Sustainability **2011**, *3*, 238-253; doi:10.3390/su3010238

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Agricultural Biodiversity Is Essential for a Sustainable Improvement in Food and Nutrition Security

Emile A. Frison *, Jeremy Cherfas and Toby Hodgkin

Bioversity International, via dei Tre Denari 472a, 00057, Maccarese, Rome, Italy;
E-Mails: j.cherfas@cgiar.org (J.C.); t.hodgkin@cgiar.org (T.H.)

* Author to whom correspondence should be addressed; E-Mail: e.frison@cgiar.org;
Tel.: +39-06-6118-1; Fax: +39-06-6118-405.

Received: 26 November 2010; in revised form: 13 December 2010 / Accepted: 10 January 2011 / Published: 14 January 2011

Abstract: Agricultural biodiversity has hitherto been valued almost exclusively as a source of traits that can be used in scientific breeding programs to improve the productivity of crop varieties and livestock breeds. We argue that it can make a far greater contribution to increased productivity. In particular, a wider deployment of agricultural biodiversity is an essential component in the sustainable delivery of a more secure food supply. Diversity of kingdoms, species and genepools can increase the productivity of farming systems in a range of growing conditions, and more diverse farming systems are also generally more resilient in the face of perturbations, thus enhancing food security. Diversity can maintain and increase soil fertility and mitigate the impact of pests and diseases. Diversity of diet, founded on diverse farming systems, delivers better nutrition and greater health, with additional benefits for human productivity and livelihoods. Agricultural biodiversity will also be absolutely essential to cope with the predicted impacts of climate change, not simply as a source of traits but as the underpinnings of more resilient farm ecosystems. Many of the benefits of agricultural biodiversity are manifested at different ecological and human scales, and cut across political divisions, requiring a cross-sectoral approach to reassess the role of agricultural biodiversity in sustainable and secure food production.

Keywords: agricultural biodiversity; food security; sustainability; nutrition; hunger

---

1. Introduction

Agricultural biodiversity includes those components of biological diversity relevant to food and agriculture as well as the components of biological diversity that constitute the agro-ecosystem. It exists at several levels, from the different ecosystems in which people raise crops and livestock, through the different varieties and breeds of the species, to the genetic variability within each variety or breed. While part of this biodiversity is directly managed to supply the goods and services that people need, much is not directly intended for production but remains important as a source of materials and for its contributions to ecosystem services such as pollination, control of greenhouse gas emissions and soil dynamics.

Modern, intensive agriculture reduces agricultural biodiversity. In fact, it is predicated on such a reduction. Farms specialize in livestock or crops, reducing the number of species; fields are enlarged, reducing the extent of field margins and hedgerows; soil amendments enhance the uniformity of soils; and monocultures of genetically uniform individuals tend to dominate. Within this framework, agricultural biodiversity is often seen simply as something to conserve as a source of traits that can be used to improve breeds and varieties (see, for example, [1-6] for this approach in several different realms). While this is certainly true, we argue that agricultural biodiversity as such is an important asset that delivers substantial benefits in many different realms and that there is increasing evidence that diversity *per se* needs to be a central element of sustainable agricultural development.

Recognition of the value of maintaining and using agricultural biodiversity is not new [7-11], although recent concerns over food availability suggest that it is timely to highlight evidence of the importance of agricultural biodiversity to agricultural production and productivity. It has been argued that the "food price crisis" of 2007–2008 was in many respects a harbinger of things to come and a new regime that will be characterized by higher and more volatile prices [12,13]. The year 2010 saw drought in the Russian Federation and floods in Pakistan, both with far-reaching impacts on food prices and availability, bringing home the need to improve global food security.

Two difficulties must be noted in making this case. First, because of the past focus on traits as the main value of agricultural biodiversity, evidence for benefits derived from diversity itself is comparatively sparse. Jackson *et al.* [9] have argued further that certain benefits, such as the insurance value of biodiversity and of the heterogeneous composition of agro-ecosystems, are not easily detected by the local-scale experiments that are typical of most agricultural research. Secondly, by its very nature, the deployment of agricultural biodiversity affects many different aspects of human livelihoods and it can be difficult to separate out the benefits and rigorously demonstrate causal relationships among these. For reasons of space we focus here on selected aspects of production and consumption, particularly those that impinge on sustainability, and do not discuss in detail the many social, cultural and conservation benefits that can also be attributed to agricultural biodiversity (see e.g., [8,14,15]). Johns and Sthapit [16] discuss in detail what they call "population-level synergies linking biodiversity conservation and human nutrition in developing countries".

2. Productivity and Stability

More diverse ecosystems, with more species or more genetic diversity within species, often have higher overall productivity than simpler systems; this is not a new idea [17,18]. Tilman and his colleagues have documented this most extensively for (non-agricultural) prairie ecosystems, where, for example, plots with 16 species produced 2.7 times more biomass than monocultures [19]. In agricultural systems, Bullock *et al.* [20] created species-rich and species-poor hay meadows; after eight years the richer meadows yielded 43% more hay than species-poor fields, an effect that was not due simply to the fertilizing effects of the greater number of legumes in the more diverse fields. This is generally true for grasslands across Europe [21]. More recent research has indicated that experimentally-manipulated diversity in grasslands promotes temporal stability at many levels of ecosystem organization simultaneously [22]. Mixtures of barley varieties in Poland generally out-yielded the mean of the varieties as pure stands [23]. Increased productivity is also associated with greater stability of yield; Tilman *et al.* [24] indicate that high-diversity plots were 70% more stable than monocultures.

Tilman's measure of stability—the ratio of mean plot total biomass to standard deviation over time—is just one version of stability, and ecologists have long debated the relationship between complexity and various measures of stability in ecosystems and food webs [25-27]. In simplified farm systems, farmers have to decide in advance which varieties of which crops they will grow in any given season. Depending on factors such as growing conditions and markets, this creates the potential for bumper harvests and for failures, which is reflected in high year-on-year variance in yields. Experimental studies and large-scale field trials have shown that agricultural biodiversity can reduce variance, thus contributing to this particular type of stability in yield.

Significant trade-offs are often involved in balancing the maintenance of diversity within a production system with appropriate (or available) management practices, and the correct balance will differ depending on production system and production objective (see, for example, Snapp, Gentry and Harwood's demonstration that management can be a more important driver than biodiversity [28]). Home gardens are some of the most diverse production systems in the world and also some of the most productive, per unit area [29,30]. Although they are usually highly labor intensive and small, they nonetheless provide direct benefits in terms of production, income and nutrition for millions of small scale farmers throughout the world. For example, Nair [31] reports that in Brazil a 10–20 ha agroforestry-based home garden generated net income comparable to 1000 ha of pasture cattle ranch, in addition to rural employment for women, and all without requiring deforestation. Home gardens in Indonesia can have higher standing biomass, produce a higher net income and improved stability, sustainability and equity than equivalent areas of rice monoculture [32]. Not all home gardens, however, are managed for domestic consumption. A project to encourage women in Senegal to grow vegetables resulted in higher incomes and social standing for the women involved and almost no change in nutritional status because the vegetables were not eaten at home and the women did not use the money earned to buy food [33].

Intensive home gardens depend to a large extent for their productivity on using many species that occupy different ecological micro-niches and make differential use of resources, for example by layering. This kind of multiple cropping can take many different forms and undoubtedly provides benefits in terms of nutrient availability and pest control which translate into higher production in many situations. Altieri [34] cites figures showing that in Latin America yield advantages of multispecies cropping range from 20% to 60%. In Mexico, one hectare planted with the very traditional mixture of maize, beans and squash produces as much food as 1.73 ha planted with maize alone. Furthermore, the maize–squash–bean polyculture can produce up to 4 t ha^{-1} of dry matter that can be returned to the soil, compared with 2 t ha^{-1} from a monoculture of maize. To some extent this reflects the presence of a leguminous crop, although niche separation, reduced depredations due to pests and diseases and weed competition and more efficient use of natural resources all play a part [35].

A detailed study of the so-called Jena Experiment, a long-term investigation of grassland of differing diversity, revealed a clear effect of species richness on productivity [36], including effects of plant diversity on invertebrate herbivores [37] and of invertebrates on plant productivity [38]. Perhaps the strongest conclusion yet to emerge from the Jena Experiment is encapsulated in the title of a review paper: *Biodiversity for multifunctional grasslands: equal productivity in high-diversity low-input and low-diversity high-input systems* [39]. In fact, "higher diversity is actually more effective in increasing productivity than higher management intensity".

Similar results have been found in food-production systems, particularly in China. Zhang and Li cite a report that "one-third of all the cultivated land area is used for multiple cropping and half of the total grain yield is produced with multiple cropping" (Tong 1993, cited in the review by Zhang and Li [40]). Figures are certainly higher today. Zhang and Li's group has made a detailed study of the effects of agricultural biodiversity and have investigated some of the underlying mechanisms. Wheat shows a 74% yield increase intercropped with maize and a 53% increase intercropped with soybean. Like the increased tillering seen in disease-resistant individuals in a field of mixed varieties of the same species (see below and [41]), Zhang and Li attribute some of the over-yielding of species mixtures to what they call competitive recovery, with above-ground and below-ground effects. Abiotic stresses can be ameliorated by intercropping. Iron-deficiency chlorosis is common in peanut (a major oilseed crop in China), especially when grown as the sole crop. Intercropped with maize, chlorosis is less severe and depends on the close intermingling of maize and peanut root systems. Peanut and maize have different iron-uptake systems, and it is hypothesized that the efficient iron-uptake system of maize mobilizes iron in a form that peanut can make better use of. Similar results have been seen in connection with phosphorus (P) uptake in maize grown with faba bean, where the faba bean is believed to make P more available to maize. Again, roots must mingle closely for overyielding to be observed. Chickpea improves P uptake by wheat and maize via a complex pathway that pits the cereals' greater ability to absorb soluble P against the legume's greater ability to mobilize organic P [42]. Intercropping reduces the accumulation of nitrate in the soil, permitting lower application rates of N and reducing downstream effects.

Diversity also acts within a crop species to boost productivity. Genetic diversity can reduce risk of crop failure in high stress environments, as shown by Ceccarelli [43] for barley, although yield levels may be below those achieved by some varieties under non-stress conditions. Many studies have suggested that risk avoidance, multiple use needs and stability are among the reasons why many small-scale farmers continue to grow traditional crop varieties and maintain high levels of genetic and crop diversity throughout the world [8,44,45].

At larger scales, there is a widespread recognition of the importance of maintaining crop variety diversity in production systems in order to avoid vulnerability and widespread crop loss as a result of the effect of a particular biotic or abiotic stress on a genetically uniform monoculture [46]. The substantial and, it has been argued predictable [47], crop losses of the food staple taro in Samoa in 1993–1994 can be attributed to such vulnerability, as can the impact of southern corn blight on the U.S. maize crop in 1970–1971 [48].

3. Pests and Diseases

Some of the yield increase associated with greater diversity is the result of the different functions performed by different plant groups and the use of different niches. Even in simpler agricultural systems, however, enhanced resistance to outbreaks of pests and diseases from effective use of both inter- and intra-specific diversity provides the main mechanism for increased yield and yield stability. Finckh *et al.* [23] identify several mechanisms underlying this effect, from simple distance between susceptible host plants and physical barriers to transmission to competition among pathogen races that reduces disease severity. Experimental mixtures of potato varieties susceptible and resistant to late blight (*Phytophthora infestans*) show less severe disease than monocultures in temperate [49] and tropical [50] trials. Large-scale deployment of barley mixtures in eastern Germany [51] and rice mixtures in southwest China [52,53] indicates clearly that mixtures with relatively few components can minimize the severity of disease with an impact on yields and yield stability. An extension of this approach to more crops and across a considerably greater area demonstrated increases in yields of between 33% and 85%, with reduced severity of diseases and increased profits [54]. It was anticipated that by summer of 2010, severe drought notwithstanding, 80% of the farmland in Yunnan province (2.9 million ha) would adopt this approach [55].

Wolfe's work on barley mixtures and powdery mildew (*Erysiphe graminis hordei*) was undertaken in the former German Democratic Republic, where an inability to manufacture or purchase fungicides prompted an assessment of alternative approaches. The benefits of mixtures in such cases arise primarily because farmers cannot predict in advance which mildew race will predominate in any given season and thus cannot choose a variety resistant to that race. In the absence of fungicides, a mixture in which each component is resistant to different races protects the entire field. In rice, resistant modern varieties offer a physical barrier to the movement of rice blast (*Magnaporthe grisea*) spores and also physically support susceptible traditional varieties, which are prone to lodging, thereby increasing the yield of the more valuable traditional varieties. Genetic diversity within fields of a single species will slow the evolution of pathogens, offering longer term protection against the breakdown of resistance, while changing the make-up of the mixture each year could promote even greater diversity in the pathogen population and thus slow down adaptation further by reducing the selection pressure on individual pathogen races. Given the nature of the protection, appropriate mixtures can control several diseases at the same time, further enhancing their usefulness.

Pests reduce global crop yields by about 40% each year [56] and Oerke [57] notes that "despite a clear increase in pesticide use, crop losses have not significantly decreased during the last 40 years". The use of biodiversity to mitigate damage by pests and macro-parasites is not as well documented as its use against diseases, although Gurr *et al.* [58] listed several examples that range in scale from the very local—harvesting lucerne fields in alternating strips preserves structural diversity and habitat for natural enemies of *Helicoverpa* spp—to the landscape—parasitism rates on armyworm *Pseudaletia unipuncta* are higher in more complex landscapes (see [59,60] for additional examples). Nevertheless, there is a long tradition of integrated pest management (IPM) in which biodiversity plays a central role, although more often in the context of promoting a diverse population of predators than in the use of host biodiversity specifically to mitigate the impact of pests (see, for example, [61]). As a clear example of the multiple benefits of the use of agricultural biodiversity, Pretty *et al.* [62] analyzed 62 IPM projects in 21 developing countries. In 47, yields increased by an average of 42% while pesticide use declined by 71%. The saving in environmental costs was not calculated, but was probably considerable. Pretty *et al.* also estimate the many other gains that accrue to "resource-conserving agriculture" while drawing attention to the difficulty of isolating and measuring different "services".

The mechanisms that underlie the effects of changed biodiversity on pests and diseases have begun to be explored in more detail. Keesing *et al.* [63] point out that for many diseases both positive and negative effects might be expected. Nevertheless, the agricultural examples that they cite all point to greater biodiversity protecting against diseases. In the case of rice blast, in addition to the greater distance between susceptible plants in a plot of mixed varieties, effectively a decrease in host abundance, the different plant architecture of the varieties results in the canopy being drier, which further slows the spread of the fungus [64]. Mundt [41] points out that induced resistance, caused by hosts being exposed to strains of pathogens better adapted to other varieties, can account for up to 30% of the protection against yellow rust (*Puccinia striiformis*) in wheat fields. Resistant varieties increase tillering and thus compensate for the absence of susceptible neighbors, another buffering mechanism. "Mixtures will not be the disease control tactic of choice in all cases," Mundt concludes. "Given the need for a more sustainable agriculture based on models of natural ecosystems, however, host mixtures will likely play a much larger role in the next 50 years than they have in the past half century."

4. Regulating and Supporting Ecosystem Services

Agricultural production depends on the operation of a range of regulating and supporting ecosystem services that include nutrient cycling, regulation of water flow and storage, regulation of soil movement and properties and regulation of biological populations (including pest and disease control as discussed above). To a large extent these services have been replaced in simplified agricultural systems by human-supplied inputs. The importance of agricultural biodiversity in respect of these ecosystem services has been reviewed by Swift *et al.* [65] and, with respect to crop diversity, more recently by Hajjar *et al.* [66]. Considerable debate remains on the amount of diversity that is needed within agro-ecosystems for different functions. Some evidence suggests that while diversity is necessary, saturation is reached at relatively low levels of species diversity; other evidence has suggested that reducing diversity often has a negative effect on specific functions (see references in [65]).

In fact, there are multiple ecosystem functions, each of which may perform optimally with a different species or genetic assembly. In this respect, Swift *et al.* [65] note the importance of maintenance of total system diversity and the use of management practices such as conservation agriculture and mulching that are themselves likely to ensure higher levels of diversity in the production system. In seeking to understand the increased productivity of more species-rich grasslands, for example, Milcu *et al.* manipulated the density of earthworms against a gradient of plant diversity [38]. Neither earthworm density nor plant diversity alone affected rates of decomposition of plant litter; however, decomposition was higher in plant assemblages with more legumes, and the effect was greater at higher plant diversity, which could contribute to the increased primary productivity associated with greater plant diversity.

Landscape heterogeneity, which involves a diverse assemblage of crop, livestock and agroforestry elements at different scales, is an important feature of many production systems [9]. As noted above, much of the diversity in agricultural landscapes exists at scales beyond the farm and its role and contribution is poorly captured in most agricultural experimentation.

Pollination is a classic and essential ecosystem service where loss of species has recently attracted substantial comment [67,68]. Memmot *et al.* [69] found that, in simulation studies, pollination networks were relatively tolerant to loss of pollinator species diversity, although certain species, such as bumble bees and some solitary bees, played a particularly important role. However, in their recent review, Hajjar *et al.* [66] argue that both within- and between-species diversity of crops enhance pollinator availability and improve production. Steffan-Dewenter and Tscharntke [70] found that increasing isolation of habitat islands among agricultural fields resulted in decreasing abundance and species richness of flower-visiting bees, and that seed production decreased with increasing distance from nearest grassland for two brassica crops. The relation between crop diversity and pollinator diversity is a good example of the importance of the interactions among different components of agricultural biodiversity—pollinators and pollinator abundance and activity benefiting from increased diversity, and improving the productivity of some of the different crops present in a production system. Genetic diversity within a bee colony also promotes the survival of the colony [71].

All of the mechanisms cited above contribute to resilience—the way in which an ecosystem responds to and recovers from disturbance—which has been attributed to the degree of connectivity within an ecosystem [72]. This resilience to perturbation may be manifested by a smaller drop in productivity, a more rapid recovery and lower variability over time; all are underpinned by biodiversity, and the risk of simplifying ecosystems is that those systems then become more vulnerable to perturbations.

5. Nutrition and Health

Improving yields, especially of the major nutrients such as proteins and calories, is not currently the most pressing challenge to food security. Despite the fact that great strides continue to be made in addressing protein-calorie shortages, around one billion people in the world still face starvation and one third of the global population suffers one or more of the micronutrient deficiencies often lumped together as hidden hunger [73]. The most important of the micronutrients are probably vitamin A, iodine and iron, although Welch and Graham [6] list 49 “essential nutrients for sustaining human life” (later expanded to 51 [74]). Nutrition security requires adequate supplies of all.

Accurate estimates of the burdens of hunger and malnutrition are probably unrealistic, and short-term numbers fluctuate unreasonably. A joint report on the *State of Food Insecurity in the World 2010* from the United Nations’ Food and Agriculture Organization and World Food Programme says that 925 million people suffer chronic hunger in 2010. There are, in addition, currently more overweight and obese than chronically hungry people [75] even in developing countries [76]. (Results from a large survey by the World Health Organization, which will give more detailed insights, are currently still being analyzed, see http://www.who.int/bmi/index.jsp?introPage=intro_4.html, accessed on 13 January 2011). The effects on health, cognition and productivity are vast.

Past efforts to address micronutrient deficiencies have been based largely on a medical model, focused on fortification (for example iodine in salt), on supplements (for example high doses of vitamin A), or on increasing the micronutrient content of staple crops, so-called biofortification. While all of these approaches have their merits, agricultural biodiversity could provide a valuable complement [77]. This approach goes beyond the use of specific food components to address specific deficiencies [78]; rather, it seeks to broaden the composition of the diet to include greater diversity in the firm belief that this delivers improved nutrition, with not only micronutrients but also other important components such as fiber, and hence better health.

There is some evidence of the beneficial effects of dietary diversity (as opposed to specific dietary components) on disease, morbidity and mortality (see references in [79]). Most notably, results from 11 developing countries indicate that, after controlling for confounding factors such as household wealth, there remains a strong relationship between dietary diversity and child development measured as height-for-age Z scores [80]. Dietary diversity thus reduces stunting. In addition, reducing malnutrition of children greatly improves childhood survival in developing countries [81] and has a direct positive impact on economic productivity as adults [82]. There is also good evidence that the addition of even small amounts of animal-derived foods to the diet results in a marked improvement in nutritional status [83].

Calls have been made to promote a more food-based approach to nutrition and health [84,85], and not just in the context of developing countries and poverty, [86,87] but to date these have largely been ignored by policy-makers and government.

Our own work on neglected and underutilized plant species, undertaken in several locations and with multiple partners, indicates that there is considerable scope for increasing the availability and consumption of these generally more nutritious alternatives, with additional positive benefits for income generation and environmental protection [88]. In India, for example, a long series of studies to improve the use of so-called minor millets among very poor farmers has shown multiple beneficial impacts on yields, incomes, profits, the nutritional value of popular snack and breakfast foods, and female empowerment, all promoting the likely conservation of these crops and their biological diversity in farmers' fields [89-92]. While it has not so far been possible to demonstrate a direct impact on the nutritional status of participating villagers, there is every expectation that the various synergistic impacts will boost food and nutrition security and ultimately increase health and well being.

6. Climate Change

It is becoming increasingly clear that climate change will result in entirely new weather patterns [93] and that these will have a profound influence on agriculture at all scales [94,95]. There is already substantial evidence of changes in the abundance and distribution of many insects [96], which can be expected to affect the distribution of pests and diseases and of control mechanisms against them.

Adaptability and resilience in the production systems will both become increasingly important to enable farmers to cope with climate change and increased climate variability, and there is evidence that this is already important. The maintenance of high levels of sorghum diversity as traditional varieties enabled farmers in Mali to maintain levels of sorghum production and productivity in stressed environments over a period of increasing drought from 1978–1998 [97].

To come full circle, plant and animal breeders will need to take advantage of existing biodiversity in order to develop new breeds and varieties that will be able to cope with changed conditions. Even in this realm, however, an advantageous complementary strategy may be to furnish farmers and others with an expanded genepool that they can use to select their own adapted and adaptable populations. These genepools could take the form of segregating populations from wide crosses, multilines, mixtures or simply accessions from the edges of the normal growing range. Indications are that this approach could speed the adaptation of farming systems to changed conditions more effectively than breeding that relies on additional external inputs [23,98].

7. Conclusions

Diversity at ecosystem, species and genetic levels, brings many direct benefits for specific aspects of agricultural production. However, our knowledge of the nature and extent of these benefits remains imperfect and further studies are needed to explore not only the intrinsic benefits but also effects manifested at different scales. The detailed experimental investigations that we have cited in many of the sections above indicate that deploying agricultural biodiversity more effectively is not simply a return to traditional practices. It requires a scientific approach to understand how different forms of agricultural biodiversity contribute to the goals of improved food and nutrition security and sustainability, and a recognition that while some principles and practices will be globally applicable, others may be constrained by locality and culture [22,36,39-41,46,51,54,63,66]. Much remains to be done. It is also important to recognize that the extent and distribution of diversity in production systems may vary substantially depending on the properties of the production systems, their resilience and the ways in which production is managed (see e.g., Wood and Lenne [99] for an alternative perspective).

Teasing apart the different ways in which agricultural biodiversity works may prove to be extremely difficult. Zhang and Li, for example, point out that both interspecific facilitation and interspecific competition contribute to intercropping advantages [40]. The same is true of impacts. We expect that increasing the deployment of biodiversity in agricultural systems will have multiple effects that go beyond the production perspective of this paper. Programs that aim to improve food security or social resilience through biodiversity may well have unmeasured effects on factors such as cultural preservation, health and incomes, and *vice versa*. Multiple case studies from one such project indicate that relatively simple interventions, such as adding poultry-keeping to a family's activities, can improve income, housing, education, food security and many other factors [100]. However, we need a greatly expanded knowledge base to respond effectively to these opportunities.

Recent concerns about high food prices and low food availability indicate that agriculture and agricultural production are clearly back on the international agenda. There is a new recognition of the profound challenges faced in increasing production to meet the needs of a growing population under changing climates and the need to do so in a sustainable manner. From this perspective, agricultural biodiversity clearly has an increasingly important role to play, not simply in the classical paradigm as a provider of traits for the incremental, never-ending improvement of staples, but more effectively as an essential component of improved production systems. Of course there are other elements of food-systems and production that require additional research and development, such as harvesting and post-harvest storage, small-scale processing (and domestic cooking methods) and marketing to ensure sustainable improvements in food and nutrition security; more effective use of agricultural biodiversity needs to take its place alongside these sectors.

While the temptation will always be to look for quick fixes, these are unlikely to be sustainable or to meet current concerns for an environmentally acceptable agriculture that responds to the needs of small-scale farmers throughout the world. Almost all of the approaches used to date in agricultural intensification strategies, for example the substitution and supplementation of ecosystem function by human labor and petrochemical products, contain the seeds of their own destruction in the form of increased release of greenhouse gases, water supplies depleted by mining, and degraded soils. We need to build production systems that deliver intensification without simplification. This will entail different dimensions, from varietal mixtures [41,52,53], to species intercropping [39,40], to broader diversification strategies [100]. This approach is particularly pertinent in areas where diverse production systems still prevail, most notably marginal areas, but better deployment of agricultural biodiversity in areas that have lost it must also receive greater attention in the future. Diversity will be essential to improve productivity, to enhance ecosystem functions, and to provide adaptability.

Acknowledgements

We thank Luigi Guarino, Chenchen Shen and two anonymous referees for their perceptive contributions to this paper.

References

1. Conner, A.J.; Mercer, C.F. Breeding for success: Diversity in action. *Euphytica* **2007**, *154*, 261-262.
2. Huang, J.; Pray, C.; Rozelle, S. Enhancing the crops to feed the poor. *Nature* **2002**, *418*, 678-684.
3. Robinson, R.A. *Return to Resistance: Breeding Crops to Reduce Pesticide Dependence*; agAccess: Davis, CA, USA, 1996.
4. Byerlee, D.; Dubin, H.J. Crop improvement in the CGIAR as a global success story of open access and international collaboration. *Int. J. Common.* **2010**, *4*, 452-480.
5. Scholten, O.E.; Van Heusden, A.W.; Khrustaleva, L.I.; Burger-Meijer, K.; Mank, R.A.; Antonise, R.G.C.; Harrewijn, J.L.; Van Haecke, W.; Oost, E.H.; Peters, R.J.; Kik, C. The long and winding road leading to the successful introgression of downy mildew resistance into onion. *Euphytica* **2007**, *156*, 345-353.
6. Welch, R.M.; Graham, R.D. Breeding for micronutrients in staple food crops from a human nutrition perspective. *J. Exp. Bot.* **2004**, *55*, 353-364.
7. Altieri, M.A.; Merrick, L.C. *In situ* conservation of crop genetic resources through maintenance of traditional farming systems. *Econ. Bot.* **1987**, *41*, 86-96.

8. Brush, S.B. *In situ* conservation of landraces in centers of crop diversity. *Crop Sci.* **1995**, *35*, 346-354.
9. Jackson, L.E.; Pascual, U.; Hodgkin, T. Utilizing and conserving agrobiodiversity in agricultural landscapes. *Agr. Ecosyst. Environ.* **2007**, *121*, 196-210.
10. Matson, P.A.; Parton, W.J.; Power, A.G.; Swift, M.J. Agricultural intensification and ecosystem properties. *Science* **1997**, *277*, 504-509.
11. McNeely, J.A.; Scherr, S.J. *Ecoagriculture: Strategies to Feed the World and Save Wild Biodiversity*; Island Press: Washington, DC, USA, 2003.
12. *Corn Price: As High as an Elephant's Eye—Another Agricultural Commodity Surges*; The Economist: St Louis, MO, USA, 2010; Available online: http://www.economist.com/node/17257767 (accessed on 29 December 2010).
13. Vidal, J. *Global Food Crisis Forecast as Prices Reach Record Highs*; The Guardian: London, UK, 2010; p. 25.
14. Nabhan, G.P. *Enduring Seeds: Native American Agriculture and Wild Plant Conservation*; North Point Press: San Francisco, CA, USA, 1989.
15. Zimmerer, K.S. Managing diversity in potato and maize fields of the Peruvian Andes. *J. Ethnobiol.* **1991**, *11*, 23-49.
16. Johns, T.; Sthapit, B.R. Biocultural diversity in the sustainability of developing-country food systems. *Food Nutr. Bull.* **2004**, *25*, 143-155.
17. Hector, A.; Hooper, R. Darwin and the first ecological experiment. *Science* **2002**, *295*, 639-640.
18. Darwin, C. *On the Origin of Species by Natural Selection*; Murray: London, UK, 1859.
19. Tilman, D.; Reich, P.B.; Knops, J.; Wedin, D.; Mielke, T.; Lehman, C. Diversity and productivity in a long-term grassland experiment. *Science* **2001**, *294*, 843-845.
20. Bullock, J.M.; Pywell, R.F.; Walker, K.J. Long-term enhancement of agricultural production by restoration of biodiversity. *J. Appl. Ecol.* **2007**, *44*, 6-12.
21. Hector, A.; Loreau, M. Relationships between biodiversity and production in grasslands at local and regional scales. In *Grassland: A Global Resource*; McGilloway, D.A., Ed.; Wageningen Academic Publishers: Wageningen, The Netherlands, 2005; pp. 295-304.
22. Proulx, R.; Wirth, C.; Voigt, W.; Weigelt, A.; Roscher, C.; Attinger, S.; Baade, J.; Barnard, R.L.; Buchmann, N.; Buscot, F.; *et al.* Diversity promotes temporal stability across levels of ecosystem organization in experimental grasslands. *PLoS ONE* **2010**, *5*, e13382.
23. Finckh, M.R.; Gacek, E.S.; Goyeau, H.; Lannou, C.; Merz, U.; Mundt, C.C.; Munk, L.; Nadziak, J.; Newton A.C.; De Vallavielle-Pope, C.; Wolfe, M.S. Cereal variety and species mixtures in practice, with emphasis on disease resistance. *Agronomie* **2000**, *20*, 813-837.
24. Tilman, D.; Reich, P.B.; Knops, J.M.H. Biodiversity and ecosystem stability in a decade-long grassland experiment. *Nature* **2006**, *441*, 629-632.
25. Pimm, S.L. The complexity and stability of ecosystems. *Nature* **1984**, *307*, 321-326.
26. Elmqvist, T.; Folke, C.; Nystrom, M.; Peterson, G.; Bengtsson, J.; Walker, B.; Norberg, J. Response diversity, ecosystem change, and resilience. *Front. Ecol. Environ.* **2003**, *1*, 488-494.
27. Ives, A.R.; Carpenter, S.R. Stability and diversity of ecosystems. *Science* **2007**, *317*, 58-62.
28. Snapp, S.S.; Gentry, L.E.; Harwood, R. Management intensity-not biodiversity-the driver of ecosystem services in a long-term row crop experiment. *Agr. Eco. Environ.* **2010**, *138*, 242-248.

29. Eyzaguirre, P.B.; Linares, O.F. *Home Gardens and Agrobiodiversity*; Smithsonian Books: Washington, DC, USA, 2004.
30. Galluzzi, G.; Eyzaguirre, P.; Negri, V. Home gardens: Neglected hotspots of agro-biodiversity and cultural diversity. *Biodivers. Conserv.* **2010**, *19*, 3635-3654.
31. Nair, P.K.R. Do tropical homegardens elude science, or is it the other way around? *Agroforest. Syst.* **2001**, *53*, 239-245.
32. Conway, G.R. Sustainable agriculture: The trade-offs with productivity, stability and equitability. In *Economics and Ecology: New Frontiers and Sustainable Development*; Barbier, E.B., Ed.; Chapman and Hall: London, UK, 1993; pp. 46-65.
33. Brun, T.; Reynaud, J.; Chevassus-Agnes, S. Food and nutritional impact of one home garden project in Senegal. *Ecol. Food Nutri.* **1989**, *23*, 91-108.
34. Altieri, M.A. Applying Agroecology to enhance the productivity of peasant farming systems in Latin America. *Environ. Dev. Sustain.* **1999**, *1*, 197-217.
35. Vandermeer, J.H. Intercropping. In *Agroecology*; Carrol, C.R., Vandermeer, J.H., Rosset, P.M., Eds.; McGraw-Hill: New York, NY, USA, 1990; pp. 481-516.
36. Marquard, E.; Weigelt, A.; Temperton, V.M.; Roscher, C.; Schumacher, J.; Buchmann, N.; Fischer, M.; Weisser, W.W.; Schmid, B. Plant species richness and functional composition drive overyielding in a six-year grassland experiment. *Ecology* **2009**, *90*, 3290-3302.
37. Scherber, C.; Mwangi, P.N.; Temperton, V.M.; Roscher, C.; Schumacher, J.; Schmid, B.; Weisser, W.W. Effects of plant diversity on invertebrate herbivory in experimental grassland. *Oecologia* **2006**, *147*, 489-500.
38. Milcu, A.; Partsch, S.; Scherber, C.; Weisser, W.W.; Scheu, S. Earthworms and legumes control litter decomposition in a plant diversity gradient. *Ecology* **2008**, *89*, 1872-1882.
39. Weigelt, A.; Weisser, W.W.; Buchmann, N.; Scherer-Lorenzen, M. Biodiversity for multifunctional grasslands: Equal productivity in high-diversity low-input and low-diversity high-input systems. *Biogeosciences* **2009**, *6*, 1695-1706.
40. Zhang, F.; Li, L. Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. *Plant Soil* **2003**, *248*, 305-312.
41. Mundt, C.C. Use of multiline cultivars and cultivar mixtures for disease management. *Annu. Rev. Phytopathol.* **2002**, *40*, 381-410.
42. Li, S.M.; Li, L.; Zhang, F.S.; Tang, C. Acid phosphatase role in chickpea/maize intercropping. *Ann. Bot.* **2004**, *94*, 297-303.
43. Ceccarelli, S. Adaptation to low/high input cultivation. *Euphytica* **1996**, *92*, 203-214.
44. Bellon, M.R. The dynamics of crop infraspecific diversity: A conceptual framework at the farmer level. *Econ. Bot.* **1996**, *50*, 26-39.
45. Jarvis, D.I.; Brown, A.H.; Cuong, P.H.; Collado-Panduro, L.; Latournerie-Moreno, L.; Gyawali, S.; Tanto, T.; Sawadogo, M.; Mar, I.; Sadiki, M.; *et al.* A global perspective of the richness and evenness of traditional crop-variety diversity maintained by farming communities. *PNAS* **2008**, *105*, 5326-5331.
46. Wolfe, M.S. Crop strength through diversity. *Nature* **2000**, *406*, 681-682.
47. Lebot, V. Genetic vulnerability of Oceania's traditional crops. *Exp. Agr.* **1992**, *28*, 309-323.

48. Ullstrup, A.J. The impacts of the southern corn leaf blight epidemics of 1970–1971. *Annu. Rev. Phytopathol.* **1972**, *10*, 37-50.
49. Garrett, K.A.; Mundt, C.C. Epidemiology in mixed host populations. *Phytopathology* **1999**, *89*, 984-990.
50. Garrett, K.A.; Nelson, R.J.; Mundt, C.C.; Chacon, G.; Jaramillo, R.E.; Forbes, G.A. The effects of host diversity and other management components on epidemics of potato late blight in the humid highland tropics. *Phytopathology* **2001**, *91*, 993-1000.
51. Wolfe, M.S.; Barrett, J.A.; Jenkins, J.E.E. The use of cultivar mixtures for disease control. In *Strategies for the Control of Cereal Disease*; Jenkyn, J.F., Plumb, R.T., Eds.; Blackwell Scientific Publications: Oxford, UK, 1981; pp. 73-80.
52. Zhu, Y.; Chen, H.; Fan, J.; Wang, Y.; Li, N.; Chen, J.; Fan, J.; Yang, S.; Hu, L.; Leung, H.; *et al.* Genetic diversity and disease control in rice. *Nature* **2000**, *406*, 718-722.
53. Castilla, N.P.; vera Cruz, C.M.; Mew, T.W.; Zhu, Y. Using rice cultivar mixtures: A sustainable approach for managing diseases and increasing yield. *IRRI Rice Res. News* **2003**, *28*, 5-11.
54. Li, C.; He, X.; Zhu, S.; Zhou, H.; Wang, Y.; Li, Y.; Yang, J.; Fan, J.; Yang, J.; Wang, G.; *et al.* Crop diversity for yield increase. *PLoS One* **2009**, *4*, e8049.
55. Qiu, J. China drought highlights future climate threats. *Nature* **2010**, *465*, 142-143.
56. Pimentel, D.; Wilson, C.; McCullum, C.; Huang, R.; Dwen, P.; Flack, J.; Tran, Q.; Saltman, T.; Cliff, B. Economic and environmental benefits of biodiversity. *Bioscience* **1997**, *47*, 747-757.
57. Oerke, E.C. Crop losses to pests. *J. Agr. Sci.* **2005**, *144*, 31-43.
58. Gurr, G.M.; Wratten, S.D.; Luna, J.M. Multi-function agricultural biodiversity: Pest management and other benefits. *Basic Appl. Ecol.* **2003**, *4*, 107-116.
59. Cantelo, W.W.; Sanford, L.L. Insect population response to mixed and uniform plantings of resistant and susceptible plant material. *Environ. Entomol.* **1984**, *13*, 1443-1445.
60. Power, A.G. Leafhopper response to genetically diverse maize stands. *Entomol. Exp. Appl.* **1988**, *49*, 213-219.
61. Altieri, M.A. Linking ecologists and traditional farmers in the search for sustainable agriculture. *Front. Ecol. Environ.* **2004**, *2*, 35-42.
62. Pretty, J.N.; Noble, A.D.; Bossio, D.; Dixon, J.; Hine, R.E.; Penning de Vries, F.W.T.; Morison, J.I.L. Resource-conserving agriculture increases yields in developing countries. *Environ. Sci. Technol.* **2006**, *40*, 1114-1119.
63. Keesing, F.; Belden, L.K.; Daszak, P.; Dobson, A.; Harvell, C.D.; Holt, R.D.; Hudson, P.; Jolles, A.; Jones, K.E.; Mitchell, C.E.; Myers, S.S.; *et al.* Impacts of biodiversity on the emergence and transmission of infectious diseases. *Nature* **2010**, *468*, 647-652.
64. Zhu, Y.Y.; Fang, H.; Wang, Y.Y.; Fan, J.X.; Yang, S.S.; Mew, T.W.; Mundt, C.C. Panicle blast and canopy moisture in rice cultivar mixtures. *Phytopathology* **2005**, *95*, 433-438.
65. Swift, M.J.; Izac, A.M.N.; Van Noordwijk, M. Biodiversity and ecosystem services in agricultural landscapes: Are we asking the right questions? *Agr. Ecosyst. Environ.* **2004**, *104*, 113-134.
66. Hajjar, R.; Jarvis, D.I.; Gemmill-Herren, B. The utility of crop genetic diversity in maintaining ecosystem services. *Agr. Ecosyst. Environ.* **2008**, *123*, 261-270.

67. Henderson, C.; Tarver, L.; Plummer, D.; Seccomb, R.; Debnam, S.; Rice, S.; Bromenshenk, J.; Glassy, J. Preliminary findings with respect to colony collapse disorder (CCD). *Am. Bee J.* **2007**, *147*, 381- 384.
68. Johnson, R. *Recent Honey Bee Colony Declines*; CRS Report for Congress; Congressional Research Service: Washington, DC, USA, 2007; Order Code RL33938.
69. Memmott, J.; Waser, N.M.; Price, M.V. Tolerance of pollination networks to species extinctions. *Biol. Sci. B* **2004**, *271*, 2605-2611.
70. Steffan-Dewenter, I.; Tscharntke, T. Effects of habitat isolation on pollinator communities and seed set. *Oecologia* **1999**, *121*, 432-440.
71. Mattila, H.R.; Seeley, T.D. Genetic diversity in honey bee colonies enhances productivity and fitness. *Science* **2007**, *317*, 362-364.
72. Holling, C.S. The resilience of terrestrial ecosystems: Local surprise and global change. In *Sustainable Development of the Biosphere*; Clark, W.C., Munn, R.E., Eds.; Cambridge University Press: Cambridge, UK, 1986; pp. 292-320.
73. Alnwick, D. Significance of micronutrient deficiencies in developing and industrialized countries. In *Food-Based Approaches to Preventing Micronutrient Malnutrition. An International Research Agenda*; Combs, G.F., Welch, R.M., Duxbury, J.M., Uphoff, N.T., Nesheim, M.C., Eds.; Cornell University: Ithaca, NY, USA, 1996.
74. Graham, R.D.; Welch, R.M.; Saunders, D.A.; Ortiz-Monasterio, I.; Bouis, H.E.; Bonierbale, M.; De IIaan, S.; Burgos, G.; Thiele, G.; Liria, T.; *et al.* Nutritious subsistence food systems. *Adv. Agr.* **2007**, *92*, 1-74.
75. Gardner, G.T.; Halweil, B. *Underfed and Overfed: The Global Epidemic of Malnutrition*; Worldwatch Institute: Washington, DC, USA, 2000.
76. Mendez, M.A.; Monteiro, C.A.; Popkin, B.M. Overweight exceeds underweight among women in most developing countries. *Am. J. Clin. Nutr.* **2005**, *81*, 714-721.
77. Johns, T.; Eyzaguirre, P.B. Linking biodiversity, diet and health in policy and practice. *Proc. Nutr. Soc.* **2006**, *65*, 182-189.
78. Low, J.W.; Arimond, M.; Osman, N.; Cunguara, B.; Zano, F.; Tschirley, D. A Food-based approach introducing orange-fleshed sweet potatoes increased vitamin A intake and serum retinol concentrations in young children in rural Mozambique. *J. Nutr.* **2007**, *137*, 1320-1327.
79. Frison, E.A.; Smith, I.F.; Johns, T.; Cherfas, J.; Eyzaguirre, P.B. Agricultural biodiversity, nutrition, and health: Making a difference to hunger and nutrition in the developing world. *Food Nutr. Bull.* **2006**, *27*, 167-179.
80. Arimond, M.; Ruel, M.T. Dietary diversity is associated with child nutritional status: Evidence from 11 demographic and health surveys. *J. Nutr.* **2004**, *134*, 2579-2585.
81. Pelletier, D.L.; Frongillo, E.A. Changes in child survival are strongly associated with changes in malnutrition in developing countries. *J. Nutr.* **2003**, *133*, 107-119.
82. Hoddinott, J.; Maluccio, J.A.; Behrman, J.R.; Flores, R.; Martorell, R. Effect of a nutrition intervention during early childhood on economic productivity in Guatemalan adults. *Lancet* **2008**, *371*, 411-416.

83. Neumann, C.; Harris, D.M.; Rogers, L.M. Contribution of animal source foods in improving diet quality and function in children in the developing world. *Nutr. Res.* **2002**, *22*, 193-220.
84. Levin, C.E.; Long, J.; Simler, K.R.; Johnson-Welch, C. *Cultivating Nutrition: A Survey of Viewpoints on Integrating Agriculture and Nutrition*. Discussion Paper. Food Consumption and Nutrition Division, International Food Policy Research Institute: Washington, DC, USA, 2003.
85. Smith, I.F. Micronutrient interventions: Options for Africa. *Food Nutr. Bull.* **2000**, *21*, 532-537.
86. Latham, M. The great vitamin A fiasco. *J. World Public Health Nutr. Assoc.* **2010**, *1*, 12-45.
87. Mozaffarian, D.; Ludwig, D.S. Dietary guidelines in the 21st century—A time for food. *JAMA* **2010**, *304*, 681-682.
88. Obel-Lawson, E. *The Efficacy of Awareness Campaigns by the African Leafy Vegetables Project on Nutrition Behaviour Change Among the Kenyan Urban Population: The Case of Nairobi*; M.A. Thesis; School of Journalism, University of Nairobi–Kenya: Nairobi, Kenya, 2006.
89. Bala Ravi, S.; Hrideek, T.K.; Kumar, A.T.K.; Prabhakaran, T.R.; Mal, B.; Padulosi, S. Mobilizing neglected and underutilized crops to strengthen food security and alleviate poverty in India. *Indian J. Plant Genet. Resour.* **2010**, *23*, 110-116.
90. Shanthakumar, G.; Mal, B.; Padulosi, S.; Bala Ravi, S. Participatory varietal selection: A case study on small millets in Karnataka. *Indian J. Plant Genet. Resour.* **2010**, *23*, 117-121.
91. Vijayalakshmi, D.; Geetha, K.; Gowda, J.; Bala Ravi, S.; Padulosi, S.; Mal, B. Empowerment of women farmers through value addition on minor millets genetic resources: A case study in Karnataka. *Indian J. Plant Genet. Resour.* **2010**, *23*, 132-135.
92. Yenagi, N.B.; Handigol, J.A.; Bala Ravi, S.; Mal, B.; Padulosi, S. Nutritional and technological advancements in the promotion of ethnic and novel foods using the genetic diversity of minor millets in India. *Indian J. Plant Genet. Resour.* **2010**, *23*, 82-86.
93. Williams, J.W.; Jackson, S.T.; Kutzbach, J.E. Projected distributions of novel and disappearing climates by 2100 AD. *PNAS* **2007**, *104*, 5738-5742.
94. Jarvis, A.; Lane, A.; Hijmans, R.J. The effect of climate change on crop wild relatives. *Agr. Ecosyst. Environ.* **2008**, *126*, 13-23.
95. Lobell, D.B.; Burke, M.B.; Tebaldi, C.; Mastrandrea, M.D.; Falcon, W.P.; Naylor, R.L. Prioritizing climate change adaptation needs for food security in 2030. *Science* **2008**, *319*, 607-610.
96. Menéndez, R. How are insects responding to global warming? *Tijdschr. Entomol.* **2007**, *150*, 355-365.
97. Traore, S.B.; Reyniers, F.; Vaksmann, M.; Kone, B.; Sidibe, A.; Yorote, A.; Yattara, K.; Kouressy, M. Adaptation à la sécheresse des écotypes locaux de sorgho du Mali. *Sécheresse* **2000**, *11*, 227-237.
98. Kotschi, J. Agricultural biodiversity is essential for adapting to climate change. *GAIA* **2007**, *16*, 98-101.
99. Wood, D.; Lenne, J.M. Received wisdom in agricultural land use policy: 10 years on from Rio. *Land Use Policy* **2005**, *22*, 75-93.

100. Batugal, P.; Oliver, J. *Poverty Reduction in Coconut Growing Communities 3: Project Achievements and Impact*; IPGRI-APO: Serdang, Malaysia, 2005.