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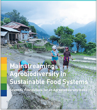

Mainstreaming Agrobiodiversity in Sustainable Food Systems

Scientific Foundations for an Agrobiodiversity Index

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.

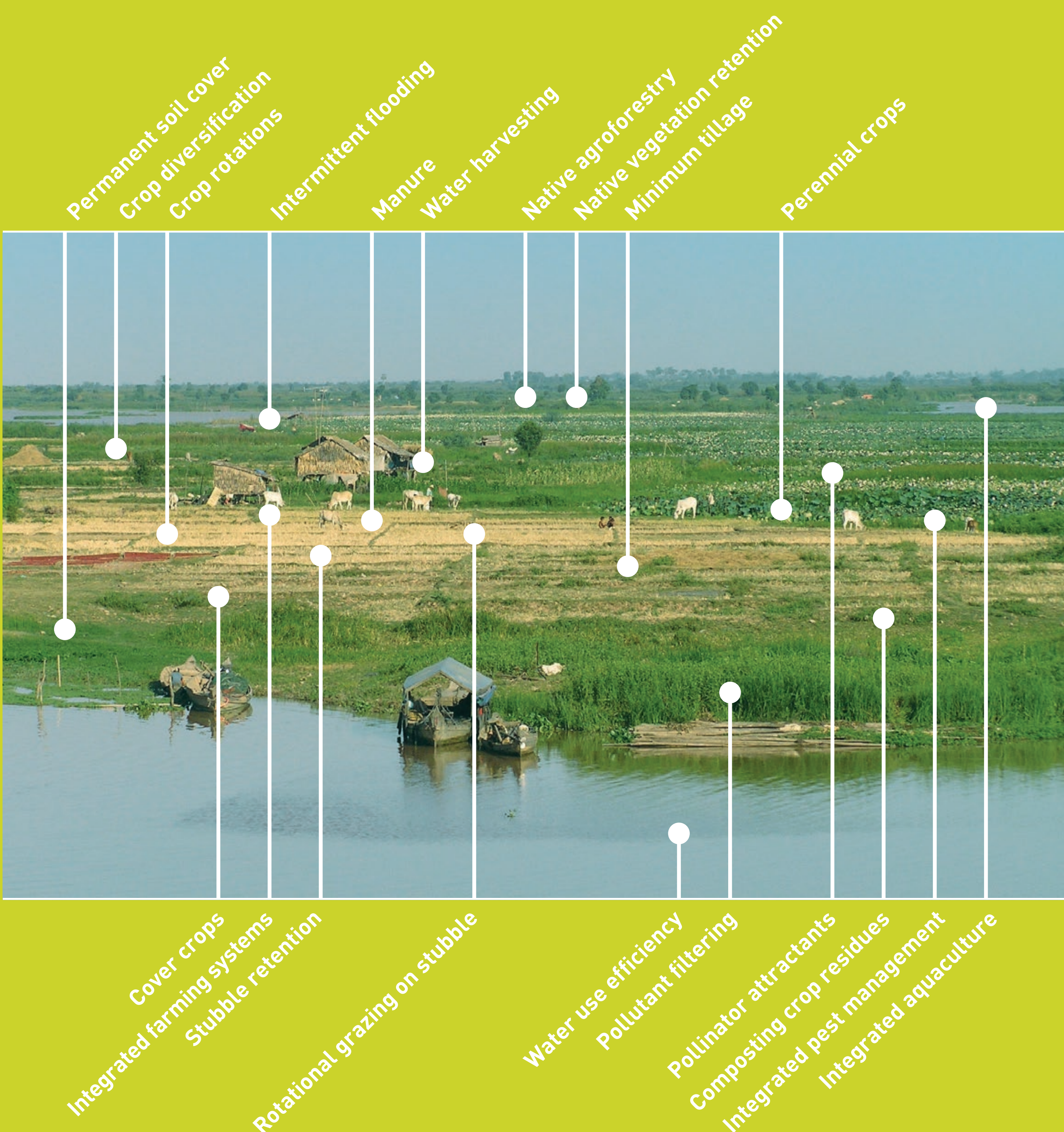
Agroecological intensification aims to widen the number of ecosystem services an agricultural landscape provides (21, 24, 25). So, while a highly industrial farming system may provide very well the service of 'yield', agroecological-based farming systems, regardless of the kind of farm or study sites, 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.

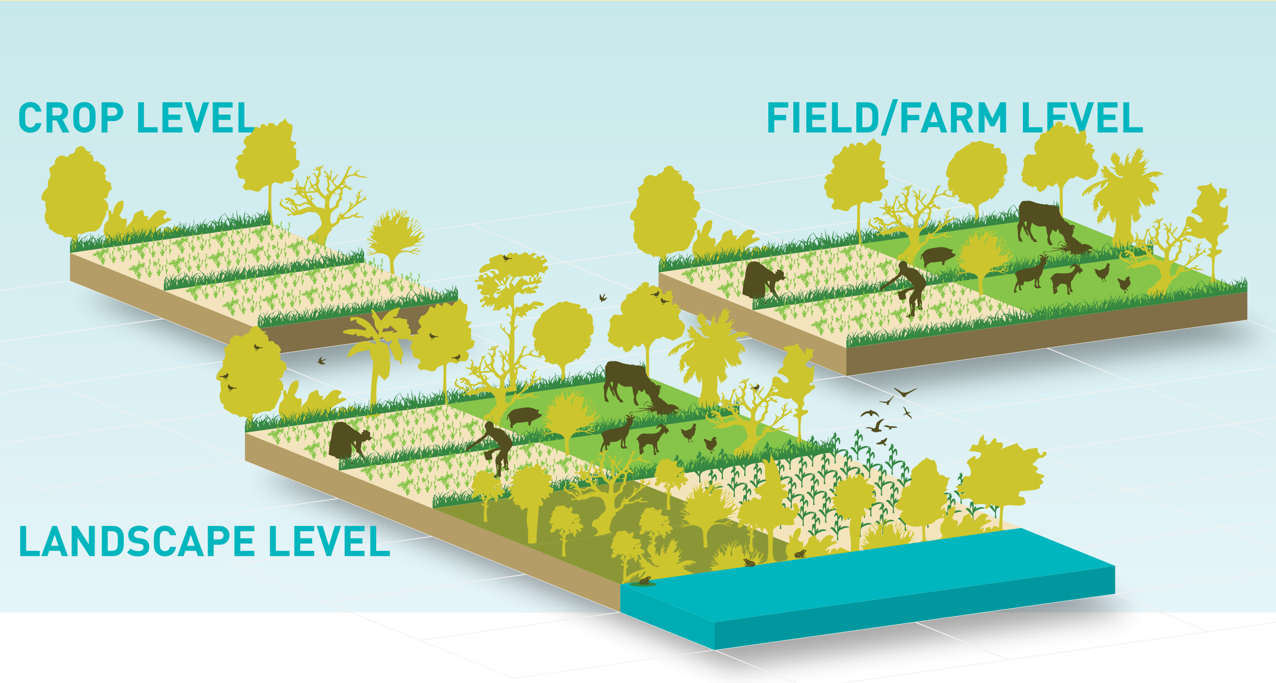
FIGURE 3.2 – Agricultural biodiversity at different levels contributes to healthy farming landscapes

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).

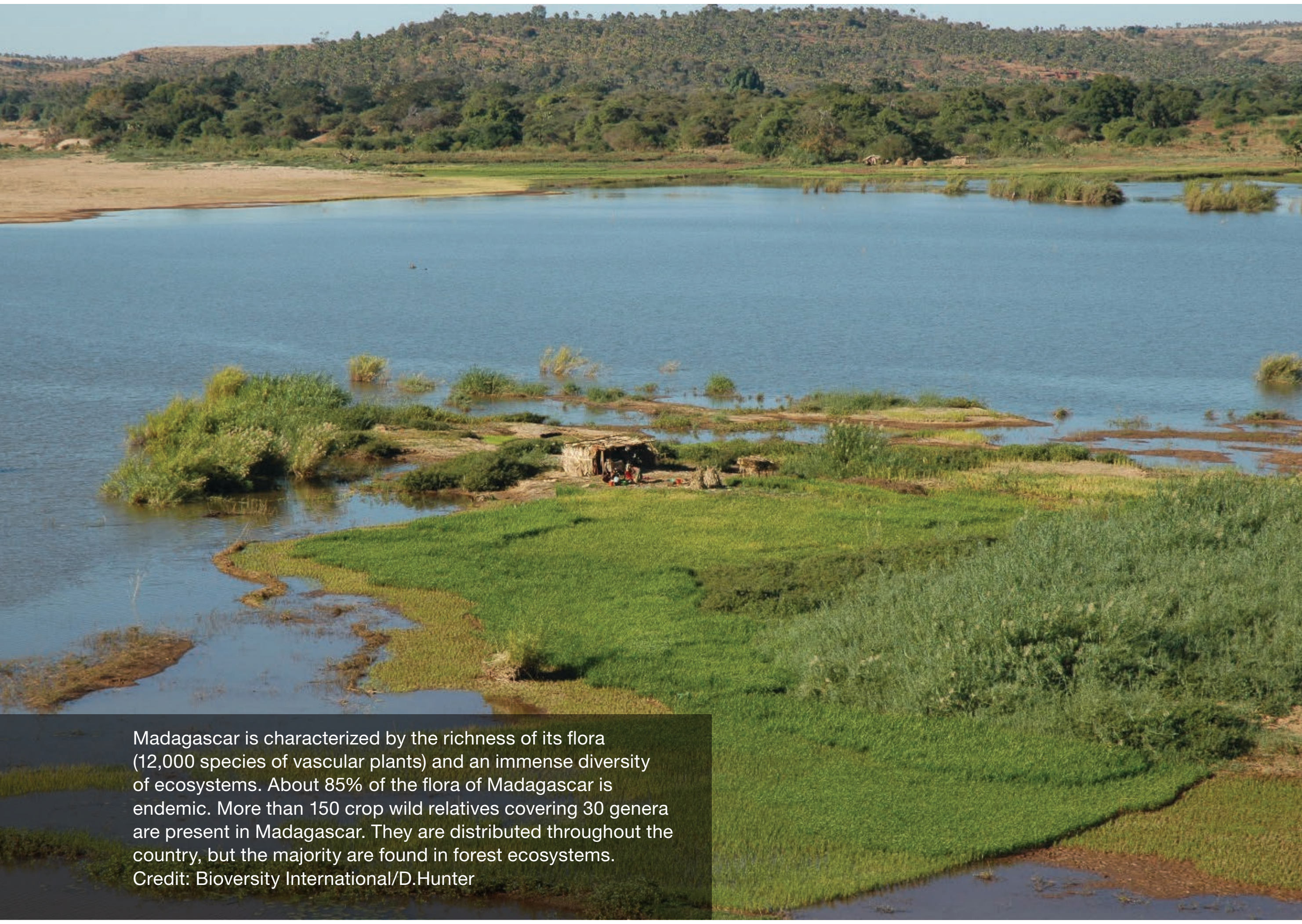
Metrics for measuring agricultural biodiversity for multiple benefits in sustainable farming systems

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.
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