding insecticides, neonicotinoid pesticides can have a severe negative impact on soil fauna (112). Organic production is associated with higher levels of soil diversity than conventional farming (87).

Conversely, there are also many management interventions that farmers can undertake to positively impact soil diversity and increase ecosystem service provision. These include reduced tillage systems, organic production and crop rotations. Cropping systems with high agricultural biodiversity from crop rotations displayed increased soil carbon by 28–112% and nitrogen by 18–58% compared to systems with low agricultural biodiversity (113). In simplified systems, adding even one or two additional crops can have a large effect. For example, adding rotation crops to a monoculture increased total soil carbon by 3.6% and total soil nitrogen by 5.3% (114). Including a cover crop in the rotations increased soil carbon by 8.5% and soil nitrogen by 12.8% (114). Earthworm abundance and diversity was greater in rotated crops than non-rotated crops (115). For microbial communities, crop rotations increased the number of microbe species by about 15%, an increase that can lead to improved ecological function and resilience (116).

Agricultural biodiversity management tends to be associated with extended periods of soil cover (both through intercropping and temporal rotations), and thus improved soil stability (13). Cover crops and agroforestry protect the soil and improve organic matter and water content, particularly during the dry season, acting as resource islands (117). Intercropping and fallow periods influence soil structure, soil nutrient availability, water-holding capacity and the capacity of the soil to hold onto essential nutrients (103).

For improved soil functions in farm fields, functional diversity is important. Species with fibrous rooting systems and high belowground biomass are useful for rapidly increasing soil carbon and organic matter (118). Conversion of plant matter to more stable humus-rich compounds depends on soil biodiversity – which in turn depends on the 'food' source it has. A diversity of root substrates will favour more balanced belowground communities and reduced disease incidence. Farmers commonly select species based on functional traits such as nitrogen-fixing ability, rooting depth, rooting type and cold tolerance (38). Similarly, cropping systems with complex and diverse root architectures facilitate water and nutrient uptake (103).

Yield of crops cultivated for food

Yield is the quantity per unit area of a crop that is harvested. It is generally classified as a provisioning ecosystem service in its own right, and is the result of the interactions of crop genetics, soil type and quality, weather, pests, diseases, pollination and external inputs (such as fertilizer). Over the last few decades, crop yields per unit area in many (although, critically, not all) agricultural regions and systems around the world have greatly increased, due to agricultural intensification (e.g. inorganic fertilizer application, synthetic pesticide use, crop specialization). In addition to total yields of crops, human well-being and food security also depend upon yield stability (119). Crop yields are projected to decline with climate change; at the same time, variability of yields (e.g. from year to year) is likely to increase (120). This can have dramatic impacts on income risk, stability of supplies and food security (121). It is important to note that yield in general is measured by amount alone, without consideration of the composition of the yield (e.g. nutritional aspects). While edible crop yield is an important measure, a novel metric, recently proposed, measures the nutritional value of the yield. It calculates the number of adults who could obtain 100% of their recommended annual dietary reference intakes for different minerals and nutrients (e.g. calories, protein, iron, zinc, vitamin A) from 1ha per year (122).

A promising strategy for reducing variation in crop yields is to diversify agroecosystems, such as through the use of crop rotations (123). Diversifying corn and soybean systems by adding crop rotations (while reducing tillage) increased yield by 7% and 22% respectively (123). Greater species richness in a natural system generally yields greater productivity (124). This is due to a combination of effects known as the sampling effect and the complementary effect. The sampling effect says that by increasing diversity, one increases the odds of including a more productive species. In contrast, the complementarity effect argues that there are complementary interactions among species that deliver community yields that are greater than the sum of individual species yields. Both concepts are applicable in ecological agriculture. The sampling effect is often used by farmers and farming communities in their seasonal selection of one or more species most likely to provide the greatest economic yield per amount of labour. Complementarity is more complex, and more frequently found in traditional systems, such as home gardens, agroforestry or farms with dedicated efforts supporting ecological agriculture. It requires selection of species cultivated in proximity because of the complementary or synergistic effects among the selected species. An often cited example is the Native American 'three sisters' system of cultivated maize, beans and squash together. These three crops are ecologically and nutritionally complementary.

Increasing within-species diversity can increase yield. A study on barley in Ethiopia found that for each unit increase in Shannon diversity (a commonly used biodiversity measure), yields increased by 415–1,338kg/ha (125).

Synergies among different species types in the production system (e.g. annual crops, perennial crops, livestock, aquaculture) can bolster yields, reduce waste and reduce dependencies on external inputs (126, 127). Waste from one part of the system can be used as a productive input to another part of the system (e.g. manure from livestock can be used as fertilizer in cropping, crop residues as mulch for other crops, livestock by products as aquaculture feed) (128).

Higher crop species diversity can lead to improved quality of produce (129). For example, shaded coffee systems (more botanically diverse systems which provide shade) promote a slower and more uniform filling and ripening process, which gives a better quality product than is generally found in unshaded plantations (130). Research on the effects of shade on popular coffee bean varieties, found that large beans (>6.7mm diameter) constituted only 49% of beans for the Caturra variety and 43% of beans for the Catimor variety, respectively, in unshaded coffee, but represented 69% and 72%, respectively, in shaded coffee (130).

Resilient agricultural landscapes

Resilience in agriculture is the capacity of an agricultural system to bounce back from shocks, and to adapt to new and changing circumstances. Resilience is not strictly considered an ecosystem service as such, but the result of the integration of functions such as pest and disease control and tolerance to different extreme weather conditions.

Diversity among and within species provides an insurance, or a buffer, against environmental fluctuations, because different species and varieties respond differently to change, leading to more predictable aggregate community or ecosystem properties (13, 131). Crop diversification that allows cultivation of different crop species spatially (mixed land use, intercropping) or temporally (rotations in different seasons) maintains stability of food production, income and nutrition, and reduces risks from climate variability, disease, pest epidemics and market changes. For example, practices that promote agricultural biodiversity, such as agroforestry systems, buffer against high temperatures and in some cases prevent frost damage (132). Hedgerows protect field crops against wind damage and desiccation (133, 134). Increased complexity of tree vegetation reduced hurricane damage on Mexican coffee farms (135).

Risks of pests and diseases can be reduced by promoting crop species diversity through crop rotations and by interchanging cereal crops with crops such as legumes, oilseed and forage crops (56, 57, 85, 136, 137), which interrupt the pest lifecycle and reduce pest densities. Within-species diversification, mixing varieties within the field or having many different varieties in adjacent fields, provides resilience against damage and reduces losses from pests and diseases (13, 50).

In managed grasslands, an ecological and economic assessment of the potential risk-reducing effects of species diversity in terms of yields and their temporal stability from a farmer's perspective reveals significant insurance values associated with diversity (138). The economic value of diversity tends to be underestimated if the role of species diversity as a valuable *ex ante* risk management strategy is not taken into account.

Smallholders traditionally diversify their production system to stabilize productivity under climate uncertainty (139–141). Farmers may choose to grow multiple varieties with different maturation times, or different levels of tolerance to stressors such as drought or frost. Using traditional varieties in production systems increases the capacity of the system to adapt to unexpected or changing climate events, as they harbour higher levels of genetic diversity, and so are more able to respond to variation in their environment (142). Diversified landscapes with redundant varieties and species respond better to change and cope better with unpredicted disturbances (143). For example, diversified systems in Nicaragua recovered better and faster than simplified systems after Hurricane Mitch in 1998 (144). In the future, farmers will need to exploit a far broader range of crop diversity than today, as agroecological zones will shift under climate change, novel climates are expected to arise, and climate variability to increase (145). Resilience to future climate scenarios will require exploiting a far broader range of crop diversity, including wild genes (145). Beyond being a source of climate-tolerant traits, agricultural biodiversity will also be essential to cope with the predicted impacts of climate change as the underpinnings of more resilient farm ecosystems in general (17).

Options towards more resilient farming systems include strategies based on crop species and variety diversification. Strategies may include cropping patterns and rotations, which adopt varieties tolerant to climate shocks, such as drought and flooding, or use varieties adapted to changes in cropping seasons, such as early-maturing varieties. Farming systems will need to maintain and reintroduce traditional varieties, adopt new species and varieties to meet newly developed production niches, and develop ways of ensuring that materials remain available, accessible and adapted (146).

Enabling environment needed to support multifunctional sustainable farming systems

Knowledge of what works for biodiversity-based ecosystem services for sustainable food systems, as outlined above, is not enough on its own. In addition to the physical components of a multifunctional farming system, supportive social, economic, governance and political institutions are also needed.

Restoring, maintaining and protecting agricultural biodiversity depends on tackling challenges at different scales. Food production's large environmental footprint is related in part to market failures (e.g. often little direct cost to producer for causing pollution) and the undervalued role of agricultural biodiversity in sustainable production functions, conservation of wild biodiversity and the production of ecosystem services. Incentives such as payment for ecosystem services or certification schemes aim to correct these failures by 'rewarding' farmers for the adoption of environmental or socially friendly practices (147) that often result in public goods such as climate regulation or soil erosion control. Mexico, Costa Rica, China, Europe, the USA and Australia are implementing agri-environmental schemes (148) and Costa Rica and Brazil are already implementing national policies that promote multifunctional landscapes through integrated land management (149) or 'biological corridors' (150, Box 3.6). At global or regional scale other actions, such as Biosphere Reserves (151) and Model Forests,[iii] support and facilitate the management of multifunctional landscapes (149). Integrated landscape management is widely practised worldwide. All locations, however, face similar challenges, such as lack of funding, lack of institutional support or policy frameworks, and difficulty engaging the private sector and other important stakeholders (149, 152, 153). Despite these efforts, the proportion of sustainably produced food and agricultural biodiversity (i.e. the share of the market) remains low in food systems compared to food produced from conventional, monocropped systems (148).

BOX 3.6 – Volcanica Central Talamanca Biological Corridor in Costa Rica

While the term 'biological corridor' may conjure up an image of linear paths connecting protected areas, the Volcanic Central Talamanca Biological Corridor (VCTBC) is actually a 114,000ha mosaic landscape comprised of coffee, cattle and sugarcane farms, a large urban area and forest (50%). The landscape is managed for multiple functions, including producing the nationally recognized 'Turrialba cheese', and an abundance of fruits and vegetables. In addition to food production, however, the landscape provides an important recreational space for rafting and mountain biking, and the three dams on the Reventazon River produce nearly 40% of the country's energy needs. How farmers manage their fields has direct impacts on all of the functions in the corridor. Agroforestry systems, such as live fences and shade coffee, are the primary means of providing habitat and connectivity for wild biodiversity passing through the corridor. Soil conservation practices have reduced sediment flows into waterways with direct impacts on the cost of energy production. Management of agricultural run-off has determined water quality in the region's rivers, impacting biodiversity, drinking water quality and ecotourism opportunities. Several benefits are felt by farmers as well – the same practices that enhance connectivity for wild biodiversity serve as barriers for agricultural pests, notably the coffee berry borer. The VCTBC is managed by a local, multistakeholder committee, but benefits from national recognition and privileged access to Costa Rica's payments for ecosystem services scheme. More importantly however, recognizing the positive impacts of agricultural practices on multiple sectors has facilitated cooperation among stakeholder groups, and provided a safe space for dialogue and managing conflicts.

Source: (150)

Institutions to maximize agricultural biodiversity use and benefits

Community-based approaches, such as community-based biodiversity management and community seedbanks, promote the capacity of local communities to access and adopt new species and varieties of crops, plus information and inputs to help them adapt to changing weather extremities (146, 154, 155). Similarly, farmer-led grassroots or participatory plant breeding approaches build social capital so that people in communities are better able to select and develop locally suited crop varieties for specific agroecological conditions (156, 157).

Farmer field schools are institutions where farmers can discuss, trial and share information about agroecological interventions (e.g. integrated pest management) designed to use biodiversity to reduce the pressures on ecosystem services (158). Approaches of this kind, in which institutions support farmers to combine their own knowledge with new practices, are effective at improving adoption of beneficial practices leading to improved agricultural production and farmers' incomes (159). As an example, farmer field schools with 200 onion growers in Nueva Ecija province in the Philippines led to a significant reduction of pesticide use, with important human health and environmental implications (160). Rural market institutions for seeds and agriculture are also important in promoting access to and availability of crop genetic diversity to minimize risks and vulnerabilities to external shocks as well as adapt to changing climate (146, 161). Formal and informal institutions and social relationships are important in facilitating or hindering adaptation to climate change (162, 163). Institutional factors, such as international agreements and intellectual property rules, can promote or hinder increased use of crop genetic resources to adapt to climate change and many other stressors and market opportunities, meaning that access to genetic resources will be determined not only by supply and demand, but also by legal and political factors (164, Chapter 4 of this publication). Unhindered flow of germplasm to farmers, breeders and researchers from international (CGIAR) and national genebanks is essential to enhance farmers' capacity to adapt to changing climates at the local and global level (165).

Incentives to maximize agricultural biodiversity use and benefits

Experiences of incentive schemes for conservation and agri-environmental schemes indicate that incentives need to be carefully designed in order to avoid pitfalls and achieve the desired outcomes. In particular, incentives should be part of long-term adaptive management and landscape planning (166). Incentives must assess trade-offs, such as reduced yield during the first years of establishment of multifunctional farms and landscapes, versus long-term increased provision of other ecosystem services (167). Incentives must have clearly articulated, achievable objectives (168) and be targeted to the requirements of priority stakeholders, whilst being mindful that there are likely to be trade-offs among some objectives, stakeholder requirements and perspectives (169).

Monitoring the impact of agricultural biodiversity on ecosystem services

In general, the greater the number of species and varieties, the greater the productivity and resource use across ecosystems (170). Higher numbers of different species and varieties at multiple spatial scales (e.g. field, community, ecosystem, region) generally lead to greater ecosystem stability and higher provision of ecosystem services (36, 171–173), which makes such ecosystems more resilient to external shocks.[iv] For this reason, the linkages between biodiversity and ecosystem services have often been assessed through counting the number of species in a given area (richness) (174, 175). Alternatively, they can be assessed by measuring the abundance of organisms associated with a given service, such as pollination (176).

However, a full assessment requires consideration of other aspects of biodiversity, such as functional diversity (177). Richness assesses the number of species, whereas functional diversity assesses the traits associated with different functions in the system, such as food groups and nutrition (178–180), or leaf nitrogen content, root length or maintenance of soil fertility (181). Functional diversity is more sensitive than richness alone (e.g. the number of species can stay the same, even when species turnover is considerable) in detecting severe declines and non-random loss of species under land-use intensification (182).

Metrics for measuring agricultural biodiversity for multiple benefits in sustainable farming systems

There is no shortage of *potential* indicators of agricultural biodiversity in farming systems. However, selecting indicators that are feasible, available (across many locations, systems and datasets), actionable (i.e. an indicator or measure can be translated into an intervention or policy to improve an aspect of farming system sustainability), and cost effective (e.g. crop varietal data is vital, but the means for collecting it could be very expensive and technically demanding), means that not all potential indicators can be used. Nonetheless, data collection, storage, analysis and access techniques are evolving and improving very rapidly, particularly in the areas of remote sensing, geographic information systems (GIS) and crowdsourced data through mobile devices. Consequently, that which may seem unfeasible, unwieldy or prohibitively expensive today may be far more feasible and achievable in the near future. Accordingly, we have tried to be both pragmatic and optimistic in the indicators and metrics proposed here.

In the context of the Agrobiodiversity Index, there are a number of existing monitoring frameworks that could be drawn on, primarily from across Europe. However, these have mostly been developed as national level biodiversity assessments for associated wildlife in agricultural landscapes, with often uncertain or under-explored linkages to ecosystem services (183).

One promising approach is BioBio,[v] a farm-focused monitoring scheme that captures parameters linked to ecosystem services provided at the farm level (183). BioBio has distilled key scientifically sound and relevant farm-scale indicators for a pan-European agricultural biodiversity monitoring system, including 23 key indicators for habitat, species and genetic diversity and farm management. Indicators are measured through habitat mapping, field recording methods and farmer interviews (184). The indicators and data collection approach are promising to assess biodiversity and ecosystem services in agricultural landscapes, but need further adaptation and development for implementing outside Europe. They are also very labour intensive, with associated costs. As such, transplanting these indicators into the Agrobiodiversity Index may not be feasible in the immediate term.

The pan-European project 'Rationalising Biodiversity Conservation in Dynamic Ecosystems' (RUBICODE)[vi] conducted a comprehensive review of 531 indicators for monitoring ecosystem and habitat ecological quality (185). This rich dataset facilitates moving beyond the common assessment of provisioning, regulating and cultural ecosystem services through remote sensing proxy data such as land cover and the normalized difference vegetation index (a way of predicting the density of vegetation by measuring the colour of wavelengths and sunlight reflected from patches of land) (186). RUBICODE lists several validated indicators across ecosystem types (e.g. forest, scrubs, grasslands, soils, agroecosystems, floodplains and landscape) which are related to ecosystem services. For example, wild biodiversity conservation and soil formation are ecosystem services connected to several indicators at national, sub-global or global scale. Other ecosystem services, such as soil composition, pest control and pollination, have only a few indicators and are at local scale. Other indicators to assess pest and disease control, which are not included in RUBICODE, include species and variety richness, evenness and divergence (52) and the percentage of non-cropped land, landscape composition and complexity (60). One indicator to

Madagascar is characterized by the richness of its flora (12,000 species of vascular plants) and an immense diversity of ecosystems. About 85% of the flora of Madagascar is endemic. More than 150 crop wild relatives covering 30 genera are present in Madagascar. They are distributed throughout the country, but the majority are found in forest ecosystems. Credit: Bioversity International/D.Hunter

assess pollination is the proportion of semi-natural habitat in the landscape and distances to potential pollinator-friendly habitat (187). Insects such as flies, beetles, moths and butterflies should also be considered, as they are also important contributors and have different responses to landscape structure than the more frequently mentioned bees and wasps. RUBICODE indicators for wild biodiversity conservation are mostly related to vegetation, soil and organism type. Other potential metrics include landscape attributes and metrics based on land cover or land-use maps. These include edge contrast (structural or compositional difference among adjacent land-use types), patch shape complexity ('crinkly' edges that facilitate cross-boundary movement or straight edges that can inhibit it), aggregation (e.g. clustering of patches), nearest neighbour distance, patch dispersion, large patch dominance, and neighbourhood (landscape composition in general). These can indicate landscape suitability for wild species movement and habitat. Selecting the most appropriate indicators to monitor the impact of agricultural biodiversity on ecosystem services at national scale is challenging due to the mismatch in temporal and spatial scale and resolution (Table 3.1).

The evidence around agricultural biodiversity and its contribution to ecosystem services and healthy agroecosystems described in this chapter indicates that agricultural biodiversity-based elements, such as hedgerows, riparian vegetation, live fences and field margins, can provide soil erosion control, pest and disease control, pollination, wild biodiversity conservation and soil quality (Table 3.1). Measuring these can be an acceptable proxy to combine with other indicators to give a global assessment of biodiversity at landscape level. However, remote sensing of land use or land cover at national or global levels with coarse resolutions might ignore or underestimate the quantity of those linear elements, and is less likely to be able to report on aspects of element quality. Similarly, increased agricultural biodiversity through crop rotation is important for soil formation and composition, but having remote sensing information available in the required seasons might be a limiting factor as well. Table 3.1 links agricultural biodiversity-based practices (and their spatial and temporal applicability) to the forms that they commonly take in agricultural systems (in-field, linear, etc.) and the ecosystem services that they are likely to deliver. This is based on the evidence

TABLE 3.1 – Linkages between practices and ecosystem services discussed in this chapter

In-field refers to practices predominantly taking place in an agricultural field or paddock, off-field refers to adjacent non-agricultural land-use types, linear refers to elements of the farm/landscape that tend to occur in linear form (as opposed to patches), such as field margins and hedgerows, and landscape refers to large-scale mosaics of multiple land-use elements.

	Scale of variability		Location or shape				Ecosystem services						
	Spatial	Temporal	Off-field	In-field	Linear	Landscape	Soil erosion control	Pest and disease control	Pollination	Wild biodiversity conservation	Soil quality and function	Yield of crops cultivated for food	Resilient agricultural landscapes
Agroecological practices based on agricultural biodiversity													
Agroforestry	●			●			●	●	●	●	●		●
Cover crops	●	●		●			●	●	●		●		●
Crop rotation		●		●				●	●		●	●	●
Intercropping	●	●		●			●	●	●		●	●	●
Live fences (herbs or shrubs): hedgerows	●				●				●	●			●
Live fences (trees)	●				●			●		●			●
Live fences (herbs or shrubs): field margins	●				●		●	●	●	●			
Non-cropped vegetation: fallow	●	●	●	●			●	●	●		●		●
Non-cropped vegetation: natural habitat (woody & herbaceous)	●		●		●	●		●	●	●	●		●
Riparian buffers	●		●		●		●	●	●	●	●		●
Crop species diversity (between species)	●	●		●			●	●	●	●	●	●	●
Crop diversity (within species)	●	●		●				●	●			●	●
Other agroecological practices													
No or reduced tillage or soil disturbance	●	●		●			●			●	●		
Organic production	●	●		●				●	●	●	●		
Pesticide reduction	●	●		●				●	●		●		●
Soil biological diversity	●	●		●			●	●		●	●		
Landscape management and planning													
Landscape configuration/composition	●	●	●	●	●	●		●	●	●			●

presented in this chapter and complemented with previous assessments (e.g. 15, 24, 66). This is very much a work in progress, as a full systematic review of agroecological and agricultural biodiversity-based management interventions and all ecosystem service responses is beyond the scope of this chapter.

Whilst it is possible to measure some of these through remote sensing (e.g. riparian/riverine vegetation), measurements at very large scales (e.g. national) of management actions are unfeasible at the time of writing. However, rapid advances in crowdsourced data may lead to equally rapid progress in gathering agricultural management data at greater spatial scales, which can be built into future iterations of the Agrobiodiversity Index.

A recent and very exciting development in assessing the relationship between land use, land management and biodiversity (principally wild biodiversity thus far) is the PREDICTS (Projecting Responses of Ecological Diversity In Changing Terrestrial Systems) database of local terrestrial biodiversity responses to human impacts (188, 189). The database contains more than 3.2 million records sampled at over 26,000 locations and representing over 47,000 species. It catalogues measures of biodiversity (e.g. richness, abundance) that result from land-use change (e.g. native vegetation to agriculture, pasture to cropping) and management interventions (e.g. cropping systems of high, medium or low intensity of management interventions). When coupled with remote-sensed land-use data (over space and time), this can provide a very powerful tool to assess how particular biological or functional groups (e.g. pollinators) respond. The analyses can shed light on the ecosystem services provided and implications for food system sustainability.

Proposed and potential indicators to assess agricultural biodiversity in sustainable farming systems

As discussed, there is a wealth of potential measures of agricultural biodiversity, but there needs to be a realistic consideration of what is feasible and useful in the immediate term, whilst maintaining an eye on where the indicator gaps are and priorities for future development and application. As such, we have considered what may be usable in the short term for the Agrobiodiversity Index, and propose a working list that will continue to be explored and iteratively adjusted:

- Crop and non-crop species richness (including plants, livestock and farmed fish) in production systems (farms, communities, regions, nations, companies), collected on (ideally) an annual basis. This could be achieved through global databases [e.g. FAOSTAT, GBIF (Global Biodiversity Information Facility), IUCN Red List of Threatened Species[vii]], national/regional data (e.g. state government data repositories), or crowdsourced data. This could be done at site scale, across site comparisons, or summed across multiple sites. Species richness data could also be collected using crowdsourced data at important points along the value chain (e.g. diversity in markets).
- Functional diversity of crop species and varieties, with an emphasis on linking functional group representation to particular ecosystem services (where feasible). Sources include global traits databases (e.g. The TRY Plant Trait Database[viii]) and global crop databases (e.g. FAOSTAT).
- Number of varieties of main species produced in production systems (farms, communities, regions, nations, companies), collected on (ideally) an annual basis. Thus far, no national level varietal data are available in an accessible form (e.g. equivalent to FAOSTAT). This is therefore: (i) a research/data gathering priority, and (ii) a candidate for ever-evolving crowdsourced data collection approaches.
- For assessing trends (rather than absolute values) in local-scale biodiversity, Chapter 5 (pp124–125) proposes a methodology (4-cell analysis) to aggregate farmers' knowledge up from farm level to national level. This can be used both for between-species and within-species diversity. The resulting indicator would assess trends (increasing, decreasing or unchanged) in area, number of household growers or varietal diversity over the previous five years.
- Land use, habitat cover and land-use intensity measures are acceptable proxies for indicating soil biodiversity of production sites. These data could be taken from the PREDICTS method of biodiversity response projections based upon land-use change and within-land use management (188). It could also draw on the Global Soil Biodiversity Atlas Maps,[viii] which describe potential diversity and potential threats,[ix] as a means to estimate ecosystem service responses at wide scales resulting from soil condition and threat status.
- Pollinator diversity also can be estimated based on land use, habitat cover and land-use intensity measures of production sites. These could also use the PREDICTS modelling of pollinators.

In addition to the above indicators, which measure biodiversity itself at various levels, we propose to assess important practices and policies which have been identified as potential barriers or enablers for multifunctional agricultural systems based on biodiversity:

- Trends in inputs (pesticides, fertilizer, water) as a measure of the extent to which biodiversity-based approaches are being substituted by external input-based approaches. The Food and Agriculture Organization of the UN (FAO) keeps statistics on input use at national level. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) uses, in particular, trends in nitrogen deposition from international nitrogen initiatives and trends in pesticide use from FAO, and this could be adopted in the Agrobiodiversity Index.
- Integrated management practices based on agricultural biodiversity to reduce specific risks (e.g. climate change, pests and diseases, soil erosion). As discussed, it is likely to prove challenging to measure these at larger spatial scales at present, but becoming increasingly feasible, more accurate and more cost effective over time and with crowdsourcing and remote sensing advances. In the meantime, one alternative is to use expert panels to provide an assessment.
- Capacity building (e.g. educational programmes) on agronomic practices for use of agricultural biodiversity (e.g. species, variety, land use) in production systems at various scales (company, region, country).
- Agricultural biodiversity in input supply purchases (for companies). This can be assessed by screening publicly available documents, such as websites and sustainability reports.

Each of these potential measures needs to be assessed for applicability and feasibility at multiple scales (farm, community, landscape, nation) and from multiple perspectives (countries, companies).

Conclusions

Agricultural biodiversity is a vital component in the pursuit of food production from sustainable systems. Not only can agricultural biodiversity boost yields and increase nutritional (and therefore, potentially, dietary) diversity, but it helps to maintain and drive a host of essential ecosystem services, such as pollination services (e.g. through pollinator habitat and resources, and landscape connectivity), several services relating to soil (e.g. soil structure maintenance, nutrient cycling), and pest and disease regulation. These services in turn can lead to increased livelihood resilience and well-being of farming communities, and reduce the need to rely upon high levels of often expensive and frequently environmentally damaging external inputs. However, despite the increasing calls for sustainable intensification, conventional forms of intensification (reliance on synthetic external inputs, system homogenization and simplification) still hold sway, and agricultural biodiversity is not yet automatically included in sustainable intensification discourse, policy and management. Consequently, there is an urgent need to: (i) increase the profile of agricultural biodiversity as a multi-pronged solution to several pressing issues in global agriculture, (ii) become more adept at measuring it, its impacts and how it can best be integrated into a range of farming systems of differing degrees of intensification, and (iii) ensure that agricultural biodiversity is much better and more explicitly represented in agricultural policy, extension and incentive mechanisms.

Rice terrace system in Begnas village area, Begnas village, Kaski district, Nepal.
Credit: Bioversity International/J.Zucker

Notes

[i] No-till (or reduced-till) agriculture is when tillage of the soil is replaced with approaches that directly drill seeds or directly plant into the soil, thus reducing soil disturbance.

[ii] https://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=2008

[iii] http://www.imfn.net/international-model-forest-network

[iv] This is a general rule. There are also incidences in which higher biodiversity has been found to have counterproductive effects on society (36, 171), such as regulation of some human disease vectors.

[v] http://www.biobio-indicator.org

[vi] http://www.rubicode.net/rubicode/index.html

[vii] FAOSTAT: http://www.fao.org/faostat/en/#home
GBIF: http://www.gbif.org/
IUCN Red List: http://www.iucnredlist.org/

[viii] https://www.try-db.org/TryWeb/Home.php

[ix] http://esdac.jrc.ec.europa.eu/content/global-soil-biodiversity-maps-0

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Seed fair in Nakaseke, Uganda to raise awareness of traditional varieties of beans. Traditional bean varieties can have valuable traits, such as resilience to certain pests and diseases or nutritional qualities.
Credit: Bioversity International/I. López Noriega

4

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

Jacob van Etten, Isabel López Noriega, Carlo Fadda, Evert Thomas

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.

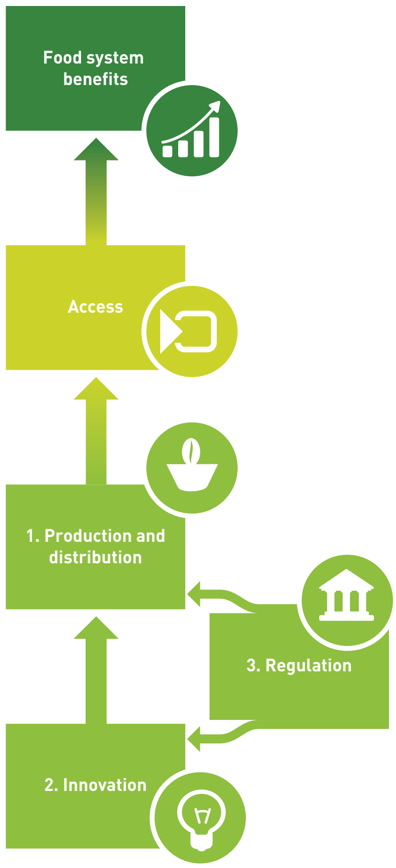
In one example, in Cochabamba (Bolivia), the international agricultural research centre Bioversity International and the NGO PROINPA[ii] worked with farmer groups to produce and commercialize certified seed of native potato varieties. Another example can be found in Nepal, where farmers have applied 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).

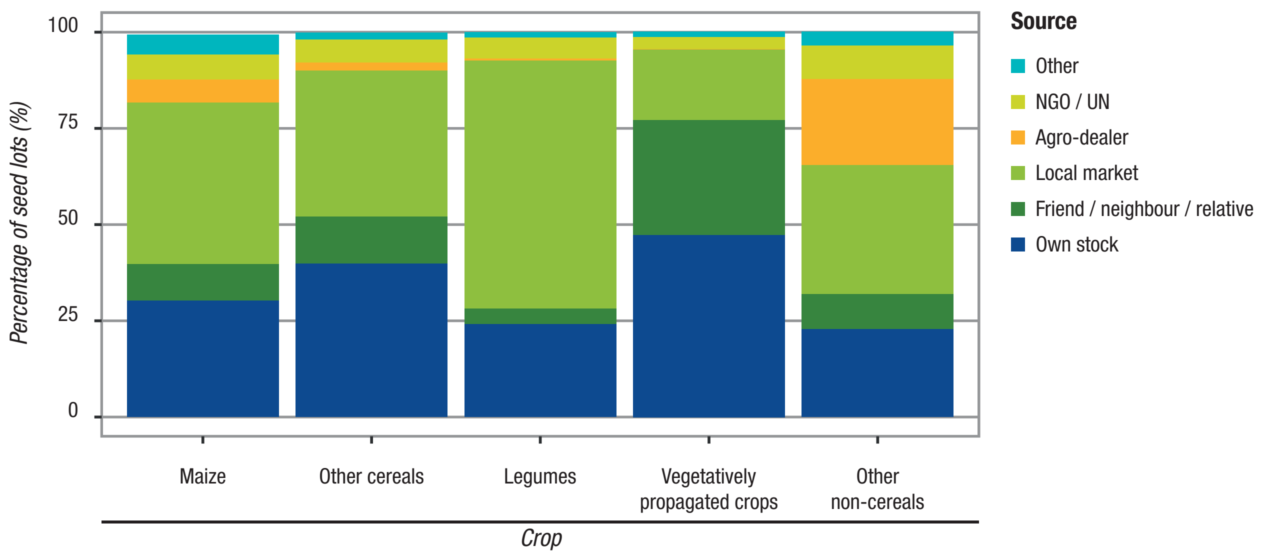
The importance of seed access for obtaining crop diversity is also evident in farmers' seed sourcing choices. A large study on seed sources reveals that informal sources including local markets are an important source of seeds for smallholder farmers (28, Figure 4.2). Availability of varietal diversity 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

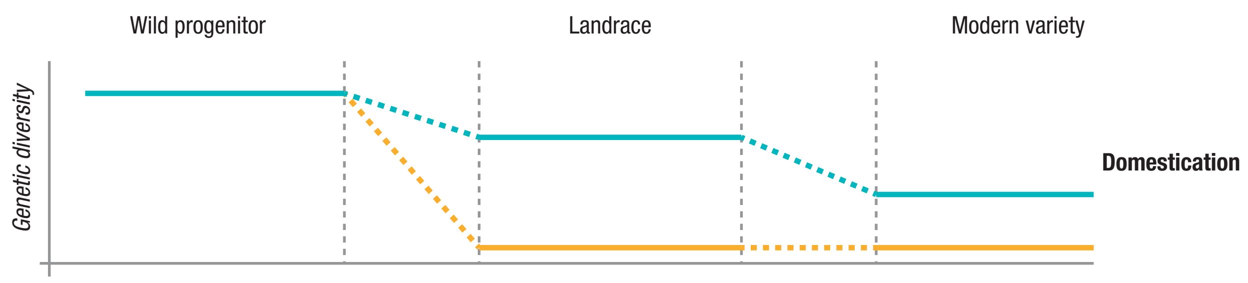
Innovation activities permit new genetic materials to be introduced into farmers' fields. Innovation may be the introduction of new species or seeds from alternative seed sources, farmer selection and plant breeding. While innovation is fundamental for crop diversity in sustainable food systems, depending 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.

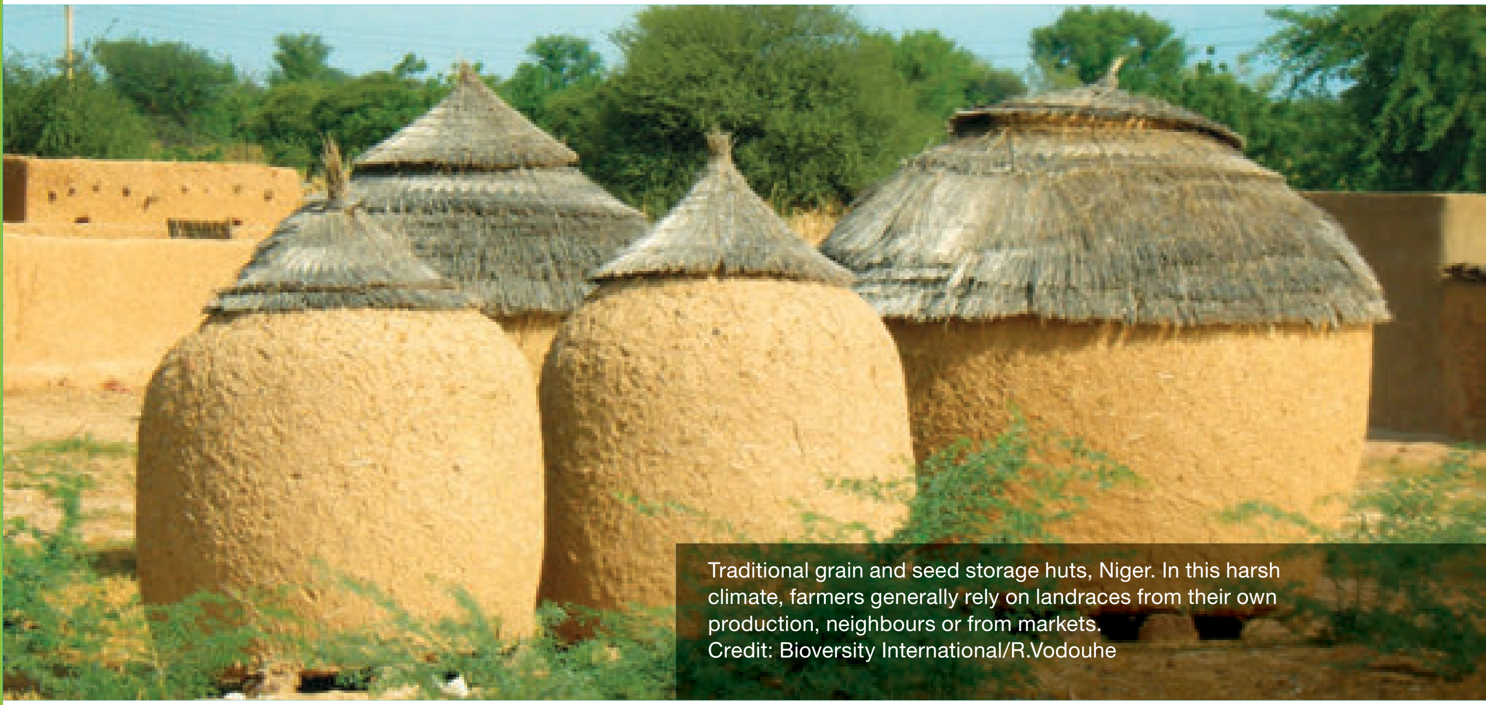


Adapted from (55).

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/

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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

5

Conserving agricultural biodiversity for use in sustainable food systems

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Conservation

KEY MESSAGES:

- The many potential benefits of agricultural biodiversity to sustainable food systems are often not realized because of poor conservation, lack of information or restrictive policies.
- Successful conservation takes an integrated approach that safeguards genetic diversity in places it has evolved, backs it up in *ex situ* facilities for posterity, and makes it readily accessible and available for use.
- Only 12 crops and five animal species provide 75% of the world's food. Yet there are thousands of neglected animal and plant species, breeds and varieties with potential uses for humans, representing one of the most poorly utilized and underappreciated food resources we have. These species must be conserved and used.

Introduction

Earlier chapters illustrate how agricultural biodiversity is one vital component of healthy diverse diets and of sustainable farming systems that provide multiple benefits to people. For these benefits to be realized, agricultural biodiversity needs to be kept available. In other words, it needs to be conserved (1). In addition to supporting benefits today, conservation of agricultural biodiversity also keeps open options for unknown future needs.

Agricultural biodiversity is wide ranging and includes all species and their genetic diversity that are of relevance to agriculture, plus landscape diversity, microbiological diversity in the soil and the diversity of pollinators. For the purpose of the Agrobiodiversity Index, in this chapter we focus only on the diversity of animals and crops, as representative of the foundations of agriculture. Once the Agrobiodiversity Index is established, it will be possible to expand its focus to cover pollinators, fish, trees and even landscapes, as is necessary.

What diversity to conserve for sustainable food systems?

The globalization and homogenization of diets and farming systems are the greatest threats to agricultural biodiversity (2, 3). From the pool of 40 animal species and at least 5,538 plant species documented as human food (4), only 12 crops and five animal species now provide 75% of the world's food (5).

Yet the diversity conserved on and around farms continues to be remarkable. A study in Benin found that households grew and gathered 65 different plant species over a year – including crops and fruit trees, wild trees and bushes (6). Similarly, single home gardens around the world often harbour 20 to 50 different plants and several small livestock species (7). Many of these are highly nutritious (8–15), adapted to marginal farming conditions (16), resilient to climate change (15, 17), with potential for income generation (18, 19) and/or closely linked to cultural identity (20, 21). Most have never been formally improved and so, despite their local and potential value, are neglected by national conservation efforts ('neglected and underutilized species' or NUS) (21). This does not mean that they are neglected or underutilized by rural communities. Many farmers cultivate them widely for various reasons, especially in marginal areas. In the case of animal genetic resources, the 'NUS equivalents' are traditional breeds or strains that produce under usually very harsh production conditions and possess adaptive attributes such as disease resistance and heat or drought tolerance (22, 23). Conservation of neglected plant species and traditional breeds on farm, along with the vast traditional knowledge developed by users over generations, is of paramount importance for keeping diversity options for future generations and for maintaining the evolutionary potential of agricultural biodiversity.

Countries make strategic conservation decisions, focusing on biodiversity that is important to people's food and nutrition security and farming systems, highly threatened, globally valuable and unique, or a combination of these. For example, certain crops have great local importance because of the role they have in local cuisine and farming systems. In these cases, it is common for there to be wide diversity in those crops. For example, in Eastern Africa, there is wide banana diversity, which underpins a unique banana-based farming system and cuisine. Other times the conservation of a species is dependent on its use in local cuisine, such as the pungent leaves of *Garcinia cowa* (a relative of mangosteen) which are used as a traditional flavouring ingredient in Thailand (24).

Some countries are centres of diversity or centres of origin for certain crops and animals, which means that they harbour a greater diversity of these species than other countries. For example, there are over 1,483 varieties of Andean tuber species found in the Andean region of Peru. When species are endemic (i.e. native to a certain place), they tend also to have large populations of related species in the wild, 'crop wild relatives', which can be a valuable source of traits for breeding improved varieties. South Africa, for instance, is a significant centre of biodiversity, with more than 12,000 endemic plant species and many crop wild relatives, including sorghum, sweet potato and cowpea. While uncertainties still surround the exact domestication centres for some livestock species, the following geographic areas are important primary centres of origin and, therefore, centres of diversity of livestock species (25–28): the Andean chain of South America (llamas, alpacas, guinea pigs), Central America (turkeys, Muscovy ducks), Northeast Africa (cattle, donkeys), Southwest Asia including the Fertile Crescent (cattle, sheep, goats, pigs), the Indus valley region (cattle, goats, chickens, riverine buffaloes), Southeast Asia (chickens, Bali cattle), East China (pigs, chicken, swamp buffaloes), the Himalayan plateau (yaks) and North Asia (reindeer). Additionally, the southern part of the Arabian Peninsula is thought to be the region of origin of the dromedary, while the Bactrian camel is thought to have originated from the area that is now the Islamic Republic of Iran, and the horse from the Eurasian steppes.

The loss of agricultural biodiversity in our global food production systems, as well as associated cultural practices and knowledge, is an issue of increasing concern, particularly in centres of origin and diversity. The Convention on Biological Diversity Aichi Target 13 addresses this concern directly:

Zebu in Ankarafantsika National Park, Madagascar. Zebu are domesticated cattle, farmed throughout the tropics, which can withstand extreme heat.
Credit: Bioversity International/D.Hunter

By 2020, the genetic diversity of cultivated plants and farmed and domesticated animals and of wild relatives, including other socio-economically as well as culturally valuable species, is maintained, and strategies have been developed and implemented for minimizing genetic erosion and safeguarding their genetic diversity.

Maintaining genetic diversity is also addressed in Sustainable Development Goal target 2.5:

Maintain the genetic diversity of seeds, cultivated plants and farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed.

Challenges in monitoring conservation status

It is notoriously difficult to measure the exact status of crop and animal genetic diversity. For animal genetic resources – where the greatest diversity content is within species (breeds and strains) – there is much better data at species level than at breed or strain level. The *State of the World´s Animal Genetic Resources for Food and Agriculture* (29) states that 62 livestock breeds became extinct between 2001 and 2007. In 2014, a total of 1,458 breeds (17% of all breeds including those that are extinct) were classified as being at risk, but more than half – 58% of breeds – were classified as being of unknown risk status (30). This latter classification is symptomatic of the data gaps in animal genetic resources. Indeed, a combination of challenges around availability of reliable data as well as a lack of a clear-cut definition of strain and breed distinctiveness in developing countries implies that conservation discourses and decisions on animal genetic resources are still based on incomplete information (31) and lesser known populations or strains in remote areas in developing countries continue to be lost (23). A close look at the list of extinct and at-risk breeds and strains of livestock, as well as their wild relatives, reveals that most of these have been identified in developed countries (where more reliable data are available) and only limited numbers have been reported in the developing world – a reflection of the data gap. The challenge is all the greater because the diversity is already quite limited – and a unit loss represents a significant part of the remaining diversity. Here the biggest cause of diversity loss is ill-conceived 'development programmes' which support cross-breeding and breed replacement, without paying due attention to the consequences (23).

Despite the fact that crop genetic resources have received much more attention and for far longer than animal genetic resources, the data situation is worse for crop genetic resources than for animal genetic resources: there is no global information of the extent of diversity of crop genetic resources on farm and *in situ* and the extent to which they are threatened, despite the existence of an information-sharing mechanism of the Food and Agriculture Organization of the UN (FAO) Global Plan of Action on Plant Genetic Resources for Food and Agriculture.[i] To monitor the status, we need first to measure the extent and trends of the diversity, and at present there are serious data gaps (such as number and distribution patterns of species, varieties and breeds, and their genetic diversity), which means that comprehensive and reliable numbers of species at risk of extinction and genetic erosion are difficult to determine (32, 33). One challenge is the vast richness of crop diversity to be conserved. Even if we consider only the 150–200 species of crops commercially cultivated, to identify, monitor and conserve all the variation therein is a daunting task, particularly since the diversity is not static but constantly evolving in response to human and natural pressures. A further complication is that at the genetic level not all differences are visible simply by looking at a plant, and not all differently named crops are in fact genetically different.

Partly as a result of these challenges, there are persisting gaps in available data for crop genetic resources. We lack the numbers of species at risk of extinction and genetic erosion remains difficult to determine (1, 33, 34). Some studies suggest that perhaps genetic erosion for some crops has not happened as much as was once thought, e.g. millets and sorghum in West Africa (35), wheat in France (36). Nonetheless, evidence exists that much crop genetic diversity in farmers' fields and in the wild is rapidly being eroded (33, 37).

Part of the loss of crop genetic resources in farmers' fields and their wild relatives has been offset by collecting and conservation away from the field in genebanks (known as *ex situ* conservation), where over 7 million samples are conserved in 1,750 genebanks worldwide (38). From a sustainable food system perspective, however, the diversity held in genebanks is only tip of the iceberg. Genebanks have largely focused on the conservation of major staple crops, while non-staple crops represent only 2% of materials stored and crop wild relatives are also poorly represented (39). Furthermore, even diversity held in *ex situ* facilities can face genetic erosion due to inadequate management practices as a result of insufficient support, lack of duly trained staff and frequently overwhelmed and underfunded conservation programmes.

How to conserve agricultural biodiversity for sustainable food systems

Genetic resources are ideally conserved within three broad interconnected realms:

- On farm in farmers' fields: managed by farmers on farm and thus allowing responses to natural and human selection
- In the wild: occurring in natural habitats, *in situ*, that are under selective forces of nature
- *Ex situ* collections: diversity that has been collected and conserved and managed in offsite facilities, e.g. genebanks.

While the concept of *ex situ* conservation is pretty clear, such is not the case for on-farm conservation and *in situ* conservation. Some authors prefer to use the term *in situ* conservation for conservation of all species that are "in their natural surroundings" (40), whether the surroundings be natural habitats or domesticated and cultivated contexts. Other authors prefer to use the term *in situ* conservation only for conservation of species purely under the forces of nature and the term on-farm conservation for species subject to selection both by nature and by farmers. In this chapter we take the latter approach, making a distinction between on-farm and *in situ* conservation, since they generally involve different players – agriculturalists in the first case and environmentalists in the second – and different approaches and methodologies (Box 5.1).

It is difficult to conserve animals anywhere apart from on farm, though strides are being made to conserve biological samples *ex situ* in tissue banks (31). Also, efforts have been limited so far to identify and protect key habitats for wild relatives of domesticated animals. For this reason, in this chapter, we discuss the conservation of animal genetic resources primarily only in the realm of on-farm conservation.

For crop genetic resources, these three realms – on-farm, *in situ* and *ex situ* – are all necessary, but none is sufficient on its own, as each serves different purposes and each has merits and limitations. Government strategies to conserve crop diversity are based on consideration of the purposes for conserving it, the biology of the species and an assessment of benefits and challenges (Figure 5.1).

Measures to safeguard the traditional knowledge associated with wild and cultivated crop and farm animal diversity are also important in order to keep alive best practices and cultures that support the sustainable use of the biological resources.

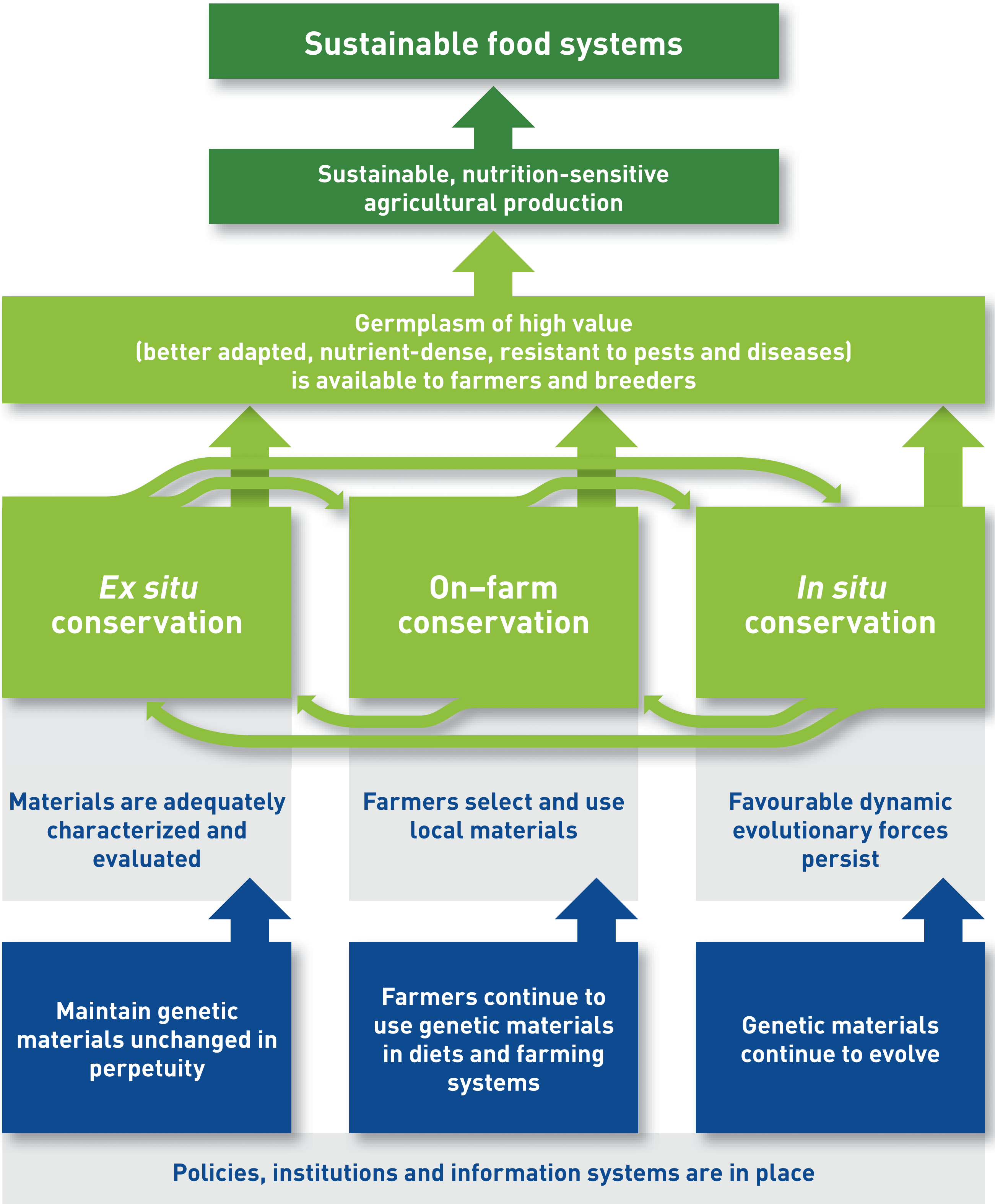
BOX 5.1 – Distinction between *ex situ*, on-farm and *in situ* conservation realms

<table>
<tr><th>Ex situ conservation</th><th colspan="2">In situ conservation in cultivated and wild habitats</th></tr>
<tr><td rowspan="3">Ex situ conservation is the conservation of components of biological diversity outside their natural habitats (40)</td><td colspan="2">In situ conservation is the conservation of ecosystems and natural habitats and the maintenance and recovery of viable populations of species in their natural surroundings and, in the case of domesticated or cultivated species, in the surroundings where they have developed their distinctive properties (40)</td></tr>
<tr><td>On-farm conservation in agricultural production systems</td><td>In situ conservation in wild ecosystems and natural habitats</td></tr>
<tr><td>On-farm conservation is a dynamic form of crop and animal genetic diversity population management in farmers' fields, which allows the processes of evolution under natural and human selection to continue (41, 42)</td><td>In situ conservation is often used to refer to conservation of wild ecosystems and natural habitats and the maintenance and recovery of viable populations of species in their natural surroundings (40)</td></tr>
</table>

FIGURE 5.1 – The three realms needed for effective conservation of genetic resources

The grey boxes are starting conditions that must be in place for conservation to be effective. Dark blue are the aims of conservation, light green are the three realms and dark green are the higher goals.

The arrows between the realms show the features of an integrated conservation system – the interconnectedness between diversity held on farm, *in situ* and *ex situ*: diversity held *ex situ* is available to breeders and farmers and can be used to restore diversity on farm and *in situ*; gene flow from wild relatives to cultivated species on farm can increase resistance; and long-term conservation *ex situ* acts as a back up for on-farm and *in situ* biodiversity.



Our premise is that the conservation of agricultural biodiversity is fundamental to realize the goal of ensuring a healthy food system and other global challenges, such as stopping land degradation and climate change. Often the many potential benefits of agricultural biodiversity to sustainable food systems are not realized because they are poorly understood and valued. In other cases, it may be difficult to get access to resources, identify traits and promote their use. This may be the result of an inability to locate information or because the agricultural biodiversity itself is eroding.

In this chapter we describe the three complementary realms of a healthy conservation system, and outline evidence for how to identify intervention points to make conservation more effective. By 'healthy conservation system', we mean a well-functioning system where the species and genetic diversity and their agricultural and natural production systems are maintained. The chapter also reviews and proposes a set of indicators and metrics for tracking progress across these three realms that can be used by policymakers, investors and farmers to assess the conservation dimension of agricultural biodiversity in the Agrobiodiversity Index.

As well as understanding what works from a technical perspective in the three realms, there are also political, legal and institutional factors that influence the ability or willingness of farmers, organizations, governments and other entities to manage, conserve and provide access to agricultural biodiversity (43). Conservation may be non-functional if the enabling environment for conservation and use of genetic resources is not adequately addressed.

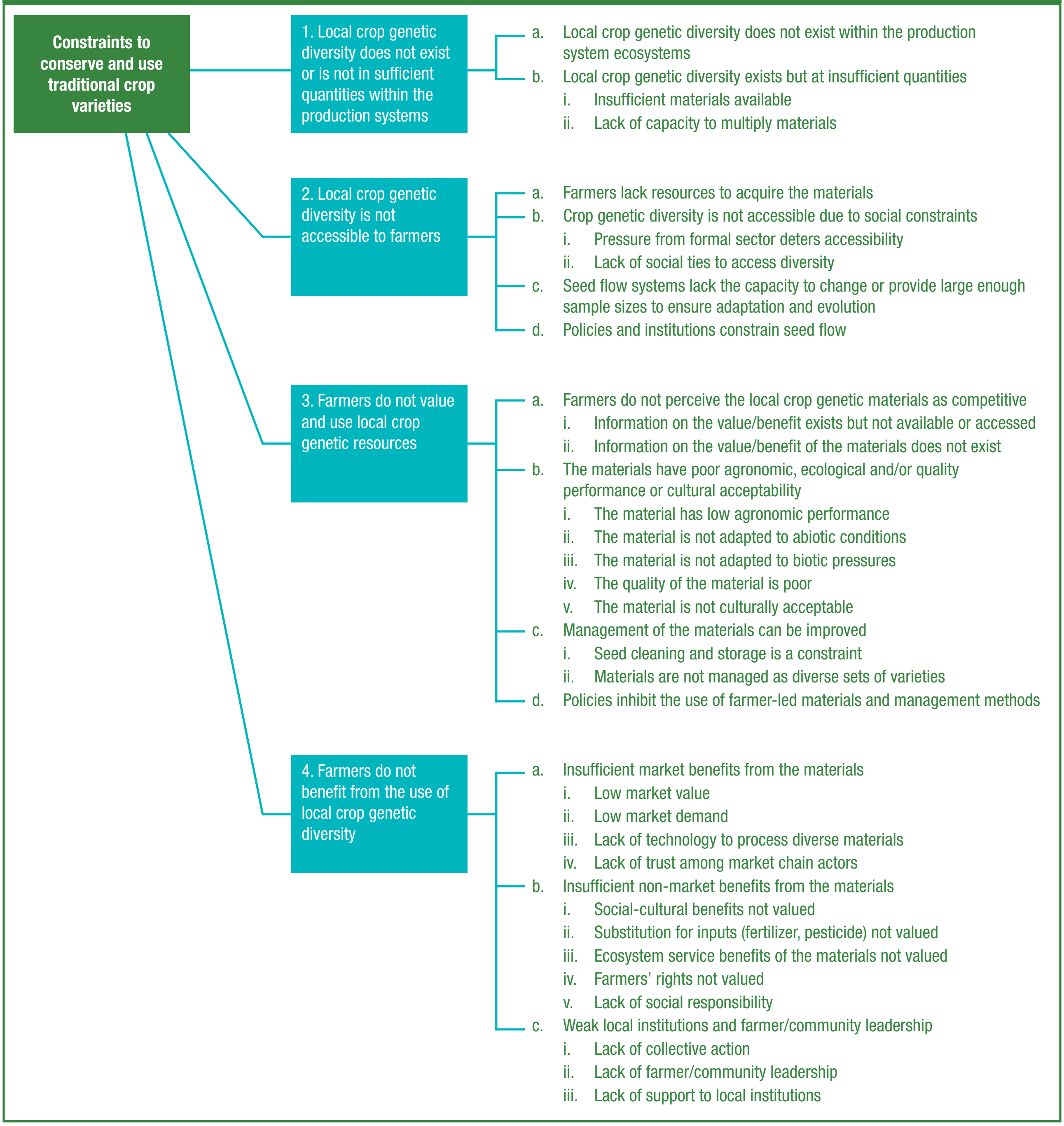
On-farm conservation

Where the main purpose of conservation is that communities should continue to benefit from the use of crop and animal biodiversity, one strategic approach is on-farm conservation. On-farm conservation is the result of networks of farmers doing different things over large areas – i.e. each engaged in their own livelihood and risk management strategies, and adapting crops to their own niche environments – with the unplanned end result across a region or country that a wide range of diversity is conserved (44). It is a highly dynamic form of crop and animal population management, which allows the processes of both natural and human selection to continue to act in the production system (41, 42, 45), thereby contributing to ecosystem services (such as soil quality, pest control and pollination, as described in Chapter 3) and the autonomy that farmers have over crop and animal genetic resources (46). An analysis of different conservation approaches for animal genetic resources concluded that the most rational strategy for conserving livestock breeds was to ensure that they remain a functioning part of the farm production system (47). Such processes help to maintain crop and animal evolution in farmers' fields, home gardens and landscapes (48). This conservation approach is valued for evolving new portfolios of adaptive traits and, therefore, enhancing farmers' capacity to cope with adversity, resulting from the consequences of socioeconomic and market forces and climate change (49). This conservation approach also covers aspects of genetic resources which cannot be protected in genebanks, such as local knowledge and ecosystem interactions (50–52) and, in fact, the processes that underpin this dynamic conservation of genetic diversity.

The second *State of the World's Plant Genetic Resources for Food and Agriculture* (38) report notes that over the last decade, promoting and supporting the conservation of genetic resources in farmers' fields, home gardens, orchards or other cultivated areas of high diversity, has become firmly established as a key component of crop conservation strategies, as methodologies and approaches have been scientifically documented and their effects monitored (1, 38).

A review of over 500 case studies documented "multiple ways of supporting the conservation and use of traditional crop varieties within the agricultural production system" (53). The review suggests an overall framework (a heuristic device) to help conservation and development workers and communities understand the preconditions that need to be in place for traditional crop varieties to be used and conserved in farming systems. It can be extended also to considerations of animal genetic resources. The heuristic framework categorizes into four groups issues faced by farmers which may increase or decrease their capacity and desire to continue to conserve and use crop or animal genetic resources on their farms (Figure 5.2). These include the existence in sufficient quantities of crop or animal genetic diversity in production systems, and the ability of farmers to benefit from the diversity, for instance through appropriate market and non-market incentives and institutions (53).

FIGURE 5.2 – Heuristic framework for identifying constraints and related actions to support the conservation and use of traditional crop varieties within agricultural production systems



Source: (53) Copyright © 2011 © Devra I. Jarvis, Toby Hodgkin, Bhuwon R. Sthapit, Carlo Fadda, and Isabel López Noriega. Published with license by Taylor & Francis. Modified with permission.

Assessing the existence of sufficient quantities of crop or animal genetic diversity

Main concepts for assessing genetic diversity on farm

Three concepts of diversity are key to estimate the levels of animal and crop genetic diversity on farm. These are:

- Richness. How many different traditional varieties, breeds and species are being maintained?
- Evenness. How similar are the frequencies of the different variants? Low evenness indicates dominance by one or a few crop varieties or animal breeds.
- Divergence. This measure reflects the probability that any two randomly chosen households within the same community are growing different varieties.

In an analysis of varietal data on 27 crop species from five continents, measurements of richness, evenness and divergence showed that considerable crop genetic diversity continues to be maintained on farm, in the form of traditional crop varieties (44). The patterns of diversity give clues as to the farmers' strategies. Understanding these strategies can inform conservation actions. For example, in some cases, farmers' fields were dominated by a few varieties, with much of the variety richness held at low frequencies. This suggests that in these cases diversity may be being maintained in low quantities as an insurance to meet future environmental changes or social and economic needs (44). In other farms and communities, a more even distribution of varieties was found, indicating that farmers are selecting varieties to service a diversity of current needs and purposes (44). Understanding the diversity of strategies employed highlights the importance of a large number of small farms adopting distinctly diverse strategies as a major force that maintains crop genetic diversity on farm (44).

Sufficient diversity for different functions

Estimating the extent and distribution of diversity provides the information needed to determine whether there is sufficient diversity of a crop within a production system to meet the various needs of farming communities. Sufficient diversity is largely defined by farmers by the functions that the diversity serves them on farm, for example ecosystem services such as pest control or soil formation (Chapter 3) or provision of culturally preferred nutritious foods all year round for sale or consumption (Chapter 2). One important function is also managing uncertainty and risk, which requires wide genetic diversity availability in order to be able to adapt to new challenges such as climate change or prevalence of certain pests. Farmers in Mali, for example, in response to changing environmental conditions, were able to shift their production of sorghum to short-cycle varieties, thanks to the availability of and access to large enough population sizes of traditional sorghum varieties (cited in 53). An example of functional diversity is from research in the Yucatán in Mexico, where it was found that to cope with unpredictable rain and poor soils, farmers had quick maturing varieties (*Na'tel*) to avoid the drought period, and other varieties (*X-nuuk nal*) which were long maturing but drought resistant. In this way, the community could increase their chances of being able to eat maize whatever the weather (54).

'Sufficient diversity' may additionally be defined using prioritizing tools (55, 56) by those with an interest in conservation per se, i.e. not focusing so much on sufficient diversity for farmers' uses, but sufficient in the sense of covering the maximum breadth of genetic diversity safeguarded within a fixed conservation budget. It is possible to combine measures related to uniqueness, risk status and conservation cost in order to estimate optimum portfolios of diversity to conserve.

Where diversity is low, farmers may be able to source seeds and planting materials from public agricultural extension services, or purchase them in formal or informal markets. They can also be (re)introduced from other communities or from genebanks – possibly through intermediaries, since most genebanks are not easily accessible to local communities. A good example comes from a poorly known Andean grain, cañahua (*Chenopodium pallidicaule*), whose varieties had been lost by local communities near Puno in Peru. Loss occurred due to the replacement of cañahua cultivations with those of quinoa, a high cash earning crop in recent years. When the quinoa crop proved to be susceptible to unpredictable morning frost occurrences, 40 varieties of cañahua were brought back to communities from *ex situ* collections, thanks to previous collecting missions carried out by a national NGO (15). Owing to its cold resistant trait, the reintroduced cañahua varieties are helping farmers to better adapt to the new unpredictable morning frosts (Figure 5.3).

FIGURE 5.3 – Cold-tolerant cañahua (left and right) and susceptible quinoa (centre) crops following a heavy frost in Corisuyo (Puno, Peru)

Credit: Bioversity International/S.Padulosi

Other ways of reintroducing diversity are through seed exchange meetings with other communities, and through community seedbanks or nurseries for trees (see Box 5.2, 57).

BOX 5.2 – Community seedbanks

Community seedbanks are one approach in developing countries, particularly in South Asia and Africa, to conserve and manage agricultural biodiversity at the community level. Community seedbanks tend to be small-scale local institutions, which store seed on a short-term basis, serving individual communities or several communities in surrounding villages (58, 59). These community seedbanks are relatively inexpensive, usually employing simple, low-cost storage technologies. The people managing the seedbanks carry out deposit of seeds, replication, storage, distribution, germination quality testing and variety selection. Community seedbanks provide options for conservation and use of neglected and underutilized crops that are not commonly undertaken by national and international genebanks (59).

In Nepal, a total of 115 community seedbanks have been reported (60). Detailed data are available for 21 of these. These 21 community seedbanks were conserving 908 varieties of 62 crop species as of 2016. From 2011 to 2016, a total of 18,136 farmers gained access to the local and modern varieties conserved in these seedbanks (61). About 43% of poor and 45% of medium-income farmers have received seeds from these community seedbanks (60). In 2015, 10t of local varieties and approximately 125t of modern varieties and varieties bred through participatory methods were produced by these community seedbanks. Sixty percent of the seed produced is marketed by local seed retailers and local extension agents to meet local needs. Total income generated by seed sale for six seedbanks (US$34,635 in 2015) is used to safeguard local crop diversity and support the day-to-day management of community seedbanks. Nepal is now piloting access and benefit-sharing mechanisms at the community level through community seedbanks as a practical way of implementing farmers' rights (62).

Ensuring benefits to farmers from market and non-market incentives and institutions

Supporting internal incentives for conservation on farm

One successful way of engaging farmers so that they gain both biodiversity and livelihood benefits from their efforts is 'community biodiversity management' (23, 63–65) Community biodiversity management of crop and animal resources entails community-driven participatory approaches that empower farmers and communities to organize themselves and develop strategies so that they can manage their agricultural biodiversity in ways that improve their livelihoods.

The community biodiversity management approach integrates knowledge and practices with social systems, institutions and regulations that support conservation and development goals set by participating communities (23, 62, 63, 66). Production practices change as the farmer acquires new sets of scientific knowledge, skills and technologies, and blends them with traditional practices for further livelihood improvements. Communities can benefit in many ways: improved agronomic practices, commercialization of certain species or varieties, improved access to elite planting materials, or new networks leading to access to funding or expertise (66). For example, in France, a self-organized network of farmers and amateur gardeners started to collect local varieties of maize and other crops, describing their special traits, and promoting them in the network. From modest beginnings of just a handful of maize varieties that had almost disappeared from farmers' fields, in 2013 they reported over 100 maize varieties, more than 10 sunflower varieties, several varieties of soybean, buckwheat, moha (Hungarian grass), lupine, and a number of vegetable and fodder crops (67).

Participatory plant breeding, which empowers farmers to set breeding goals using local crop diversity, also demonstrates a successful method to provide benefits to farmers from their existing agricultural biodiversity (68). One example is that of making an aromatic rice landrace competitive by selection from 338 populations of a landrace called Jethobudho (69). Together with the local community, researchers improved milling recovery (by 5%), tolerance to being flattened by wind and rain, consistent and aromatic cooking quality, and resistance to diseases. Consumers are willing to pay a relatively high price because of its special cooking quality measured by grain expansion, taste and aroma, which are not available with other high quality types, such as Basmati. Once this variety was released, seed companies started marketing it in other parts of the country, which supported its conservation.

Also for animal diversity, participatory breeding approaches have proved successful in providing livelihood benefits which support conservation goals. For example, in Côte d'Ivoire from 1983 to 2000 a large community-based national sheep improvement programme was carried out for the local breed Djallonké. While the primary goal was to increase the benefits to smallholders by improving the performance of the breed, which is appreciated for its tolerance of tsetse-borne diseases, the activities also had the aim of improving conservation of the breed. The programme learned that the main factor for success was the desire on the part of the farmer to adopt new management techniques. Although not all farmers continued to breed Djallonké after government financial support was withdrawn, still numbers of sheep were greatly increased (from about 3,000 ewes in 1984 to well over 14,000 in 2000) and genetic analyses showed that the genetic values of the breed had been maintained, or even slightly improved, during the period (70).

Incentive mechanisms for conservation can also be indirect. One example is the establishment of community biodiversity management (CBM) funds that can be used at a local level to tie community conservation goals with individual microcredit. In this context, a CBM fund can be set up by linking ongoing savings and credit schemes for members to a community seedbank. Its operational modality is similar to other microfinance schemes (71). In Nepal, where this approach was developed (60, 72), seed money from an international project[ii] contributed to the establishment of the fund and matching funds were collected within the community. Every household within the village is eligible to apply for loans from the CBM fund, on condition that they abide by some local codes of conduct, such as multiplying seeds of rare varieties, or paying a locally determined interest rate in cash or in seeds (57, 64, 66). CBM funds have led to the cultivation of crop varieties that had been at risk of disappearing. They also support landscape level and wild biodiversity. For example, in a scheme in a town called Begnas in Nepal, loans for raising livestock were given, on condition that the receiver planted 30 saplings of local fodder tree species. In the area of Lake Rupa, loan conditions are that people take on the care of the local wetlands, which house wild rice, local fish, birds and white lotus (74).

From the traditional pollination of date palms in North Africa, to the many mixed cropping systems developed by farmers around the world to leverage ecosystem functions of different species, to the huge array of food recipes that characterize agricultural areas and 'terroir' identity, indigenous knowledge associated with crop genetic diversity plays a fundamental role in supporting the benefits that farmers obtain from diversity (73). Traditional cultivation, management and use practices need to be monitored and supported to prevent their erosion (74).

Creating external incentives for conservation on farm

Where the livelihood benefits of conserving biodiversity are not sufficient and smallholder farmers start to abandon certain species, breeds or varieties that may be prioritized from a public good conservation perspective, incentive schemes can be created to compensate farmers for conserving agricultural biodiversity on their farms. The importance of positive incentives for the conservation of biodiversity has been explicitly recognized by the Convention on Biological Diversity (Aichi Biodiversity Target 3).

Value chain development is one incentive mechanism that has gained increasing attention in recent years as a tool for harnessing the potential of agricultural market channels to promote the use of specific livestock breeds and neglected and underutilized crop species and varieties (examples include minor millets, Andean grains, African leafy vegetables, peach palm, cherimoya and mango, see 75) with consumers ultimately paying for the on-farm conservation of locally adapted genetic resources through mechanisms such as eco-labelling, certification or 'denomination of origin' schemes. Such support can generate enhanced private benefits for farmers through access to improved species and varieties, increased choices of input suppliers and product outlets, increased accessibility to credit, better management capacity, improved employment opportunities and associated income generation (76, 77). As an example, in Peru a private company (Kai Pacha Foods) is contracting a local community to produce 10ha worth of the *Chulpi* variety of quinoa in order to process it and market it as quinoa milk (78), which will likely support the conservation of this variety. However, value chain development has limitations as a conservation strategy and its impact on agricultural biodiversity conservation may be less than once assumed (79). The growth in sales of quinoa worldwide has not led to increased management of the wide genetic base of the crop; only 10–15 quinoa varieties (out of thousands) are found in national and international markets (Rabines, Ministry of Agriculture, Peru, personal communication, Sept 2014).

An alternative approach is to compensate farmers directly for conserving targeted agricultural biodiversity on their farms. Tested and proven concepts from 'payments for ecosystem services' (PES) schemes, where incentives to farmers are given to maintain ecosystem services that benefit wider society (e.g. maintaining wild biodiversity, forests or water quality), can be applied to agricultural biodiversity as Payments for Agrobiodiversity Conservation Services (PACS, see Box 5.3). Applied within an innovative prioritization framework and competitive tender context that allows for scarce conservation resources to be allocated in such a way as to maximize diversity and associated ecosystem services, incentives are offered at community level (e.g. women's or producers' groups). Such schemes are expected to support farmers to diversify their livelihood strategies to include not only agricultural production, wage labour and value chain development, but also provision of agricultural biodiversity conservation as a public good.

A PACS approach can also benefit farmers by strengthening their farmers' rights (62). The approach puts into practice the right to equitably participate in sharing benefits arising from the use of plant genetic resources for food and agriculture. Farmers define the conditions of their participation, so the approach can be tailored to benefit certain target groups, such as women farmers or certain ethnic groups.

BOX 5.3 – Payments for Agrobiodiversity Conservation Services (PACS)

PACS schemes have been tested since 2009 on plant genetic resources in Peru, Ecuador, Bolivia, India, Nepal and Guatemala; on animal genetic resources in Slovenia and on crop wild relatives in Zambia. They were recognized by the SIRGEALC (Latin American and Caribbean Genetic Resources International Symposium) in 2011 as an innovative tool that should be promoted in the region and with the International Treaty on Plant Genetic Resources for Food and Agriculture and Commission on Genetic Resources for Food and Agriculture. PACS schemes involve landscape-wide competitive tenders inviting communities to cultivate a priority portfolio of crop species and varieties and to name their conditions for doing so. Efficiency and social equity are the criteria used to select the communities which offer the best bids. At the end of the agricultural season, if cultivation has proceeded according to the contract, in-kind rewards – e.g. agricultural inputs and machinery, school building and materials – are given to the community groups. Participating groups define the conditions for their participation (i.e. which priority species or varieties to cultivate, what level of reward is needed and which women and men farmers will participate), and how to share the rewards amongst themselves and other community members.

By creating a low-risk environment for farmers to experiment in, farmers are able to explore whether the threatened crop species or varieties benefit their families sufficiently to keep cultivating them even in the absence of future incentives. Results from 2010/11 revealed that 30–50% of participating farmers had decided to do so.

The Peruvian Ministry of Environment (MINAM) has recognized the complementary role that PACS can play, in a programme called Euro Eco-Trade, which facilitates the value addition and export of organic products from selected native crops while seeking to ensure that the underlying genetic resource base is not degraded as a result. MINAM incorporated PACS approaches into its 2015 annual work plan with a view to promoting the adoption of this kind of incentive scheme at the national level.

Spades, wheelbarrows, cement and mattresses – some of the rewards requested by farming communities in Peru for cultivating priority conservation varieties of quinoa.
Credit: Bioversity International/A.Drucker

In situ conservation

When the purpose of conservation is the continued evolution of novel traits for breeding, conservation in the wild and on farm (i.e. *in situ*) is a strategic choice. *In situ* conservation refers to the maintenance and recovery of viable populations in their natural surroundings where they have evolved as a result of natural selection. Where the species and their genetic diversity are declining due to a number of threats, mostly as a result of human actions, *in situ* conservation involves the recovery of populations through active conservation actions or, in the case of whole ecosystems, it involves taking restoration measures. *In situ* conservation complements *ex situ* and on-farm conservation by preserving both the population and the evolutionary processes that enable the population to adapt by allowing them to evolve in their natural state or within their normal range (80). The term *in situ* conservation spans a diversity of approaches including ecosystem-based, species-based or genetic-based approaches (81). For each of these approaches, detailed methodologies and protocols have been developed (81, 82).

The wild relatives of crops and animals serve as a large repository of genetic diversity of value for crop and animal improvement, which can be used to strengthen the sustainability of food systems. They are potential sources of traits beneficial to crops and domesticated animals, such as pest or disease resistance, yield improvement, better taste or stability. For example, in the 1970s, the US maize crop was severely threatened by corn blight, which destroyed almost US$1,000 million worth of maize and reduced yields by as much as 50% in 1978 (83). The problem was resolved through the use of blight-resistant genes from wild varieties of Mexican maize (84). Breeders' use of crop wild relative diversity in improving food production has been estimated at an annual value of US$115–120 billion worldwide (85, 86). In the individual case of producing sweeter tomatoes for the US market, a single gene from the tomato wild relative *Solanum chmielewskii* increased sales by US$5–8 million per year (87).

For species to be able to adapt to changed conditions (climate change, for example), they need to have the largest and widest genepool possible, improving the likelihood that the population has the genetic material to be able to adapt to future conditions (88, 89). *In situ* conservation is a way to maintain the maximum level of genetic diversity within and among wild populations of targeted species. *In situ* methods have the additional benefit of being able to conserve multiple plant species, particularly species producing seeds which cannot be stored in genebanks because of the nature of their seeds (90).

The limitations of *in situ* conservation are that the materials are not easily accessible for use, and may be vulnerable to natural and human-made calamities and to other natural interferences such as invasive alien plants (90, 91) unless backed up in *ex situ* facilities. *In situ* conservation needs to be well designed with well-trained personnel, a legal framework and political will to ensure long-term success of the conservation sites (92).

The second *State of the World's Plant Genetic Resources for Food and Agriculture* report by the Commission on Genetic Resources for Food and Agriculture notes that, over the last decade, a large number of surveys and inventories have been carried out and that awareness of the importance and value of crop wild relatives and the need to conserve them *in situ* has increased (38). *In situ* conservation is reflected in the FAO Second Global Plan of Action for Plant Genetic Resources (priority activities 1–4) and Article 8 of the Convention on Biological Diversity. Article 5.1 section (f) of the International Treaty on Plant Genetic Resources for Food and Agriculture refers to the promotion of *in situ* conservation of crop wild relatives and wild plants for food production, including in protected areas, by supporting, among other actions, the efforts of indigenous and local communities.

For animal genetic resources, wild relatives are even more at risk of extinction than domestic animals: 44% of sheep and goats, 50% of pigs and 83% of cattle. More wild relatives of chicken are also at risk (25%) than bird species overall (93).

The key elements that need to be in place to make *in situ* conservation of agricultural biodiversity effective and sustainable are:

- Strategies and management plans or action plans for the *in situ* conservation and sustainable use of genetic resources
- Genetic reserves
- Conservation activities
- Policy and enabling environment
- Effective information systems.

Strategies and management plans

Resources are not unlimited and thus, when planning the conservation and management of crop wild relatives, an essential step is to prioritize sites and interventions for conservation. In order to optimize the use of resources, countries are encouraged to develop National Strategic Action Plans for the conservation and use of genetic resources.[iii] Governments are supported to review, develop or strengthen national strategies for the *in situ* conservation of crop wild relatives through protected area networks and the development of integrated approaches that link conservation of these resources to their sustainable use (94). A number of countries have elaborated national crop wild relative checklists, identifying thousands of species with potential value for future breeding efforts (Table 5.1).

TABLE 5.1 – National crop wild relative checklists, showing the number of species inventoried in various countries

Area, country or region	Number of species	Group of species considered if not a complete checklist	Source of information
Armenia	2,518		(95, 96)
Benin	266		(97)
China	24,499	This checklist includes crop wild relatives and crops, accounting for around 70% of the flora of China	(98)
Cyprus	1,613		(99)
England	1,471		(100)
Finland	1,905		(101)
Germany	2,874	Wild species for agriculture and nutrition	(102)
Guatemala	105	Crop wild relatives of 29 selected crops	(103)
India	ca. 5,000	Wild relatives of ca. 2,000 cultivated plant species	(104)
Ireland	208	Relating to key species as prioritized by the International Treaty on Plant Genetic Resources for Food and Agriculture, and species from under-recorded areas	(105)
Italy	10,773	Crop wild relative and wild harvested plant checklist	(106)
Mauritius	528		(107)
Netherlands	1,274	83% of the Dutch flora	(108)
Norway	2,538		(109)
Portugal	2,319		(110)
Rodrigues	142		(107)
Russia	1,629		(111)
South Africa	1,593	Food and fodder crops	(112)
Spain	930		(113)
Sri Lanka	410	Food crops	(114)
Switzerland	2,749	Includes ornamentals, socioeconomically important plants and plants listed for Switzerland in the Euro-Mediterranean catalogue of crop wild relatives)	(115, 116)
United States of America	2,495		(117)
Venezuela	228	48 priority crops	(118)
Zambia	572	59 crops prioritized by national stakeholders	(119)
South African Development Community	>1,900	Species related to human food and beverage crops, as well as non-food crops	(107)
Europe and Mediterranean	23,483		(115)

These checklists are a first essential step in developing a national strategy to protect priority crop wild relatives relevant to sustainable food systems (See Box 5.4 for an example).

BOX 5.4. – The value of crop wild relative checklists and national strategies

For many national programmes facing the responsibility of conserving national crop wild relative diversity, the problem is where to start and what to do. An established methodology sets out an approach that breaks down the activities into a series of steps (120) as illustrated for the UK.

1. *Checklist* – The UK flora contains approximately 4,800 taxa of which 2,109 crop wild relative taxa are found in the same genus as agricultural, horticultural, forestry, ornamental, medicinal and aromatic crops. These 44% of the UK flora constitute the crop wild relative checklist.
2. *Prioritization* – The checklist was too long a list for detailed conservation planning so was prioritized to include: (1) human food or animal forage and fodder crop wild relatives only, (2) native crop wild relatives, (3) economic value of the related crop, (4) degree of relatedness to the crop, (5) threat assessment, (6) national conservation designations.
3. *Inventory* – following prioritization, a UK inventory of 223 priority crop wild relatives formed the basis for the conservation planning.
4. *Ecogeographic and gap analysis* – An ecogeographic dataset for all available 223 priority inventory crop wild relative taxa was analyzed using: (1) richness analysis, (2) complementarity analysis and (3) incidence of priority crop wild relatives within protected areas to identify priority conservation actions both *in situ* (27 sites in priority order) and *ex situ* (77 crop wild relatives needed further collection).
5. *National crop wild relative strategy* – The priority *in situ* and *ex situ* conservation actions were reviewed by national stakeholders and a consolidated strategy was published by the responsible national agency that included priority actions and institutional responsibilities.
6. *Implementation* – Subsequent to the publication of the strategy, the first UK crop wild relative genetic reserve has been established on the Lizard Peninsular in Southwest England by Natural England. Natural England with the Royal Botanic Gardens Kew are collecting priority crop wild relatives for genebank conservation.

One point in developing and implementing the national crop wild relative strategy cannot be over-emphasized: that is the need to involve the widest stakeholder community in the process described above. Experience has shown it is only with the widest stakeholder community that there will be buy-in and implementation.

Source:Nigel Maxted/University of Birmingham using an example from (100)

Protected areas are generally seen as the cornerstone of *in situ* conservation (81, 82). Protected areas that have specifically been set aside for the conservation of genetic diversity of target species, are referred to as genetic reserves.[iv] The goal of genetic reserves is to conserve *in situ* the maximum range of genetic variation within the target species. This is achieved by locating, designating, managing and monitoring the diverse populations of the target species within specific natural habitats designated for active long-term *in situ* conservation (81, 82).

Sites are identified using established conceptual models (82). The designation of genetic reserves should be founded on appropriate national legislation that provides long-term site security, as well as financial support, which is fundamental. A second critical factor that needs to be carefully considered is the dependence of local people on the area that is to be designated as a genetic reserve (96). Local people need to be part of the management of the reserve through mechanisms like managed access to the reserve or to an alternative source of material, so that neither livelihoods nor the reserve are threatened (Box 5.5). Once designated as a genetic reserve site, the target species is actively monitored and managed to ensure the best chance of long-term survival of the target populations.

BOX 5.5 – Participatory assessment of use of wild plants by local communities in Armenia

The Erebuni State Reserve in Armenia contains 292 vascular plants of which 40 species are wild relatives of wheat, rye and barley. Given its close proximity to the city of Yerevan, there is a strong pressure on the wild plants, which are collected for food and medicinal purposes and sold in the city markets. As a result, many of these species have become threatened. In a project[v] on '*In situ* conservation of crop wild relatives through enhanced information and field application' a series of workshops and a survey were conducted with local communities to gather information on the collection, use and conservation status of a range of plants; to raise awareness among local communities about the benefits and importance of conserving these valuable resources; and to train local communities on the correct use of particular plant species. The participatory engagement with the local communities was vital for the long-term maintenance of wild plants in the Erebuni State Reserve.

Source: (96)

Wild chives (*Allium schoenoprasum*) growing in the Lizard crop wild relative genetic reserve.
Credit: H. Fielder

Conservation activities

Once a strategy and a management plan have been developed and the site identified for the establishment of a genetic reserve, precise conservation activities in the field are required to ensure the safe conservation of the targeted populations of the target species. Conservation activities will depend on the threats present at each site. If the site already has a healthy target species population, in terms of numbers and a stable structure of plants of different ages (seedlings, saplings, immature and mature individuals), the necessity for management intervention may be minimal or even confined to periodic monitoring to confirm a healthy population is being maintained (120). Often, however, due to the effects of human activities, like pollution, invasive species, land conversion and over exploitation, the ecosystems and habitats of crop wild relatives are degraded and fragmented and require activities for their restoration or rehabilitation (Box 5.6).

BOX 5.6 – Restoration of a crop wild relative-rich degraded forest in Mauritius

The island of Mauritius possesses a rich diversity of endemic plants, including wild relatives of important crops such as coffee. Over hundreds of years, as a consequence of human colonization, the native vegetation had become greatly threatened, largely as a result of deforestation, agriculture and the invasion of introduced species that had displaced native species (121). In the 1980s, a series of experimental areas, termed Conservation Management Areas, were established to develop managed plots in representative areas of native vegetation specifically with the aim of restoring the forest. The main intervention used was to weed out invasive species.

Ten to twelve years after the initial weeding, the forest had recovered so well that the structure was close to that described by early ecologists in the 1930s (122). Many of the native species including the endemic coffee wild relatives in the Conservation Management Areas are now naturally regenerating, an indication that *in situ* conservation efforts have paid off.

Source: (123)

Ex situ conservation

Ex situ conservation is literally the off-site conservation of species, populations and varieties. It is defined as the "conservation of components of biological diversity outside their natural habitats" (40). *Ex situ* conservation occurs when individuals of a species are maintained in artificial conditions outside the selection pressures of their natural habitat. *Ex situ* conservation is important at different levels. First, many natural habitats, including traditional agroecosystems, in which most cultivated diversity is grown, are threatened. In these cases, *ex situ* conservation is an efficient and quick means to prevent this often unique diversity from disappearing. Second, *ex situ* conservation greatly facilitates access to diversity for a wide range of uses, including direct use and research. Third, *ex situ* conservation can be a source of materials for various uses such as breeding materials for breeders or restoration of lost diversity in its natural habitat or on farm.

In the context of sustainable food systems, *ex situ* conservation can contribute to sustainable production systems and nutritious diets by providing breeding materials for uses such as saline-, pest- or drought-tolerance, or which need lower synthetic inputs, or have high nutrient content. *Ex situ* conservation can make varieties and species that already have those traits easily available.

In vitro evaluation at the International Potato Center (CIP) genebank.
Credit: CIP/C.Ynouye

Typically the choice of the type of conservation method depends on the biology of the species to be conserved and on the facilities available for storage. These include seedbanks (for seeds), field genebanks (for live plants), *in vitro* genebanks (for plant and animal tissues and cells), pollen banks, DNA banks and cryobanks for ultra-long preservation (124). Seedbanks, which consist of conserving dried seeds at low temperatures, are commonly used, as the samples stored can be easily handled, require low maintenance and frequently remain viable for decades (124). However, not all types of seeds can be conserved in seedbanks. Some species produce seeds that are sterile (like the cultivated banana), or produce seeds that cannot be dried and stored at low temperature (recalcitrant species, for example tropical fruits such as mangosteen, rambutan, mango and cacao) (90). Other species are clonally propagated because they are grown for their roots and tubers (e.g. yams, potato, cassava and aroids) or propagated to maintain specific gene combinations (e.g. vine, citrus species or banana). Conservation options for these crops are to grow them out in field genebanks or preserve them as tissue culture, embryo or cell suspensions grown in test tubes (*in vitro*). Field genebanks are easy to set up, but are space and time consuming, as they need to be regularly replanted, and are very vulnerable as the germplasm is exposed to changing climatic conditions, pest and diseases, floods and droughts. *In vitro* conservation is more secure at least for medium-term storage (125). Cryopreservation (i.e. the storage of tissue, embryo and cell-suspensions above or in liquid nitrogen) is preferable for longer-term storage, but requires highly specialized expertise and equipment.

Challenges to *ex situ* collections include securing long-term funding and local combinations of environmental hazards such as hurricanes, earthquakes or severe drought episodes, and political instability, including wars. Thus, the storage of duplicates of the conserved material at another genebank, preferably in another country and on a different continent, is foreseen as part of the standard *ex situ* storage of germplasm (91). In addition, and in response to these threats, in 2008, the Svalbard Global Seed Vault, was launched as an additional safety backup for national and international collections. Situated halfway between mainland Norway and the North Pole, the Svalbard Vault has the capacity to conserve 4.5 million different crop varieties under the form of seeds. It currently holds more than 860,000 seeds that represent more than 10,000 taxa and more than 5,000 species of crops and some of their wild relatives (126).

There are two forms of *ex situ* conservation of animal genetic resources: *ex situ in vivo* of animal herds or flocks maintained as conserved populations, mainly by public sector institutions across the world; and *ex situ in vitro* mainly in the form of semen banks and, to a very limited extent, embryos. FAO (127) identifies possible biological materials for consideration in *ex situ* programmes: semen, embryos, oocytes, somatic cells and DNA. Semen banks (held as the core of artificial insemination programmes) have been the major method of *ex situ* conservation of livestock species, especially in cattle – where semen technology has been in use for a long time. There have also been recent initiatives – mostly by research establishments – to put together banks of biological material or purified DNA (biobanks). However, because these cannot, for now at least, be mainstreamed into wide-scale breeding programmes, investments in biobanks remain limited.

Policies and enabling environment

For conservation of agricultural biodiversity to happen successfully and contribute to sustainable food systems, conservation actions need to be supported by appropriate policies, mechanisms and institutions. In this section, we seek to determine the policy and regulatory elements that enable progress by looking at cases where countries are showing progress in integrating conservation with use in sustainable food systems. The focus on a sustainable food system leads to a particular emphasis on local, native and/or traditional biodiversity and neglected and underutilized species. Getting the policies right involves action at many levels. The case study of Peru (Box 5.7) illustrates how changes in policies in different sectors and at different levels can combine to produce an enabling environment for agricultural biodiversity to be valued and conserved.

BOX 5.7 – Policies, civil society and business converge around agricultural biodiversity: Peru's journey

Peru, a megadiverse country,[vi] has made considerable progress regarding laws, strategies and action plans to conserve and sustainably use its biodiversity, including its native agricultural biodiversity.

Starting in the 2000s, there has been increased recognition by policymakers, researchers and entrepreneurs of the contributions of traditional farmers to agricultural biodiversity, and of genetic resources to food security and to the economy, given an increased demand for native crops and for benefits to the environment. The gastronomic renaissance of Peruvian food, where chefs and cooks celebrate native crops, has contributed to an improved societal perception about crop genetic resources and the smallholder farmers who grow them. The media has played an important role in the debate about climate change, adaptation, non-certified seeds and smallholder farmers. Businesses too have started to pay attention to biodiversity, for example with a 'Business and Biodiversity' initiative, led by large businesses, which aims for "productive conservation".

The government for its part is supporting various programmes: ValBio, which is a government grants programme to fund research projects to value native biodiversity (128); GENESPERU, a one-stop-shop platform to facilitate access to genetic resources and benefit sharing. The Ministry for Agriculture, in a departure from the priority focus on export crops, has indicated interest in smallholder farmers, approving regulations for the recognition of agrobiodiversity zones, and announcing the creation of the National Center for Genetic Resources of Agrobiodiversity. Peru appears poised to take advantage of its agricultural heritage for sustainable development.

Laws, regulations and institutions relevant for the conservation and sustainable use of agrobiodiversity in Peru 1986–2016 (Adapted from 129)

Norms	Year	Basic tenets
Promotion, production and consumption of agricultural food products from the Andes (Law 24520)	1986	Promotion of production and consumption of Andean native foodstuffs
Environmental & Natural Resources Code (Legislative Decree 613)	1990	Cultural diversity, natural patrimony and genetic diversity
Convention on Biological Diversity (CBD)	1993	*In situ / ex situ* conservation, agricultural biodiversity
National Commission on Biological Diversity	1993	Compliance with CBD at national level
National Council on the Environment (CONAM) created (Law 26410)	1994	Responsible for national environmental policy, focal point for CBD
Conservation of Biological Diversity (Law 26839)	1997	Species with cultural value, traditional knowledge, cultural patrimony
Regulations Law 26839	2001	Agrobiodiversity zones to protect indigenous culture, native crop species, allowing tourism
National Strategy of Biological Diversity	2001	*In situ* conservation, agricultural biodiversity
Protection of Collective Knowledge of Indigenous Peoples related to biological resources (Law 27811)	2002	Legal protection of collective knowledge associated with biodiversity – including agricultural biodiversity – by communities
CONAM National Programme of Agrobiodiversity created, which guides regional agricultural biodiversity agendas	2004	Sustainable use of agricultural biodiversity and components
National commission against Biopiracy (Law 28216)	2004	Biopiracy, protection of traditional knowledge, sovereignty
Native crops, landraces and wild relatives are national patrimony (Law 28477)	2005	Germplasm conservation, national patrimony, species of crops and landraces
General law about the environment (Law 28611)	2005	Biological diversity, genes, cultural diversity, benefit sharing, genetic resources, traditional knowledge, biotechnology, *in situ* conservation
Ministry of Environment (MINAM) created (Decree 1013)	2008	Responsible for national environmental policy
MINAM National Strategy on Biological Diversity and Action Plan to 2021 (NBSAP) (Decree 009)	2014	Includes actions on agricultural biodiversity, agroecosystems and genetic resources for food and agriculture
Ministry of Agriculture Regulation of agrobiodiversity zones	2016	Mechanisms and procedures for recognition of agrobiodiversity zones

Maize diversity in a community seedbank, Cuchumatanes highlands of Western Guatemala
Credit: Bioversity International/G.Galluzzi

Evidence from the case studies gathered suggests that some of the key mechanisms for an enabling environment are as follows:

Coordination between different ministries

National programmes that involve different sectors of government are a prerequisite for effective conservation and use of agricultural biodiversity to support sustainable food systems. An in-depth look at the expression of international agreements in national policies and practices indicates that, although most international agreements aim to have a positive influence on crop and animal genetic resource conservation and farmers' livelihoods, at national level policies tend to focus only on the non-agricultural parts of conservation, such as forests, wildlife and protected areas. This has negative consequences on the cultivation of traditional species, varieties and breeds. Efforts are more successful when different sectors of government (i.e. environment and agriculture) that normally do not work together are supported by policies to coordinate their work (38). For example, in Central American countries, complementary to a process of economic integration over the last decade, there has been a rapprochement between the environment and agriculture sectors that led to the joint formulation of a climate change agenda of work between the Council of Ministers of Agriculture and the Council of Ministers of Environment of Central America (130, 131), thus in one step favourably advancing interagency coordination within countries. The Council of Ministers of Agriculture belonging to the Central American Integration System (SICA from the Spanish acronym) has endorsed an action plan to conserve and use native plant genetic resources in adaptation to climate change, called the *Strategic Action Plan for the Conservation and Use of Plant Genetic Resources of Mesoamerica (SAPM)* (132).

Participatory planning

The development of national strategies and action plans, such as National Biodiversity Strategy and Action Plans (NBSAPs) and National Adaptation Programmes of Action (NAPAs, for climate change action) need to involve all relevant stakeholders, including those working on agricultural biodiversity, to ensure the involvement of stakeholders other than the state. Broad participatory planning processes used for the development of the *Strategic Action Plan for Mesoamerica*, involving stakeholders from six countries (132), resulted in immediate and concrete action. For example, in Guatemala, the National Institute of Agrarian Technology (INTA) planned collection missions to fill genebank gaps, and a community-based organization, the Association of Associations of the Cuchumatanes, Guatemala (ASOCUCH), used the Strategic Action Plan to design projects that implement its actions (133). In Honduras, a Commission on Genetic Resources was formally recognized. The implementation of NBSAP actions is, however, most effective if there are funding allocations by governments. For example, Peru's NBSAP is being systematically implemented by the Ministry of the Environment with sector funding: national experts are bringing together baseline inventories of priority crops, and incentive mechanisms for on-farm conservation are being pilot tested (75, 133).

Recognition and strengthening of conservation at local level

On-farm conservation, by its nature, takes place through actions by farmers and communities at a local level. Community-level initiatives such as participatory plant breeding and the development of community seedbanks have proven to be successful local solutions for the conservation and use of agricultural biodiversity in several countries, such as Nepal and India (58, 59). For example community seedbanks in Nepal have been recognized and registered by some local governments, and the government has started to provide some of them with technical and financial support. There are now more than 100 community seedbanks in Nepal with functions from pure conservation to commercial seed production (59). In addition, recognizing the outstanding efforts of custodian farmers – farmers who actively maintain, adapt and disseminate agricultural biodiversity and related knowledge, over time and space, at farm and community levels and are recognized by community members for it – is one way to strengthen their contribution. (Box 5.8).

BOX 5.8 – Bolivian and Indian custodian farmers recognized by their governments as contributing to *in situ* and on-farm conservation

The Bolivian government announced in 2014 that custodian farmers are important complementary contributors on farm to the *in situ* conservation of biodiversity, and are integral members of the Germplasm Banks Network and the construction of the National System of Genetic Resources. A manifesto of Gratitude to Agricultural Biodiversity Custodian Farmers was signed and presented highlighting the establishment of a network of custodian farmers.

Source: (134)

In India, the Protection of Plant Varieties and Farmer Rights Authority, after a competitive process conferred the award 'Plant Genome Saviour Community Award' to the Society for Conservation of Mango Diversity, an NGO, for safeguarding mango genetic resources of the Malihabad district *in situ* and on farm.

Source: (135)

Bolivian farmer in a quinoa field.
Credit: Bioversity International/E.Gotor

Social and cultural attitudes

Social and cultural attitudes can play a large role in creating an environment favourable for conserving agricultural biodiversity and using it sustainably. Public awareness about the benefits of biodiversity and people's roles as stewards are thus key (Box 5.9).

BOX 5.9 – Social and cultural attitudes favouring biodiversity

The Union for Ethical Biotrade (UEBT) has released its Biodiversity Barometer every year since 2008. UEBT surveys countries on their attitudes towards biodiversity – including biodiversity used for food and agriculture. Their most recent report reveals that overall attitudes towards biodiversity and knowledge about it have improved worldwide. However, there are differences between countries. In Peru, biodiversity is a term known by most people (94% of respondents) and the highest percentage of people interviewed gave the correct definition of biodiversity (72% of those surveyed) among the 16 countries surveyed. The study noted a close connection between the levels of biodiversity and people's awareness of it: high biodiversity in countries such as Brazil, Peru and Colombia, goes hand in hand with high biodiversity awareness and the ability to describe it. In Latin America, unlike in other parts of the world, biodiversity is recognized and a source of pride in the continent. Many respondents in Latin America (over 95%) say it is important to personally contribute to biodiversity conservation and express the willingness to pay more for biodiversity-based products. When illustrating what biodiversity means, many Brazilians, Colombians and Ecuadorians point to the Amazon. In Peru and Mexico, biodiversity appears also deeply associated with local cuisines, world famous for the variety of natural and traditional ingredients.

Source: (136)

Information system for conservation

An effective functioning system of conservation, management and use of agricultural biodiversity relies on information and knowledge, both new and traditional, about what diversity is available, where it is, threats to it, its conservation status, where it is conserved (*in situ*, on farm or *ex situ*), and what characteristics or traits it has. Availability of, and accessibility to, these kinds of information are vital to enable farmers, scientists and policymakers to take decisions on what agricultural biodiversity to conserve, manage and use, where and how. There has been much progress in documenting diversity of plant genetic resources held in *ex situ* collections in information systems at global and regional levels (e.g. GeneSys, EURISCO, GRIN-Global, FAO WIEWS, State of the World reports on plant genetic resources) (38). However, information systems at national and local level are underdeveloped and need to be strengthened. For on-farm and *in situ* crop genetic diversity, there are not even global or national level information systems, except for the reporting mechanism of the FAO, which monitors implementation of the Second Global Plan of Action on Plant Genetic Resources for Food and Agriculture.

For animal genetic resources, the Domestic Animal Diversity Information System (DAD-IS) developed by FAO is a globally accessible, dynamic, multilingual database of animal genetic resources. It aims to assist countries in the implementation of the Global Plan of Action for Animal Genetic Resources. DAD-IS provides the user with searchable databases of breed-related information and images, management tools, a library of references and links, and contact details of regional and national coordinators for the management of animal genetic resources. Currently, the database contains more than 14,000 national breed populations from 35 species and 181 countries. A number of countries have developed their own national databases or information systems for animal genetic resources. For example, Ireland has developed a national version of DAD-IS known as EFABIS, with the assistance of the FAO and Europe. India has developed an Information system on Animal Genetic Resources of India (AGRI-IS). With a focus primarily on Africa and Asia, the Domestic Animal Genetic Resources Information System (DAGRIS) is an information system developed by the international Livestock Research Institute (ILRI) to facilitate the compilation, organization and dissemination of information on the origin, distribution, diversity, present use and status of indigenous farm animal genetic resources from past and present research results in an efficient way. The State of the World Reports on animal genetic resources prepared by FAO (29, 31) provide comprehensive summaries and useful analyses of the status of global animal genetic resources, and help to focus global attention at high levels on critical conservation and use issues.

Metrics to measure conservation of crop and animal genetic diversity for sustainable food systems

Proposed indicators to assess on-farm conservation of genetic diversity

Crop genetic diversity

Monitoring genetic diversity of crops and breeds in production systems over time is a very challenging exercise. There is no internationally agreed set of indicators that satisfactorily measure the state of crop genetic diversity (32, 137). Most indicators draw on a DPSIR (driving forces–pressure–state–impact–response) framework,[vi] but mainly measure driving forces, pressures and responses rather than the state of genetic diversity per se (32). The most direct measure of genetic diversity is allelic diversity measured at the DNA level with molecular tools (138, 139). This is the most elemental level of biodiversity that drives the formation of new species and underpins other levels of biodiversity, including functional traits, species and ecosystems (32, 137). This metric is very robust and the methodology for measuring genetic diversity is getting better and more feasible with advances in genomics, but data on allelic diversity are still not readily available, are expensive and can only be done on a limited scale. Instead, trends in genetic diversity on farm can be assessed and monitored by different proxies such as area of coverage of traditional varieties (in hectares), richness of crop varieties, evenness of crop varieties, number of growers (44, 140, 141) and, for animals only, effective population size and population level estimate of inbreeding (142). However, even for these proxies, data at national level are patchy and there are no mechanisms in place for systematically collecting data.

The most up-to-date set of indicators for monitoring crop genetic diversity is that for monitoring the implementation of the Second Global Plan of Action for Plant Genetic Resources for Food and Agriculture, which has been endorsed by members of the Commission on Genetic Resources for Food and Agriculture (143). For on-farm conservation, the relevant indicators fall under priority area 2 'Supporting on-farm management and improvement of plant genetic resources for food and agriculture' as follows:

- Number of farming communities involved in management and improvement activities for on-farm plant genetic resources for food and agriculture
- Percentage of cultivated land under farmers' varieties/landraces in areas of high diversity and/or risk
- Number of farmers' varieties/landraces delivered from national or local genebanks to farmers (either directly or through intermediaries).

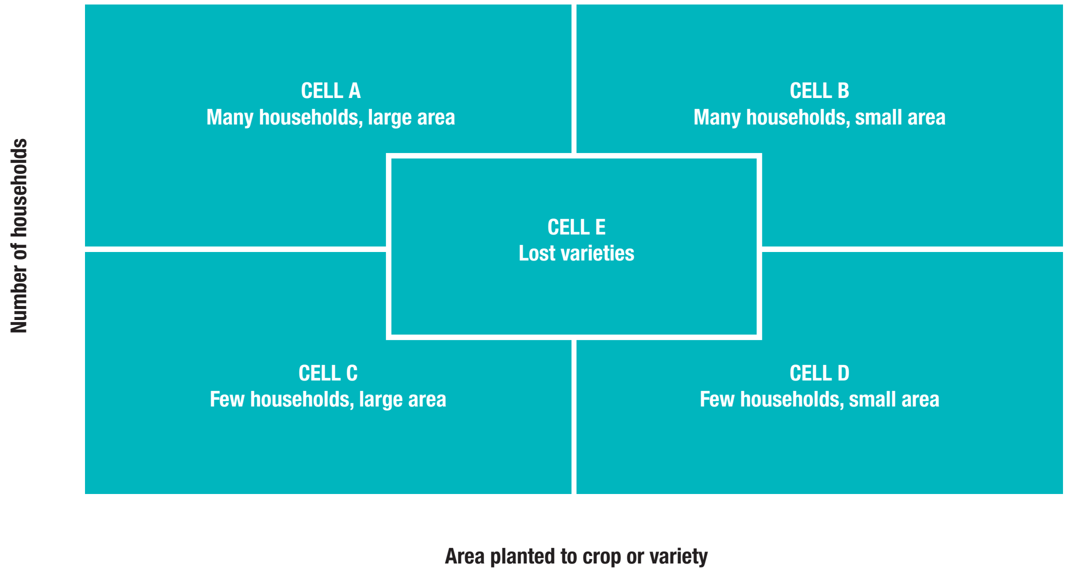
While the Global Plan of Action indicators are a proxy with global consensus, which are collected at national level following standard guidelines and reporting mechanisms developed by FAO (144), they have one major limitation: they do not give a precise measure of the status of crop genetic diversity on farm.

The ideal indicator to aspire to would be one which aggregates up from farm level, since knowledge of crop genetic diversity and how this is changing over time resides among local communities. There are proven socioeconomic research approaches that could be developed into a low-cost methodology for gathering data at this level, such as focus group discussions and seed fairs, where farmers can provide information on whether local diversity is increasing, decreasing or stable. A participatory bottom-up mechanism can support participatory documentation of local crops by communities and the flow of this information to the national level through the assistance of extension services and NGOs.

A community-level methodology named 4-cell analysis can be used to assess local diversity. The method was originally developed in Nepal and is based upon local assessment of richness (area planted to a crop or variety) and evenness (number of farmers growing the crop or variety) at the village level (145). The method is intuitive and has been widely adopted in many countries and contexts (6, 66, 146). A later development, 5-cell analysis, adds an extra cell in which lost varieties can be listed as a record of trends or with an eye to reintroduction (147) (Figure 5.4).

FIGURE 5.4 – Layout of the 5-cell analysis

Crops falling into cell D may be at risk. Those in call E may be recovered from neighbouring communities or genebanks.



With a system using the 5-cell analysis put in place at district or country level, a simple indicator to measure on-farm diversity could be:

- Trends (increasing, decreasing or unchanged) in: area, number of household growers or varietal diversity over the past five years.

Ideally, data originating from local communities would be consolidated by government agencies to provide a broader picture of crop diversity status. It must be stressed, however, that while this assessment and monitoring of diversity on farm represents an ideal decentralized mechanism, it would require financial resources for its mainstreaming (infrastructure and capacity building of community members) as well as careful procedures regarding the management and disclosure of sensitive information about varieties that some communities may not want to release to the general public.

If such data cannot be easily generated, useful proxies for crop genetic diversity on farm, based on data that are available in official national agricultural statistics, could include:

- Number of farmers' varieties/landraces registered in the national seed board/registries
- Number of species cultivated at national level.

"Humanity's collective knowledge of biodiversity and its use and management rests in cultural diversity; conversely, conserving biodiversity often helps strengthen cultural integrity and values" (148). Local languages spoken might therefore have potential to be a proxy for indigenous knowledge of biodiversity, as this is the mechanism by which knowledge is transferred from generation to generation. However, research on ways to monitor the status of indigenous knowledge related to agriculture is negligible. A monitoring system for assessing the status of indigenous knowledge could be developed using the 5-cell methodology.[viii]

Animal genetic diversity

The Global Plan of Action on Animal Genetic Resources (149), includes 23 strategic priorities for action grouped into four priority areas: characterization and monitoring; sustainable use and development; conservation; and policies, institutions and capacity-building. The main responsibility for implementing the Global Plan lies with national governments. Progress in the implementation of the Global Plan is monitored using two types of indicators. Process indicators are used to describe the extent to which the actions set out in the Global Plan have been implemented. Resource indicators are used to describe the state of animal genetic diversity itself and therefore the impact of the Global Plan. The indicators contribute to the measurement of progress towards Aichi Biodiversity Targets 13 (maintenance of genetic diversity), 7 (sustainable management of agriculture, aquaculture and forestry) and 4 (sustainable production and consumption). Information on the implementation of the Global Plan is obtained regularly from national governments, regional networks and international governmental and non-governmental organizations and the data are collected in the DAD-IS database described earlier.

FAO has led major efforts to develop and facilitate the application of tools and measures for quantifying and tracking animal genetic resources over time and space. The focus of this work has been on: (a) quantitative estimates of relationships among livestock breeds and strains; and (b) establishing risk status of breeds based on population figures and trends as well as herd/breeding structures (to incorporate effective population size). In 2004, FAO produced guidelines for development of national farm animal genetic resource management plans – measurement of domestic animal genetic diversity (MoDAD) (150), and the study of diversity in livestock populations using neutral markers is now widespread across the globe (151). FAO, ILRI and other international organizations have developed and tested tools for on-farm breed surveys, which have been adapted for use in many countries and provide the basis for risk status classifications and tracking of trends in breeds (152–155) (Box 5.10). In addition, FAO has been working to support countries to establish national breed inventories (by species). Many countries have established inventories, but the majority (63%) consider that their inventories are incomplete (31). Lack of human and financial resources are consistently reported as the major constraint to the conduct of surveys, establishment of inventories and implementation of effective programmes that support animal genetic resource management. More recently, FAO has developed guidelines for helping countries to design and implement integrated animal recording systems to support management and improvement (144).

The need for indicators for genetic diversity in animal genetic resources has come to prominence only relatively recently and only limited progress has been made, mainly in Europe. Lack of data has been the major challenge to the development of useful indicators. The risk status categories (see Box 5.10) of approximately 64% of reported breeds are available in the Domestic Animal Diversity Information System (29, 151), but a lack of regular updates of countries' breed population data means that trends cannot be described adequately at present (156). This presents a major constraint to tracking status of diversity. However, where risk statuses are available, one can use these, and we here propose the following candidate indicators:

- Proportion of breeds already at risk that slide a level or more down towards the 'critical' status
- Proportion of new breeds that enter 'at risk' classification (e.g. for a country) over a given time period.

BOX 5.10 – Risk status classification of livestock breeds

Extinct: a breed in which there are no breeding males or breeding females remaining. Genetic material that would allow recreation of the breed may, however, have been cryoconserved. In reality, extinction may be realized well before the loss of the last animal or genetic material.

Critical: a breed in which the total number of breeding females is less than or equal to 100 or the total number of breeding males is less than or equal to five; or the overall population size is less than or equal to 120 and decreasing and the percentage of females being bred to males of the same breed is below 80%; and which is not classified as extinct.

Critical-maintained: a breed that meets the criteria for inclusion in the critical category, but for which active conservation programmes are in place or populations are maintained by commercial companies or research institutions.

Endangered: a breed in which the total number of breeding females is greater than 100 and less than or equal to 1,000 or the total number of breeding males is less than or equal to 20 and greater than 5; or the overall population size is greater than 80 and less than 100 and increasing and the percentage of females being bred to males of the same breed is above 80%; or the overall population size is greater than 1,000 and less than or equal to 1,200 and decreasing and the percentage of females being bred to males of the same breed is below 80%; and which is not classified as extinct, critical or critical-maintained.

Endangered-maintained: a breed that meets the criteria for inclusion in the endangered category, but for which active conservation programmes are in place or populations are maintained by commercial companies or research institutions.

At risk: a breed classified as either critical, critical – maintained, endangered or endangered-maintained measurement.

Proposed indicators to assess *in situ* conservation of genetic diversity

The best set of indicators currently available for *in situ* conservation of genetic diversity are those under the FAO indicators for monitoring the implementation of the Second Global Plan of Action for plant genetic resources for food and agriculture (PGRFA) for *in situ* conservation, under priority activity 4: 'Promoting *in situ* conservation and management of crop wild relatives and wild food plants':

- Number of crop wild relatives and wild food plants *in situ* conservation and management actions with institutional support

- Percentage of national *in situ* conservation sites with management plans addressing crop wild relatives and wild food plants
- Number of crop wild relatives and wild food plants species actively conserved *in situ*.

However, as with on-farm conservation, these indicators do not assess the actual genetic diversity conserved *in situ*, but drivers of change and responses to change.

Here we propose a Crop Wild Relative Index as a single indicator to better document the effective status of *in situ* conservation of crop wild relatives. This indicator would measure the actual state (and not the responses) of crop relatives in the wild. The suggested index would be calculated by using existing data from the International Union for Conservation of Nature Red List Index for threatened species, which is the globally recognized index measuring trends in the extinction risk of sets of species (157). The index would not provide an exact indication of the status of genetic diversity, but would be a robust proxy.

As an illustration, we applied the Crop Wild Relative Index to three countries' crop wild relative threat assessments: Bolivia (158), Jordan (159), South Africa (Box 5.11) and a regional crop wild relative assessment for Europe (160) (Table 5.2), using a standard set of procedures (161). A case study on conservation of crop wild relatives in South Africa (Box 5.11) describes the process implemented in a project designed to inventory and characterize wild relatives of crops important for food security in the South African region.[ix]

BOX 5.11 – Conservation status of crop wild relatives in South Africa

South Africa has a large and diverse flora, with approximately 20,500 indigenous species recorded and more than 8,000 species that have been introduced into the country. Many plant species in South Africa are used for a wide range of purposes, including food and beverages, medicines, perfumes and repellents, soap and cosmetics, poisons for hunting and fishing, dyes, fuel, weaving and building materials. As part of a project on '*In situ* conservation of crop wild relatives in three countries in the Southern African Development Community' (SADC CWR project for short), the South African National Biodiversity Institute, in collaboration with the Department of Agricultural Forestry and Fisheries and Agricultural Research Council, developed a checklist for South African crop wild relatives, which covered 420 crop genera of food (including beverages) and fodder crops, with a focus on the wild relatives of major global crops. 1,479 species were identified. Based on a set of criteria, including socioeconomic value, use potential for crop improvement, relative distribution and conservation status, 272 crop wild relatives were prioritized. Of these, 249 species had reliable information for Red List assessment using the IUCN Red List Categories (threats) and were assigned to one of five IUCN Red List categories as follows: critically endangered (25), endangered (26), vulnerable (16), nearly threatened (2) and least concern (180).

Source: (107)

Storage facilities and nurseries for traditional Andean grains, roots and tubers. Bolivia is home to roughly 20,000 species of plants and more than 2600 species of vertebrates. The National Protected Area System (NPAS) was established in 1997 with the objective to 'maintain representative samples of biogeographic provinces'. The NPAS contains more than 66 protected areas of national, departmental, municipal or private interest and accounts for more than 15%of the national territory.
Credit: Bioversity International/D.Hunter

TABLE 5.2 – Crop wild relative threat assessment in Bolivia, Jordan, South Africa and regional crop wild relative threat assessment in Europe

	Bolivia	Jordan	South Africa	Europe
Data source	(158)	(159)	(107)(Box 5.11)	(160)
IUCN Red List category (weight)				
Extinct (5)	0	0	0	0
Critically endangered (4)	7	19	25	19
Endangered (3)	22	54	26	25
Vulnerable (2)	16	33	16	22
Near threatened (1)	20	11	2	26
Least concern (0)	62	806	180	313
Total Threat Score (T) (total number of species x weight)	146	315	212	221
Maximum Threat Score (M) [total number of species x weight of maximum threat (5)]	635	4615	1245	2025
Crop Wild Relative Index [(M – T) / M]	0.7701	0.9317	0.8297	0.8909
0=all Extinct	1= all Least Concern			

Table 5.2 indicates that, of the countries and regions considered, Bolivia is the country where crop wild relatives are most at risk, and Jordan where they are of least concern. In order to monitor trends across years, the Crop Wild Relative Index would need to be calculated over regular periods of time, depending on species biology. Normally a period of five years is judged as acceptable. At this stage, only a few countries have started to assess the conservation threat of their crop wild relatives, but the numbers are growing (38), so this is a realistic indicator to develop in coming years.

Proposed indicators to assess *ex situ* conservation of genetic diversity

Compared to on-farm and *in situ* conservation, measuring the genetic diversity of *ex situ* collections is less challenging. Materials for assessing the diversity are readily accessible and, by and large, information about conserved material is readily available for large genebanks. With recent advances in genomics and greater accessibility to molecular tools, more and more genebanks are doing molecular characterization of their collections and this information will become more available in near future with initiatives like DivSeek (162), which aims to empower genebank managers, breeders, researchers and farmers to better characterize, disseminate and use plant genetic variation. While this initiative is being developed, proxies are needed to represent the diversity held in *ex situ* facilities that contributes to sustainable food systems.

The relevant FAO indicators under the Second Global Plan of Action for PGRFA for measuring the state of diversity in *ex situ* genebanks fall under priority activity 6 'Sustaining and expanding *ex situ* conservation of germplasm' as well as one indicator under priority activity 7 'Regenerating and multiplying *ex situ* accessions' as follows:[x]

- Number of species conserved *ex situ* under medium or long-term conditions
- Number of accessions conserved *ex situ* under medium or long-term conditions
- Percentage of *ex situ* accessions safely duplicated
- Percentage of *ex situ* accessions in need of regeneration.

If the aim is to measure the breadth of genetic diversity in collections, we would suggest, as an alternative indicator, an adaptation of the 'Enrichment Index'.[xi] The Enrichment Index could be used at country level to measure the diversity within a portfolio of the main species identified as most important for local food systems. It can also be used to assess levels of neglected and underutilized species and crop wild relatives maintained in collections, applicable to both species and within-species levels. The Enrichment Index uses data readily available in genebanks and is very easy to calculate. It assesses the pool of accessions entering a given collection each year according to their uniqueness when compared to the accessions already present in the collection. Accessions in *ex situ* collections are always described by passport data (163), which contain information such as the species and country of origin. The uniqueness of each accession can be determined based on the plant family and the country of origin from which the accession was collected. These two pieces of information together give an idea of how different the new accession is from what is already in the collection.

An illustration of how the Enrichment Index works in practice is provided in Box 5.12.

BOX 5.12 – Application of the Enrichment Index to the world banana collection at the International Transit Center (ITC), Leuven, Belgium

The world *Musa* (banana and plantains) collection at the International Transit Center (ITC) genebank in Belgium contains approximately 1,500 accessions. We will use it as an example of a method to assess diversity in *ex situ* collections.

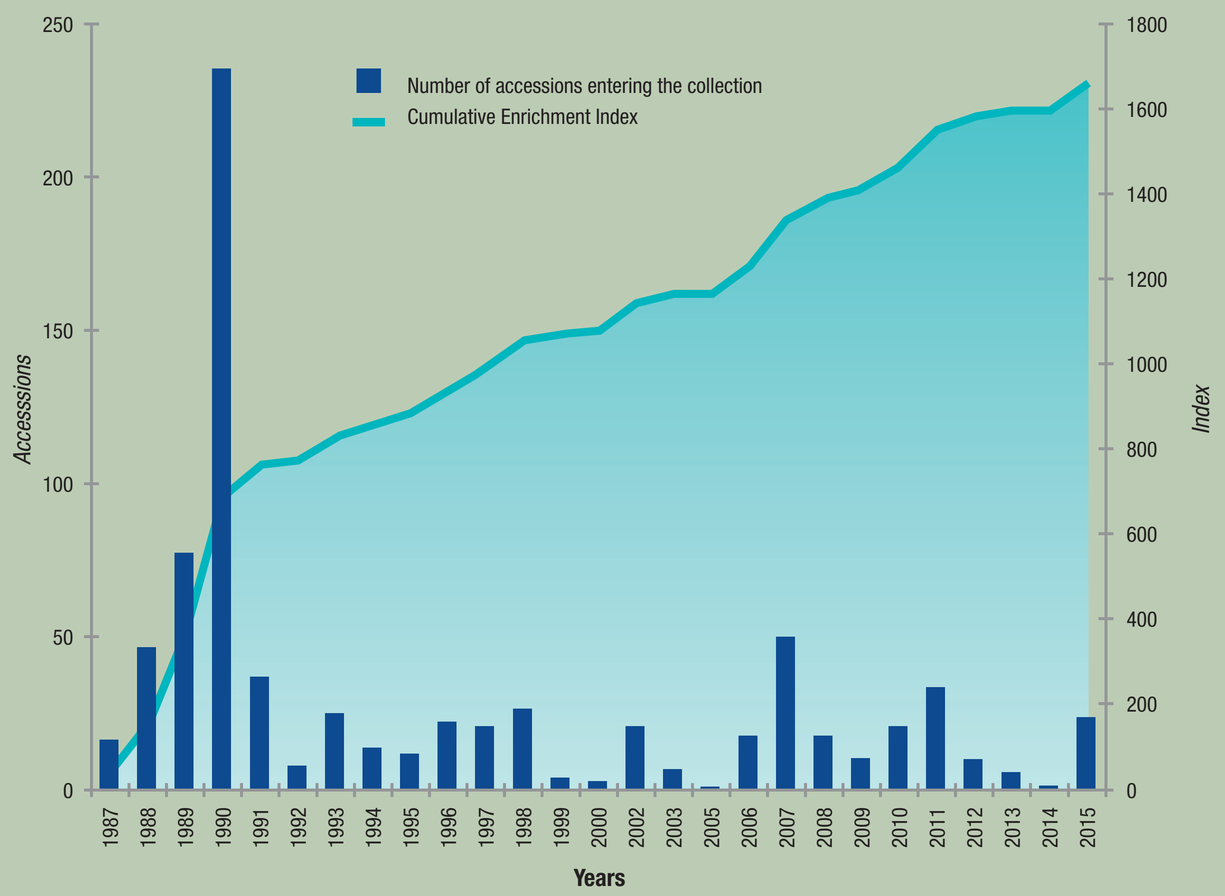
1. Select a valid dataset. We selected a dataset based on the completeness of the passport data fields: genus, species, country of origin and acquisition date. This took us from 1,501 to 769 accessions, representing 80% of the total species and 93.3% of the total countries.

2. Check for duplicates. We ran a duplication analysis over the valid dataset by searching for any accession sharing the exact same combination of values across the fields: genus, species, country of origin, latitude, longitude and acquisition date. From the 769 validated accessions we identified 152 duplicated records. Duplicated accessions should not be discarded, as they may contain useful information, but they receive a lower weighting.

3. Calculate the index. The increase of the Enrichment Index for the selected *Musa* accessions in ITC from 1987 till 2015 is represented together with the number of accessions that entered the collection each year. (Figure 5.5). Here the cumulative value in 2015 is 1,660. Applying the exact same methodology (taxonomic units, time units, etc.), this should be comparable between collections.

FIGURE 5.5 – Enrichment Index of the ITC collection between 1987 and 2015

An increase in the index represents the addition of accessions to *ex situ* collections. The steepness of the line indicates the diversity being incorporated into collections. A steeper line indicates that greater novelty is being added to collections with regard to both taxonomy and source country. A horizontal line indicates that no accessions are being added to collections. The steep increase from 1989 to 1990 corresponds to an important collecting mission in Papua New Guinea, when 215 accessions out of 236 entered the collection.



Banana accessions conserved at the world's largest banana genebank - the Bioversity International Musa Transit Centre in Leuven, Belgium.
Credit: Bioversity International/N.Capozio

Proposed indicators for policy and enabling environment

There are currently two global initiatives which collect data on the policy enabling environment for genetic resources. The first is the World Bank Group initiative 'Enabling the Business of Agriculture' (164) that collects yearly data from 62 countries on Environmental Sustainability, including on conservation of plant genetic resources. The second is the FAO Commission on Genetic Resources for Food and Agriculture which has established processes for collecting data to monitor the implementation and impact of the Global Plans of Action for both plant and animal genetic resources. The data are collected through the FAO WIEWS reporting system for plant genetic resources (165) and DAD-IS for animal genetic resources. Data are compiled and reported to the regular meetings of the Commission every two years.

Existing databases

Based on the analysis above of what is important for the conservation of genetic resources across the three realms of on-farm, *in situ* and *ex situ*, we propose to use these existing databases as a starting point for a scorecard observing the existence or not of key policies and practices that enable conservation of agricultural biodiversity. Further to these, we would add the annual Biodiversity Barometer, measuring social and cultural attitudes towards biodiversity.

Suggested candidate questions for crop and animal diversity in the scorecard could thus be as follows:

From Enabling the Business of Agriculture:

- Does your country have operating genebanks or collection systems for plant genetic resources?
- Has one of them been established by law or regulation as the national genebank or collection system for plant genetic resources?

- Are any of the following activities performed by the officially designated national genebank?
    - Collecting germplasm
    - Germplasm distribution
    - Viability testing
    - Characterization
    - Evaluation
    - Regeneration
    - Multiplication
    - DNA fingerprinting
- Are any of the data relating to these activities available in an online database?
- Does your country have policies, regulations or programmes that establish the following practices?
    - Community seedbanks
    - Diversity fairs
    - Participatory plant breeding
- Does your country have an inventory of crop wild relatives?
- Which of the following information is publicly available for each crop wild relative included in the list?
    - Geographical distribution
    - Conservation status (e.g. vulnerable, endangered or critically endangered)
    - Specific traits
    - Known uses including cultural values or practices associated with the crop wild relative
    - Others

From the FAO Global Plan of Action for plant genetic resources (priority areas in brackets):

- Does your country have national policies that promote development and commercialization of all varieties, primarily farmers' varieties/landraces and underutilized species? (PA11)
- Does your country have a national entity (agency, committee, etc.) functioning as a coordination mechanism for plant genetic resources for food and agriculture activities and/or strategies? (PA13)
- Does your country have a formally appointed national focal point or coordinator for plant genetic resources for food and agriculture? (PA13)
- Does your country have a governmental policy framework and strategies for plant genetic resources for food and agriculture conservation and use? (PA13)
- Does your country have a national information-sharing mechanism for plant genetic resources for food and agriculture? (PA13)
- Does your country have a national system to monitor and safeguard genetic diversity and minimize genetic erosion? (PA16)

From the FAO Global Plan of Action for animal genetic resources (priority areas in brackets):

- Does your country set and regularly review *in situ* conservation priorities and goals? (PA3)
- Does your country have an *in situ* conservation programme for breeds and populations that are at risk? (PA3)
- Does your country set and regularly review *ex situ* conservation priorities and goals? (PA3)
- Has your country established or strengthened fully functional National Focal Points for animal genetic resources? (PA4)
- Does your country have strong national coordination between the National Focal Point and stakeholders involved in animal genetic resources, such as the breeding industry, government agencies, civil society organizations and networks and advisory committees?
- Does your country promote coordination and synergy between the different authorities dealing with various aspects of planning, within and across ministries, as well as with other stakeholders, and ensure their participation in the process?

We suggest integrating the results of the Biodiversity Barometer into the resulting scorecard results, as a measure of social and cultural attitudes favouring biodiversity.

Conclusions

A sustainable food system is ultimately dependent on the availability of and access to a wide diversity of animals and crops, which represent the foundation of agriculture. Of particular importance are those species, varieties and breeds that are important to people's food and nutrition security and farming systems, and which are highly threatened, globally valuable, unique, or a combination of these. The three realms where the genetic diversity of plants and animals is conserved (on farm, *in situ* and *ex situ*) are regarded as complementary and any conservation strategy for agricultural biodiversity needs to consider these realms in a truly integrated system. Governments, companies and other stakeholders with an interest in conserving a wide genetic base for future agricultural challenges will need to take into account the scientific underpinnings that characterize the diversity across these three realms. The scientific evidence can suggest enabling policies and measures to establish simple monitoring systems, based on easy-to-measure or available indicators to better understand the status of agricultural biodiversity. A healthy conservation system will ensure that the raw materials necessary for sustaining our food system will always be available for agricultural improvements.

Diverse crops growing in a field as part of an on-farm conservation project in Ecuador.
Credit: Bioversity International/M.Bellon

Notes

[i] Global Plans of Action are negotiated by the Commission on Genetic Resources for Food and Agriculture, at the Food and Agricultural Organization (FAO) of the UN. They "seek to create an efficient system for the conservation and sustainable use of genetic resources for food and agriculture. Global Plans of Action are intended as comprehensive frameworks to guide and catalyze action at community, national, regional and international levels through better cooperation, coordination and planning and by strengthening capacities. They contain sets of recommendations and priority activities that respond to the needs and priorities identified in global assessments: the reports on the state of the world's genetic resources for food and agriculture." http://www.fao.org/nr/cgrfa/cgrfa-global/cgrfa-globplan/en/

[ii] This work was carried out under a large, multiyear, multicountry research project on 'Strengthening the scientific basis of *in situ* conservation of agrobiodiversity', which was started in 1997 in nine countries, with financial support from the governments of Canada, Germany, the Netherlands and Switzerland, led by Bioversity International (then called the International Plant Genetic Resources Institute, IPGRI).

[iii] The mechanism for the encouragement of countries is a joint notification by the secretariats of the Convention on Biological Diversity (CBD) with its Financial Mechanism – the Global Environment Facility (GEF), the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) and its Benefit Sharing Fund, the CGRFA and Bioversity International.

[iv] Genetic reserves are also known as genetic sanctuaries or gene management zones.

[v] This project, for the safe and effective conservation of crop wild relatives and their increased availability for crop improvement, was funded by the Global Environment Facility (GEF), 2004–2010, in Armenia, Bolivia, Madagascar, Sri Lanka and Uzbekistan. GEF Project ID: 1259. http://www.cropwildrelatives.org/

[vi] There are 17 megadiverse countries in the world. They are countries that harbour very high numbers of endemic species.

[vii] In the DPSIR framework there is a chain of causal links starting with 'driving forces' (economic sectors, human activities) through 'pressures' (emissions, waste) to 'states' (physical, chemical and biological) and 'impacts' on ecosystems, human health and functions, eventually leading to political 'responses' (prioritization, target setting, indicators).

[viii] As part of the CGIAR Research Program on Roots Tubers and Banana, a consortium of international agricultural centres – International Potato Center (CIP), Bioversity International, International Institute of Tropical Agriculture (IITA), and International Center for Tropical Agriculture (CIAT) – organized an international expert meeting on 'Development of Systematic Agrobiodiversity Monitoring Approaches' from 4 to 8 November 2013 in Huancayo, Peru. The aim of the meeting was to share state of the art methods and metrics for the systematic monitoring of *in situ* conserved diversity of crops and crop wild relatives in centres of origin and diversity, and to define a minimal core set of standard procedures to be shared among different organizations and countries. The report can be found at (166).

[ix] The project, on *in situ* conservation of crop wild relatives in three countries of the Southern African Development Community (SADC) region, was co-funded by the European Union and the Secretariat of the African, Caribbean and Pacific (ACP) group of States through the ACP-EU Co-operation Programme in Science and Technology (Grant: FED/2013/330-210).

[x] An accession is a "distinct, uniquely identifiable sample of seeds representing a cultivar, breeding line or a population, which is maintained in storage for conservation and use" (167).

[xi] The Enrichment Index has been Developed by FAO, IRD (Institut de Recherche pour le développement) and Bioversity International under the Biodiversity Indicators Partnership programme (168).

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Farmer with one of her goats, Nepal.
Credit: IWMI/N.Palmer

6

Towards an Agrobiodiversity Index for sustainable food systems

Roseline Remans, Simon Attwood, Arwen Bailey, Stephan Weise

Measuring

KEY MESSAGES:

- Agricultural biodiversity is measured in many ways: in healthy diets, sustainable land use, agriculture, climate change adaptation, resilience and biodiversity conservation.
- Bioversity International proposes the development of an Agrobiodiversity Index that brings agricultural biodiversity data together in innovative combinations across these functions in the food system to give novel insights, help countries identify policy levers, and be usable in real time to guide companies and investments.
- We welcome input from readers, experts and potential users for the development and utility of the Agrobiodiversity Index for sustainable food systems.

Introduction

"What gets measured, gets managed."

The previous chapters review and summarize the evidence base for how people use agricultural biodiversity to achieve different aspects of sustainable food systems. Agricultural biodiversity is important in four dimensions: in consumption for nutritious diets and human health; in production for long-term productivity, resilience and multiple ecosystem services; in seed systems for access to options that serve diverse needs and help adaptation to changing conditions; and in integrated conservation methods for enabling future uses and insurance against shocks.

The evidence combined illustrates that agricultural biodiversity sits at the nexus of different food system components and sustainability dimensions (Figure 6.1). Such a perspective on agricultural biodiversity for multiple goals aligns with one of the core food system principles proposed by the International Panel of Experts on Sustainable Food Systems: "Food systems must be fundamentally reoriented around principles of diversity, multi-functionality and resilience." (1)

Many indicators and methods have been developed and applied to measure the many facets of agricultural biodiversity. For example, metrics illustrated in Table 6.1 inform pathways that connect agricultural biodiversity to diet quality, sustainable agriculture, ecosystem services, the diversity within seed systems, or biodiversity conservation. This variety in measurements is both agricultural biodiversity's strength and its weakness. Its strength because evidence of agricultural biodiversity's contribution to each of these ambitions has been collected and has triggered interest in agricultural biodiversity across sectors, Sustainable Development Goals and Aichi Biodiversity Targets. Its weakness because data, information and metrics are scattered across locations, disciplines (e.g. conservation, ecology, agriculture, markets, nutrition) and scales (from crop varieties and species to ecosystems, entire regions and countries). No coherent monitoring exists, which limits our effectiveness to manage agricultural biodiversity for sustainable food systems.

Starting from the scientific evidence base in the four dimensions described in this book, we are designing an Agrobiodiversity Index, which brings agricultural biodiversity data together in innovative combinations across functions in the food system to give novel insights, which can help countries and companies identify policy and business levers, and guide public and private sector investments.

FIGURE 6.1 – Agricultural biodiversity contributes to multiple sustainability dimensions and development goals

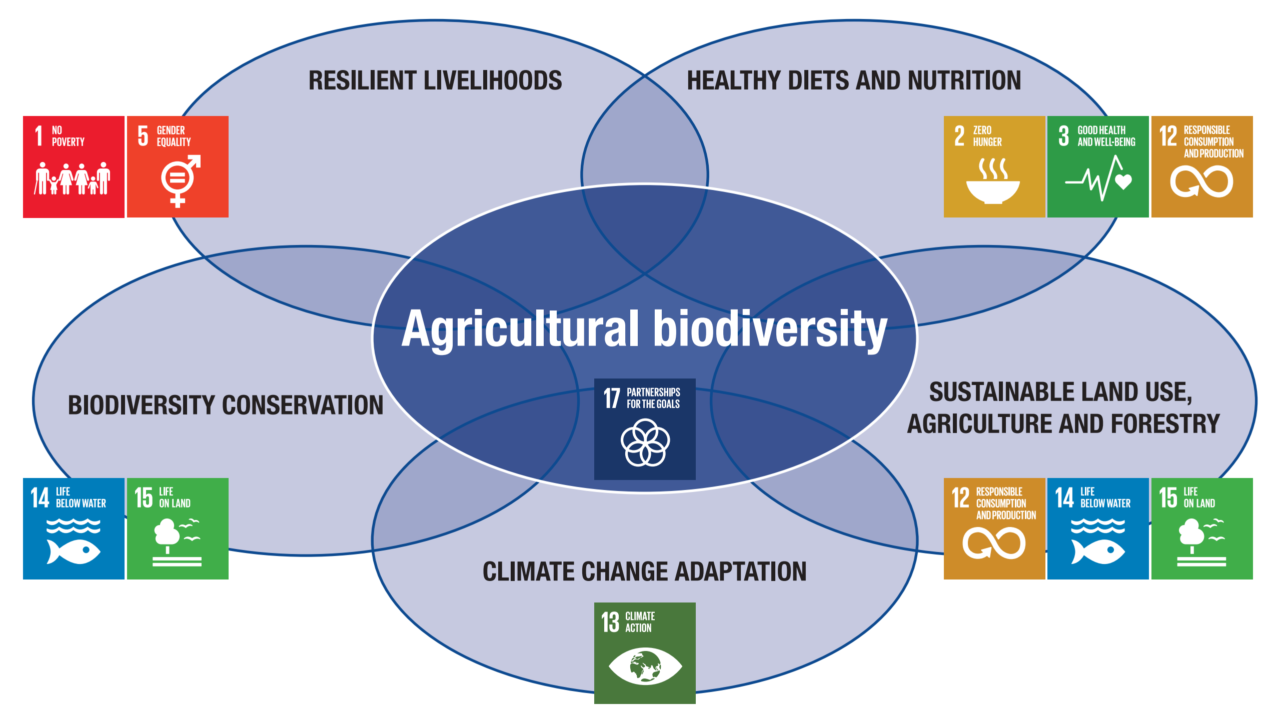


TABLE 6.1 – Illustration of indicators, both existing and proposed, that measure agricultural biodiversity and its contributions to dimensions of a sustainable food system

Agricultural biodiversity contributing to...

HEALTHY, DIVERSE DIETS

DIET DIVERSITY

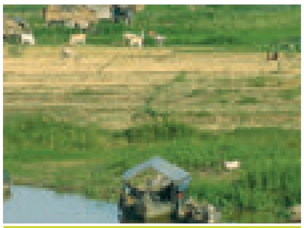
- Minimum diet diversity for children and women
- % consumption of targeted food groups
- Dietary species richness (number of different plant and animal species per person per day)
- Grams and dietary energy per capita of different food groups/ items
- % dietary energy from non-staples

MARKET/ VALUE CHAIN DIVERSITY

- Prices of principal foods representative of diverse food groups
- Ultra-processed food retail (vol/capita)
- Fresh food retail (kg/ capita)
- Diversity of retail outlets for elements of a healthy diet
- Average price of a healthy diet

ENABLING ENVIRONMENT

- Consideration of ABD in a country's National Dietary Guidelines
- Food subsidies and public procurement programmes in place that promote ABD for diets/nutrition
- Consideration of ABD mainstreaming for diets/nutrition in NBSAPs



MULTIPLE BENEFITS IN SUSTAINABLE FARMING SYSTEMS

DIVERSITY WITHIN SPECIES

- Varietal diversity of major crops in production systems

DIVERSITY AMONG SPECIES

- Evenness/diversity of production area and yield across crops

DIVERSITY AT FARM AND FIELD LEVEL

- Soil biodiversity in agricultural production systems
- Functional trait diversity of crops
- % agricultural area under sustainable agricultural practices

DIVERSITY AT LANDSCAPE LEVEL

- Landscape and land-use heterogeneity
- Coverage (e.g. extent) of habitat related to particular ecosystem services (e.g. pollinator habitat)

ENABLING ENVIRONMENT

- Policies that explicitly aim to conserve and/or promote ABD
- National policies and incentives around multiple ecosystem services in agricultural landscapes

CROP DIVERSITY FOR SUSTAINABLE FOOD SYSTEMS

SEED ACCESSIBILITY

- Information availability
- Amount and diversity of seed sources
- Proximity of seed sources
- Seed price

SEED PRODUCTION AND DISTRIBUTION

- Amount of seed produced and distributed
- Range of crops and varieties multiplied and distributed
- Number and diversity of seed multipliers and seed suppliers

CROP INNOVATION

- Range of species covered by innovation efforts
- (Local) genetic diversity used in innovation efforts
- Degree of recognition of farmers as innovators in intellectual property right systems

REGULATIONS

- Extent to which variety registration procedures allow for the release of varieties responding to different environmental and socio-economic conditions
- Extent to which seed quality control and certification schemes respond to different types of seed producers and farmers

CONSERVATION FOR USE IN SUSTAINABLE FOOD SYSTEMS

ON-FARM CONSERVATION

- Percentage of cultivated land under farmers' varieties/landraces in areas of high diversity and/or risk
- Proportion of breeds already at risk that slide a level or more down towards 'critical' status

***IN SITU* CONSERVATION**

- Number of crop wild relatives and wild food plants species actively conserved *in situ*
- Crop Wild Relative Index based on IUCN Red Listing

***EX SITU* CONSERVATION**

- Number of accessions conserved *ex situ* under medium or long-term conditions
- Enrichment Index

ENABLING ENVIRONMENT

- NBSAP includes ABD
- Farmers and their knowledge recognized and their role explicitly facilitated
- Regional, local ordinances to support ABD conservation/use.
- Participatory, broad-based development of strategies and implementation plans specifically targeting participation of women farmers

ABD = agricultural biodiversity, NBSAP = National Biodiversity Strategy and Action Plan

What we can learn from agricultural biodiversity data, metrics and monitoring for the design of the index

The importance of agricultural biodiversity data and reporting is increasingly recognized. The Food and Agriculture Organization of the UN (FAO) is publishing a new milestone, the *State of the World's Biodiversity for Food and Agriculture*. There is, however, a gap in terms of tools and approaches for quantitatively synthesizing existing and emerging data into actionable trends, dynamics and summaries. To make measures actionable, we need to know how the diversity is used, how uses are changing over time, and what major enablers and constraints leverage or block the potential of agricultural biodiversity for human and environmental health. For example, we want to know: Is diversity entering the marketplace? Do farmers have access to diverse planting materials? How much diversity is ending up on people's plates?

Learning across agricultural biodiversity measures and monitoring efforts, we can draw several lessons to help guide the design and initial architecture of the Agrobiodiversity Index.

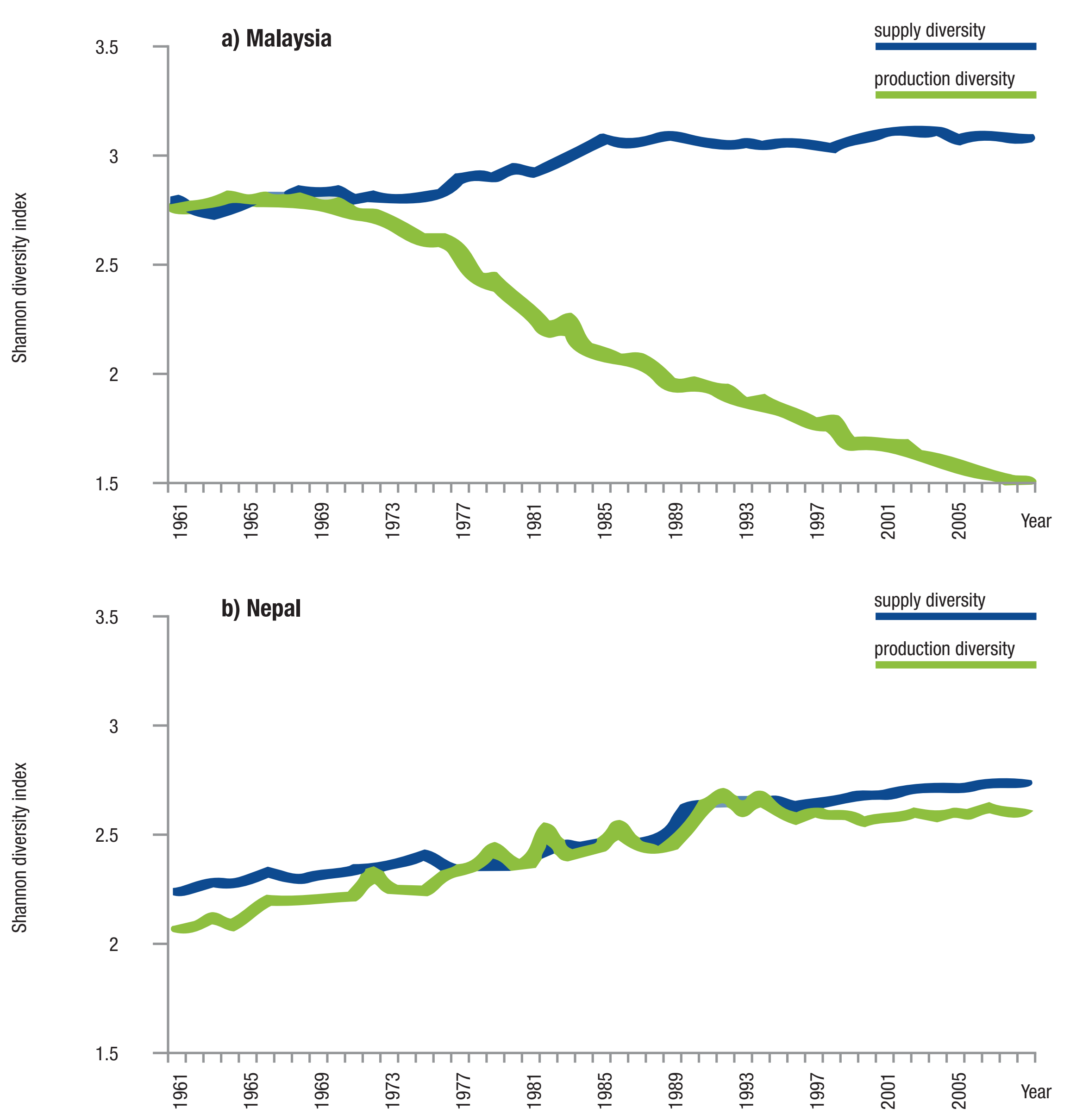
First, agricultural biodiversity is used and measured throughout the food system (Chapters 2 to 5, Table 6.1). Understanding agricultural biodiversity trends across, and interactions among, multiple food system dimensions helps to identify points of constraint, trade-off, synergy or action. For example, if levels of agricultural biodiversity in production are increasing, but diet diversity is not, then there is potential to strengthen local markets for increased access to, and consumption of, food biodiversity. Mobilizing existing databases and applying a consistent set of simple agricultural biodiversity indicators (e.g. species richness, or commonly used measures of diversity, such as the Shannon diversity index[i]) across food system

Jaya Bahadur Thapa and his daughter-in-law, Saraswati Thapa, from Chaur, Begnas, Nepal. Jaya Bahadur and his wife Lal Kumari Thapa (not in the picture) are custodian farmers who specialize in medical plants. They make herbal remedies and powders and also sell saplings of medicinal plants. Sale of their medicinal products is generating a steadily increasing income. They are passing on their knowledge of medical plants and remedies to their daughter-in-law.
Credit: LIBIRD/Sajal Sthapit

dimensions (consumption and markets, production, seeds, conservation) enables trends in these dimensions to be identified and compared (2–4). Two examples can illustrate how useful, novel insights can be drawn from synthesizing publicly available data with a diversity lens.

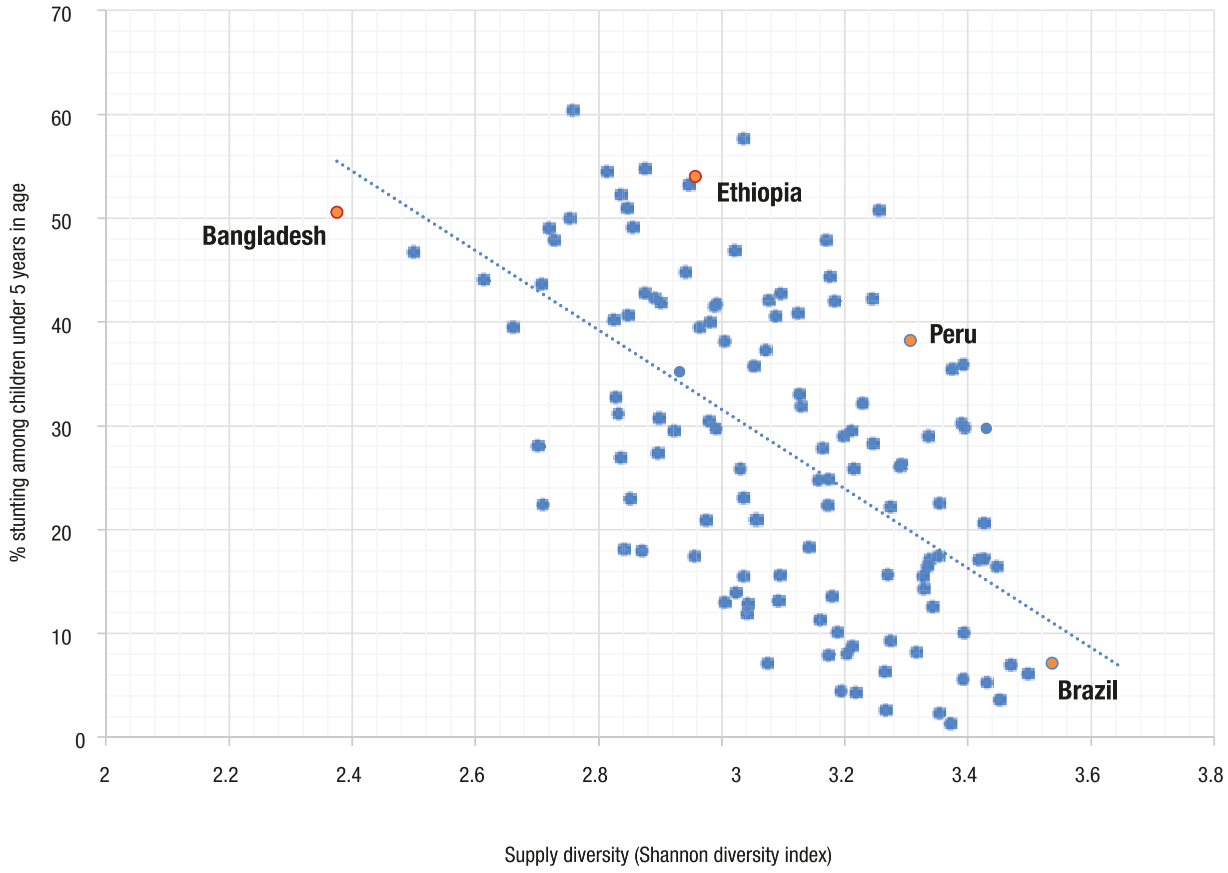
The first (Figure 6.2) compares over 40 years of data on production diversity (i.e. number of species produced in a country) with data on supply diversity (i.e. a measure of the diversity of species available for human consumption in a country, considering production, export, import, feed and waste). In Malaysia, while the diversity in production has dropped drastically through intensification of palm oil production, the diversity in food supply has increased through import of diversified food items. The example illustrates that international trade can provide people with diverse foods to eat, but the drastic reduction in production diversity raises concerns about the environmental consequences as well as the country's dependence on palm oil. In Nepal, on the other hand, production and supply diversity have slowly increased together over time, suggesting that the country is achieving food supply diversity through a system of diverse food production. This indeed reflects Nepal's agricultural and food policy (5, 6), which has been closely integrated with its multisectoral nutrition policy and plan (7). Nepal is still a low-income country with limited international trade and high levels of chronic undernutrition (40% stunting among children under five years of age), despite recent accelerated reductions in stunting (8). A key question here is how Nepal can further climb up the economic development ladder, while smartly managing its production and supply diversity.

FIGURE 6.2 – Production and supply diversity in Malaysia and Nepal based on FAOSTAT data



Source: Adapted from (9)

FIGURE 6.3 – Comparison of data on supply diversity with data on levels of stunting among children

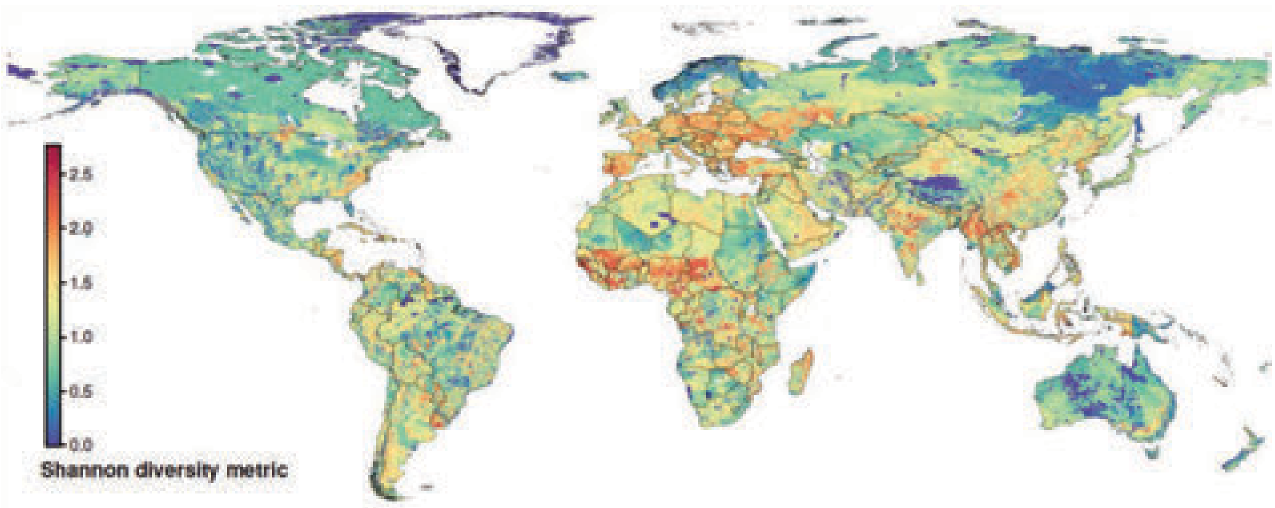


Another example (Figure 6.3) compares data on supply diversity with data on levels of stunting (i.e. low height for age) in children under five years old. Higher levels of supply diversity correlated closely with lower levels of stunting. While this does not necessarily indicate a cause–effect relationship between diversity and the reduction of stunting, it does suggest an interesting and strong relationship which scientists can explore to understand better how to address malnutrition.

Second, it is possible to combine existing crop and livestock data with farming system and spatial modelling in order to generate global agricultural biodiversity maps (e.g. species diversity illustrated in Figure 6.4). Visualizing data in this way helps trigger novel insights into spatial distribution of agricultural biodiversity, and how this is changing over time. The data can be overlapped with other spatially explicit data, for example on Sustainable Development Goals, wild biodiversity or agricultural production.

Figure 6.4, for example, illustrates how agricultural production in Europe, Africa and Asia is more diverse than most parts of the USA and Latin America. These regional differences are associated with the scale of farms and the type of major crops: large-scale farms are dominant in many parts of the Americas, and in the production of sugar and oil crops (10). The landscapes of these large-scale sugar and oil crop farms are less agriculturally diverse than landscapes with small-scale farms (10). While global analyses may be subject to making some broad generalizations, this does imply that small farms and smallholder farmers play a vital role in maintaining agricultural biodiversity at global to village scales.

FIGURE 6.4 – Global spatial distribution of species diversity of crops and livestock



Source: Adapted from (10)

Third, by considering diversity at different spatial scales, researchers have shown that, while species diversity in national food supplies is increasing (more diversity available to consumers), at global level, food supplies are becoming more homogeneous (less diversity between countries) (11). This has sparked debate about implications and related actions needed for food and nutrition security as well as environmental sustainability.

Fourth, there are still many important data gaps in all four dimensions (consumption, production, seed systems, conservation) and at various levels of diversity (landscape diversity, species diversity, varietal and genetic diversity, functional diversity). Further, many of the data are collected and used only at small scales, often sitting on researchers' and local institutes' desks or on computer hard drives. Biodiversity monitoring increasingly uses crowdsourcing and citizen science (12). Linking high-level monitoring efforts with local crowdsourced agricultural biodiversity information in the index could be a highly innovative development which enables decision-makers to: (1) ground-truth high-level data insights, (2) increase monitoring sensitivity and (3) apply the index at different spatial scales. One potentially very powerful tool that could be used to predict how agricultural biodiversity may change with altered land use and management is the PREDICTS project. PREDICTS is collecting small-scale data from scientists worldwide in order to produce a global database of terrestrial species' responses to human pressures. It investigates how local biodiversity typically responds to human pressures, such as land-use change, different intensities of management within land uses, pollution, invasive species and infrastructure, ultimately combining this analysis with satellite data and improving our ability to predict future biodiversity changes.

Fifth, measurements or scorecard information on drivers, commitments and strategies, which are needed in an enabling environment or a business case for agricultural biodiversity in food systems, are more readily available than measurements on the actual state of agricultural biodiversity. They provide a critical way to identify entry points for action. At the country level, national or company strategies could, for example, include policies and programmes that explicitly commit to managing agricultural biodiversity in conservation and/or production systems, increasing food biodiversity in diets, and providing incentives for growing food items other than major staples. At the company level, such strategies could include, for example, product lines that consider a diversity of varieties or species in their supply chain, land restoration efforts, application of agroecological principles and interventions on production farms, and leveraging benefits from diversified, mixed systems.

What we can learn from other composite indices for the design of the index

There are many composite indices constructed to inform decision-making and different types can be distinguished based on the audience targeted and the type of data used. For example, the Global Biodiversity Outlook, Global Food Security Index, Global Hunger Index and the Environmental Performance Index, all use national datasets, aggregate well-established indicators and mainly target national governments. Some of these focus on measuring drivers (e.g. Global Food Security Index), while others capture outcomes (e.g. Global Hunger Index). Other examples, particularly those assessing issues that are difficult to quantify, like the Corruption Perception Index and the Ease of Doing Business Index, also target national governments and relevant stakeholders, but collect input from a sample of experts or other priority stakeholders using index-specific questionnaires. The Access to Medicine, Access to Seeds, Access to Nutrition type of indices, focus on companies and use company-specific information. Other private sector indices are specifically designed for and used in investment, like the Dow Jones Sustainability Index, which is based on an annual questionnaire completed by the company. These different types of indices indicate that different groups of decision-makers (e.g. national governments, local governments, private actors, NGOs) require different resolutions and time frequencies of index reporting.

Across the broad range of those existing indices, we can draw several general lessons to help guide the process of developing an Agrobiodiversity Index:

First, no index is perfect and there is always space for improvement. Most important from the user perspective is that the index steers progress on intractable challenges. Therefore indices need to be informative, sensitive to relevant change, actionable and inspire communications with other end users (e.g. consumers and farmers).

Second, composite indices emphasize multiple dimensions of a certain issue. While the overall index often serves mainly to attract attention and provide comparisons of performance, analyses of trends in sub-indices allow policymakers to identify entry points for action.

Third, many datasets exist, often collected at great expense and increasingly experienced by users as an overload of information. Indices that aim to prioritize and filter data to make them useful and manageable in decision making, or to score issues that are difficult to quantify, are increasingly in demand, used and referred to.

Fourth, most robust indices are developed, improved and adapted over time through an iterative and adaptive process, engaging end users throughout and adopting lessons learned.

Fifth, no examples of indices were found that mobilize recent digital opportunities, such as crowdsourcing, as input of data. This seems like an underexplored opportunity with powerful potential to link the local with the national and global scales.

Perspectives for the Agrobiodiversity Index

Building on the above, we summarize our perspectives for the development of the Agrobiodiversity Index. We start from the demand side. Five user groups have expressed strong interest in the Agrobiodiversity Index:

- National governments: to monitor and manage agricultural biodiversity at national level in order to guide country-specific policies and public investments in sustainable food systems
- Private companies: to monitor and manage agricultural biodiversity at company level to robustly and transparently rate food and agriculture companies listed on stock markets in terms of their commitment to and use of agricultural biodiversity
- Public and private investors: to monitor and manage agricultural biodiversity at project/investment level to guide and track investments in sustainable bond markets
- Farmer and consumer groups: to guide best practices and influence policies and programmes
- Groups developing or maintaining other indices: to include or strengthen an agricultural biodiversity dimension.

The Agrobiodiversity Index must be fit for purpose, easy to use and straightforward to interpret. It can be tailored in different ways to provide the decision-supporting knowledge that these different user groups need. Contributing data to the index and pulling measurements out should be made easy. For example, investment in lean data approaches (i.e. tailored, focused questions delivered directly to key users through low-cost technologies) can make data collection easier. Sharing data directly in compelling visualizations, scorecards and dashboards in near real time (or at regular intervals) will increase the user-friendliness of the index and more clearly inform decision-making. New institutional, business and innovative financing arrangements can use agricultural biodiversity to connect data for use in risk management.

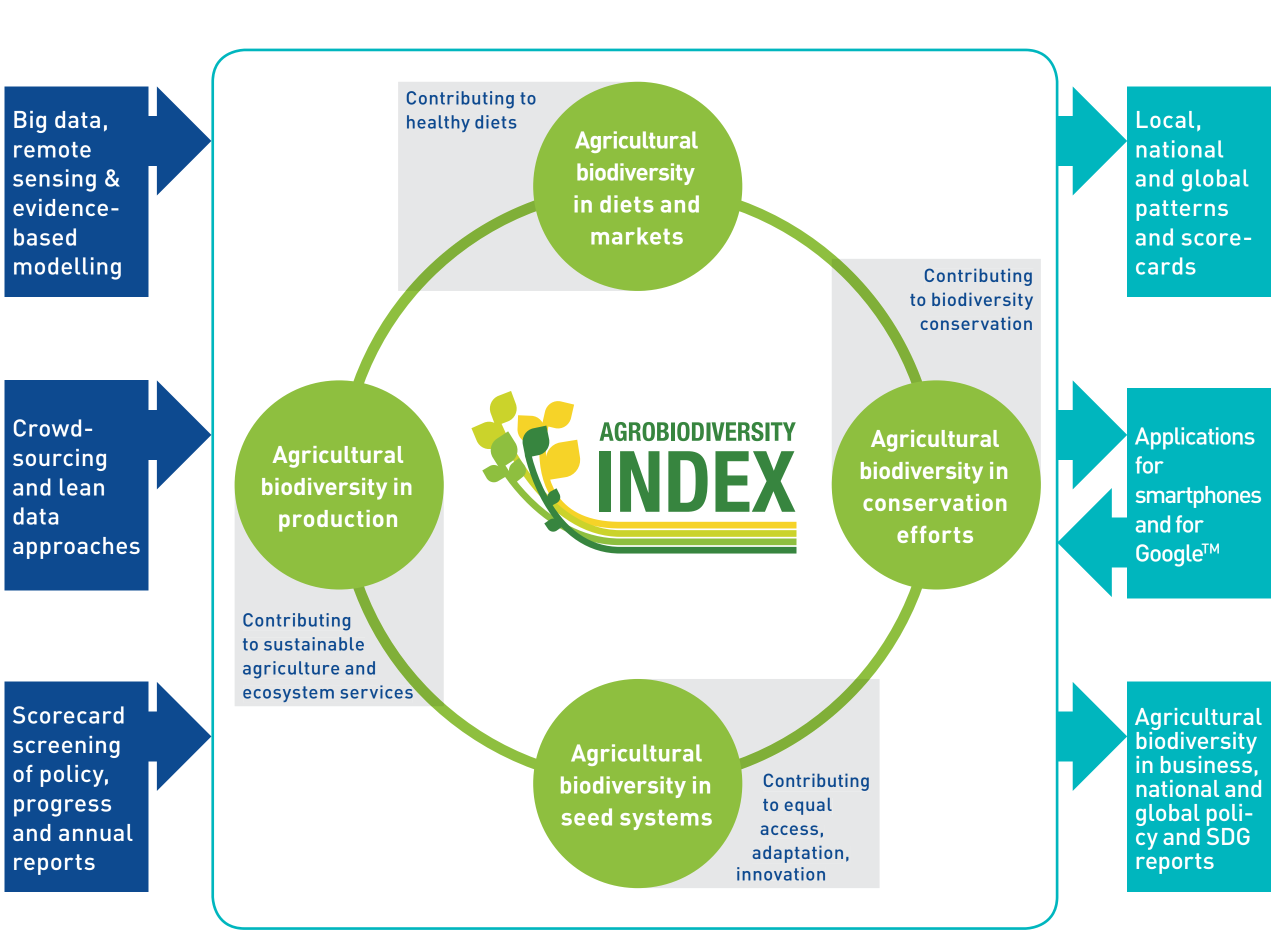
A first step is to combine existing datasets, integrating crop and livestock data for food systems, agricultural biodiversity measures, country and company reports and public data. These high-level monitoring efforts can then be enriched with local crowdsourced agricultural biodiversity data and remote sensing data. An iterative step is to test the Agrobiodiversity Index with multiple users (national governments, investors, companies) by further engaging with stakeholders, pioneering and testing an initial design through use cases. We thereby continuously welcome interactions with readers, experts and potential users for the development and utility of the Agrobiodiversity Index for sustainable food systems.

Five years from now, we expect that the methodology for the Agrobiodiversity Index (Figure 6.5) will:

- Combine big data with new crowdsourced data in a georeferenced model
- Provide information on the status of agricultural biodiversity along the food system chain, from genetic resource management, to production systems, to markets and consumption, relevant for countries and companies
- Be used in the design of sustainable investment
- Inform global reports and publications, such as those of the Sustainable Development Goals and the Convention on Biological Diversity
- Increase local and global demand for agricultural biodiversity monitoring and use.

FIGURE 6.5 – Conceptualization of the Agrobiodiversity Index

The Agrobiodiversity Index will draw on input from existing databases, combined with crowdsourced data and a screening of public and private policies and reports on issues connected with agricultural biodiversity's contribution to global goals. Users can consult scorecards, and access and input information through applications. The results from the Agrobiodiversity Index can be used to monitor risk related to poor agricultural biodiversity and report on commitments to global goals.



Conclusion

Diversity is increasingly identified as key to food system sustainability and integrated into the Sustainable Development Goals and the Aichi Biodiversity Targets, but there is no consistent way of tracking it across diets, production, seed and conservation systems.

A recent collaboration between research scientists and influential business leaders identified the top 40 research priorities for managing the complex relationship between food, energy, water and the environment (13). Four of their priority research questions (RQ) identify the role of biodiversity directly at that nexus, and ask how to measure and communicate that complex relationship:

- How can the role of biodiversity on the supply and interdependence of food, energy and water be measured and assessed to enable improved decision-making? (RQ 10)
- How can complex nexus interactions and uncertain outcomes be communicated such that they can be easily understood and applied by non-experts (customers and the public)? (RQ11)
- What common metrics can be devised to enable nexus comparisons to be made to help businesses and investors choose priorities and inform decisions? (RQ12)
- How does the lack of food crop diversity (dominance of wheat–maize–rice) impact upon the sustainability of the food–energy–water–environment nexus and what are the risks to business? (RQ17)

Building on agricultural biodiversity science combined with new innovative approaches, interconnected databases and an active, ground-rooted network, it seems feasible to build an innovative Agrobiodiversity Index and initiate a new global service of agricultural biodiversity tracking that can help answer these questions and move the needle in our food systems.

The Agrobiodiversity Index aims to help guide more sustainable practices, for individuals, communities, governments and companies through presenting food system sustainability data in a digestible form. In our era of data overload, there is a unique opportunity to reach a wide variety of change leaders with newly gained scientific insights. The Agrobiodiversity Index turns the lens around to the consumer, the company, the farmer, government and the globe and asks: 'Why and how is agricultural biodiversity important to you?'

Farmer in Uganda during a baseline assessment study for a project investigating the role of crop diversity in combatting pests and diseases. Here she is sitting with her children in an agricultural landscape belonging to multiple farmers.
Credit: Bioversity International/P.De Santis

Notes

[i] The Shannon diversity index reflects the richness and abundance of diversity in a system. The closer it is to zero, the lower the levels of diversity.

[ii] http://www.predicts.org.uk

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Amaranth plant, Barotse floodplain, Zambia. Amaranth is a versatile and nutritious crop eaten in every continent. Both grains and leaves can be eaten and contain protein and high levels of minerals and vitamins, such as manganese, iron and folic acid. Amaranth grows rapidly and produces many seeds, even under difficult growing conditions.
Credit: Bioversity International/E.Hermanowicz

Glossary

Accession	Distinct, uniquely identifiable sample of seeds representing a cultivar, breeding line or a population, which is maintained in storage for conservation and use (1)
Agricultural biodiversity or Agrobiodiversity	The variety and variability of animals, plants and micro-organisms that are used directly or indirectly for food and agriculture, including crops, livestock, forestry and fisheries. It comprises the diversity of genetic resources (varieties, breeds) and species used for food, fodder, fibre, fuel and pharmaceuticals. It also includes the diversity of non-harvested species that support production (soil micro-organisms, predators, pollinators), and those in the wider environment that support agro-ecosystems (agricultural, pastoral, forest and aquatic) as well as the diversity of the agro-ecosystems (2)
Agroecological intensification	A means by which farmers can simultaneously increase yields and reduce or reverse negative environmental impacts, through the use of biodiversity-based approaches and the production and mobilization of ecosystem services
Agroecology	The application of ecological concepts and principles that integrate biological and ecological processes into food production, minimizing the use of non-renewable inputs that harm the environment (3)
Agroforestry	A production system in which trees are integrated with crops, thus providing many synergistic relationships, such as shade or nutrients
Biodiversity	The variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems (4)
Community biodiversity management	A community-driven participatory approach that empowers farmers and communities to organize themselves and to develop livelihood strategies that support the on-farm management of agricultural biodiversity (5)
Community seedbank	A popular approach in developing countries, particularly in South Asia and Africa, to conserve and manage agricultural biodiversity at the community level. Community seedbanks tend to be small-scale, the local institutions, which store seed on a short-term basis, serving individual communities or several communities in surrounding villages (6)
Cover crops	Crops which are sown for agroecological purposes, such as containing soil erosion, controlling pests or enriching the soil with nutrients. Green manure is one specific instance of a cover crop. Nutrient-rich plants (usually legumes) are planted and then ploughed into the earth to improve soil quality

Crop rotation	Different crops grown in succession in the same field (e.g. cereal followed by legume), often to reduce risks of pests and diseases or to add nitrogen to the soil
Crop wild relatives	Crop wild relatives are wild plant species that are genetically related to cultivated crops.
Cultivar	A plant or grouping of plants selected for desirable characteristics that can be maintained by propagation. Most cultivars have arisen in cultivation, but a few are special selections from the wild (3)
Ecosystem	A dynamic complex of plant, animal and micro-organism communities and their non–living environment interacting as a functional unit
Ecosystem services	The direct and indirect contributions of ecosystems to human wellbeing, such as clean water, habitats for pollinators and waste decomposition (7)
***Ex situ* conservation**	The conservation of components of biological diversity outside their natural habitats (4)
Food biodiversity	The diversity of plants, animals and other organisms used for food, covering the genetic resources within species, between species and provided by ecosystems (8)
Food system	Collaborative network that integrates all components from food production through food consumption based on ecological, social and economic factors and values of a region or sub-region
Genetic diversity	The genetic variability among or within a sample of individuals of a variety, population or species (3)
Genetic material	Any material of plant, animal, microbial or other organisms containing functional units of heredity
Genetic resources	Genetic material of plant, animal, microbial or other organisms containing a diversity of useful characters of actual or potential value to society
Hybrid variety	Variety resulting from crossing genetically distinct parents. Commercially, the parents used to produce hybrids are usually inbred for specific characteristics. If hybrid seed is recycled by farmers, its yield often drops.
***In situ* conservation**	The conservation of ecosystems and natural habitats and the maintenance and recovery of viable populations of species in their natural surroundings. In the case of domesticated or cultivated species, it refers to conservation in the surroundings where they have developed their distinctive properties (4)
Intercropping	A mixture of crop species in the same field at the same time, often with synergistic effects, such as pest suppression

Landrace (also referred to as 'farmer variety')	A crop variety, often harbouring some genetic variability, yet, with a certain genetic integrity that has evolved in cultivation, usually in a traditional agricultural system over long periods, and has adapted to a specific local environment or purpose (3)
Live fences	Fences of herbs, shrubs or trees (e.g. hedgerows), either retained from existing native vegetation or deliberately planted
Non-cropped vegetation	Fields left fallow or patches of natural vegetation, such as forest patches, which are retained or persist on farm
No-till agriculture	Tillage of the soil is replaced with approaches that directly drill seeds or directly plant into the soil, thus reducing soil disturbance
On-farm conservation	A dynamic form of crop and animal genetic diversity population management in farmers' fields, which allows the processes of evolution under natural and human selection to continue (4, 9)
Protected area	A geographically defined area which is designated or regulated and managed to achieve specific conservation objectives
Riparian buffers	Vegetation planted or retained on river banks to protect river systems from adjacent agriculture
Seed system	An ensemble of individuals, networks, organizations, practices and rules that provide seeds for plant production
Species	Below the level of genus, a group of actually or potentially interbreeding individuals that are reproductively isolated from other such groups, share a common ancestor more recently than with individuals of related species, and have similar ecology and morphology (3)
Subspecies	Populations of organisms sharing certain characteristics that are not present in other populations of the same species
Value chain	The linkages between individuals or enterprises needed to move a product or service from production to consumption, along with related inputs and technical, business and financial service
Variety	A plant or group of plants selected for desirable characteristics and maintained in cultivation. It may be traditional and maintained by farmers, or modern and developed as a result of deliberate breeding programs (3)
Wild foods	Wild plants, animals and insects that are not cultivated or reared in captivity.; They are part of the minor crops and underutilized species, and include roots and tubers, vegetables and leafy vegetables, fruits, insects, amphibians, reptiles, birds and mammals gathered for food (8)

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"A well researched book that illustrates the important, but undervalued, role of biodiversity in the world's food systems. With a host of case studies, facts and figures about this growing area of research, this is a must-read for anyone interested in how we can use all our biodiversity resources for more nutritious food while reducing damage to the planet."
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"One of the reasons our current food systems are unsustainable is that we haven't focused enough on the concept of diversity: of the thousands of food species available we only consume a handful of the least nutritious. The Agrobiodiversity Index and its accompanying book instead do just that, providing us with scientific evidence and policy options to connect biodiversity, sustainable food systems and healthy nutrition."
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