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5. Agricultural biodiversity, food security and human health

1. Introduction

The world's population has increased from roughly 2.5 billion people in 1950 to more than 7 billion today (USCB 2013) and is anticipated to exceed 9 billion by 2050. This development, in parallel with global affluence and associated dietary shifts (Alexandratos and Bruinsma 2012; Tilman et al. 2011), has been accompanied by a parallel rise in demand for food and other agricultural products (Godfray et al. 2010). Food production is expected to have to rise by a further 70–100% by 2050 (Tilman et al. 2001; Foley et al. 2005; Green et al. 2005). Global food production systems have largely kept pace with population growth over the past 50 years due to conversion of natural ecosystems to agriculture, intensification of farming practices on existing agricultural lands, improved varieties of crops and breeds of animals, and improved agronomic practices (Wilby et al. 2009). From 1980 to 2001, global cereal production increased by 36% with a simultaneous increase of 34% in areas under permanent crop and in the use of nitrogen fertilizers (FAO 2003). While increases in food production have contributed to feeding an additional 4 billion people, improved human nutrition and reduced hunger prevalence from 33% to 18% over the past 40 years (Sanchez et al. 2005), the number of chronically or acutely malnourished people remain stubbornly high, still exceeding 800 million (FAO 2014). The improvements in food production (and consequent benefits in overall human health in many areas) have also generally been accompanied by a loss of biodiversity in agro-ecosystems, and led to new public health challenges.

An adequate supply of safe and nutritious food is one of the cornerstones of human health, and the ways in which biodiversity and food production are interrelated and influence each other are key aspects of this relationship. Agriculture and food production are also significantly implicated in the extent to which planetary boundaries have been or are likely to be exceeded with respect to nitrogen flows, water usage, and land use change (Rockstrom et al. 2009; Steffen et al. 2015), and in the negative effects of loss of biodiversity on human health described in other chapters of this volume.

This chapter focuses on the links between agricultural biodiversity, food security and human health. It covers both direct impacts, such as the loss of arable land and natural habitat, and health outcomes associated with modern agricultural practices. The relationships between biodiversity and nutrition are dealt with in a related chapter in this volume.

2. Agricultural biodiversity[1]

2.1 The contribution of agricultural biodiversity to human health

Agricultural biodiversity (often referred to as agrobiodiversity) includes all the components of biological diversity of relevance to food and agriculture, and those that constitute the agro-ecosystem: the variety and variability of animals, plants and microorganisms at the genetic, species and ecosystem levels, which sustain the functions, structure and processes of the agro-ecosystem (FAO/PAR 2011). Created, managed or influenced by farmers, pastoralists, fishers and forest dwellers, agricultural biodiversity continues to provide many rural communities throughout the world with stability, adaptability and resilience in their farming systems and constitutes a key element of their livelihood strategies (Altieri and Merrick 1987; Brush 1999; Jarvis et al. 2011).

Agricultural biodiversity plays a critical role in global food production and the livelihoods and well-being of all, regardless of resource endowment or geographical location. As such, it is an essential component of any food system. Productive agro ecosystems, both wild and managed, are the source of our food and a prerequisite for a healthy life, and agricultural biodiversity contributes to all four pillars of food security.[2] The sustainability of agroecosystems is dependent on the conservation, enhancement and utilization of biodiversity. Agricultural biodiversity provides the basic resources needed to adapt to variable conditions in marginal environments and the resources required to increase productivity in more favourable settings. Further, with global, especially climate, change, there will be increasing interdependence between farmers and communities all over the world, who will be ever more reliant on the global

benefits agricultural biodiversity can provide (MA 2005; Frison et al. 2011; Lockie and Carpenter 2010). All too often, the food used for human consumption and the nutritional and health benefits biodiversity provides have been ignored (De Clerck et al. 2011). When these links are considered, biodiversity, agriculture and health can form a common path leading to enhanced food security and nutrition (Toledo and Burlingame 2006).

It has been estimated that some 7000 plant species have been used by humans at one time or another although some 82 crop species provide 90% of the energy currently consumed by humans (Prescott-Allen and Prescott-Allen 1990). From this total, 40% is provided by only three crops. Despite this homogenization of production systems, there remain several hundred neglected and underutilized crops with significant potential to support diversification, improve adaptability to change and increase resilience (Kahane et al. 2013). In contrast, about 40 livestock species in total contribute to today's agriculture and food production and only five species provide 95% of the total (FAO, 2007; Heywood 2013).

For aquaculture, it has been estimated that over 230 spp. of finfish, molluscs and crustaceans are utilized but that 31 species are responsible for 95% of production (85% of which takes place in Asia) (FAO 1996).[3] As discussed in the chapter on nutrition in this volume, crop, animal and aquaculture species diversity also contribute to dietary diversity, the variety of macro- and micronutrients needed by humans, and multiple livelihood benefits.

Genetic diversity plays a particularly important role in agriculture (FAO 2010). The development of new varieties and breeds depends on the use of

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[1] In this chapter, agriculture is taken to include crop and animal production, and freshwater aquaculture for food and other goods and services. It does not include marine aquaculture and wild fish harvesting and covers forest production systems only insofar as they contribute to food production.

[2] The Committee on Food Security describes food security as existing when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life. It identifies four pillars of food security – availability, access, utilization and stability, and notes that the nutritional dimension is integral to the concept of food security. See: http://www.fao.org/fileadmin/templates/cfs/Docs0910/ReformDoc/CFS_2009_2_Rev_2_E_K7197.pdf

[3] See ftp://ftp.fao.org/docrep/fao/011/i0283e/i0283e02.pdf

Box 1. Risks to animal genetic resources

A total of 7616 livestock breeds from 180 countries are mentioned in the Food and Agriculture Organization (FAO)'s Global Databank for Animal Genetic Resources for Food and Agriculture. It has been estimated that 30% of these are at risk of extinction. In contrast to crops plants where significant populations of potentially valuable crop relatives exist in the wild, *The state of the world's animal genetic resources for food and agriculture* (FAO 2007) notes that "with the exception of the wild boar (*Sus scrofa*), the ancestors and wild relatives of major livestock species are either extinct or highly endangered as a result of hunting, changes to their habitats, and in the case of the wild red jungle fowl, intensive cross-breeding with the domestic counterpart. Thus, domestic livestock are the depositories of the now largely vanished diversity" (FAO 2007:6).

Box 2. Aquatic agroecosystems and human health

Aquatic agroecosystems, such as fish–rice systems of South and South-East Asia, contain a rich diversity of edible species. For many rural populations living in these areas, rice and fish are the main dietary staple. Aquatic animals are often the most important source of animal protein and are essential during times of rice shortages, providing essential nutrients that may otherwise not be adequate (Halwart 2006). Thus, wild and gathered foods from aquatic habitats provide important diversity, nutrition and food security. Recent studies on the utilization of aquatic biodiversity from rice-based ecosystems during one season only in Cambodia, China, Laos and Viet Nam found that 145 species of fish, 11 species of crustaceans, 15 species of molluscs, 13 species of reptiles, 11 species of amphibians, 11 species of insects and 37 species of plants were caught or collected (Halwart 2013; Halwart 2006; Halwart and Bartley 2005).

Bangladesh contains a great variety of inland water bodies, including beels, ponds, rivers, canals, ditches and rice paddy fields, which contain more than 267 freshwater fish species (Rahman 1989). In particular, small indigenous fish species (*Parambassis baculis, Parambassis ranga, Rohtee cotio, Esomus danricus, Corica soborna, Chanda nama, Amblypharyngodon mola, Channa punctatus, Puntius* ssp.) are a rich source of highly bioavailable nutrients, animal protein and some, with a high fat content, contain beneficial polyunsaturated fatty acids. Indigenous fish species, such as darkina (*Esomus danricus),* have a high iron, zinc and vitamin A content (Thilsted 2013; see also the chapter on nutrition).

Integrated aquatic agroecosystems demonstrate the many beneficial interactions between the different elements of biodiversity that enhance food production and the ecosystem services that support it while significantly increasing agricultural biodiversity and reducing production risks. Rice plants contribute to improved water quality and ensure temperatures for optimum prawn and fish production. Plants provide habitat and shelter for fish, reducing the risk of predation. Foraging on aquatic sediments, including pests and weeds, and the consumption of phytoplankton by fish enhances nutrient exchange between water and soil, and reduces the need for pesticides and fertilizers. Small indigenous fish species also tend to be preferred by farming households and constitute an important source of minerals, micronutrients and vitamins (Bunting and Ahmed 2014).[4]

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[4] See also Climate change and adaptation and prawn-fish-rice agroecosystems, Landscapes Blog for People, Food and Nature http://blog.ecoagriculture.org/2014/07/14/climate-change-adaptation-and-prawn-fish-rice-agroecosystems/

the genetic diversity present in the target species. The continuing increases in productivity achieved over the past century have depended to a significant extent on the continuing improvements made by plant and animal breeders. The development and maintenance of different crop varieties, animal breeds and aquatic species' populations provide the variety of food products that human societies require. Their continued improvement provides the basis for meeting increased food demands and adaptability to changing production conditions and practices. The importance of maintaining genetic diversity is reflected in the global concern with the conservation and use of genetic resources, as evidenced by the publication of reports on the state of the world's plant, animal and forestry genetic resources (FAO 2007, 2010, 2014; see also Box 1), the work of the FAO Commission on Genetic Resources for Food and Agriculture, the establishment of the Global Crop Diversity Trust and the entry into force of the International Treaty on Plant Genetic Resources for Food and Agriculture.

Genetic diversity within production systems is essential for the provision of ecosystem services (Hajjar et al. 2008). Although production systems have become increasingly uniform, and dominated by a few varieties of major crops, many small-scale farmers grow and maintain a number of different traditional varieties or breeds. Reasons for maintaining genetic diversity include: stability and risk avoidance; adaptation and adaptability to variable, difficult or marginal environments and to environmental change; provision of key ecosystem services such as pest and disease control, pollinator diversity, below-ground diversity and soil health; meeting changing market demands, coping with distance to market and adult labour availability; dietary or nutritional value; and meeting cultural and religious needs (see review by Jarvis et al. 2011).

3. Agricultural production, land use, ecosystem services and human health

Agricultural crops or planted pastures have become the dominant form of land use, comprising almost onethird of terrestrial land (Scherr and McNeely 2008). Today more than one third (38%) of the terrestrial landscape has been converted for agriculture, with the majority (26%) of converted land dedicated to livestock production (Foley et al. 2011). In addition to food production from agriculture, between 1% and 5% of food is produced in natural forests (Wood et al. 2000). Ellis and Ramankutty (2008) have estimated that more than 75% of the earth's ice-free land shows evidence of alteration as a result of human residence and land use. Over 1.1 billion people, mostly dependent on agriculture, live within the world's 25 biodiversity "hot spots" (Cincotta and Engelman 2000; Myers et al. 2002). The ways in which humankind has influenced or managed the different biomes around the world has resulted in a wide diversity of production systems (Ellis et al. 2010), and each production system or combination has different features, both in terms of the biodiversity found within the system and associated impacts on human health.

Changes in land use and agricultural intensification have been two of the most important drivers of biodiversity loss in both natural and agricultural productions systems (MA 2005). In the section that follows, the major effects of these changes on agricultural biodiversity and human health are summarized, and alternative pathways to ensuring adequate food production in ways that support co-benefits are identified.

3.1 Land use, land conversion and intensification

3.1.1 Land use and the expansion of arable land

Heterogeneous patterns in land cover change have followed human settlement and economic development (Richards 1990; Grigg 1974; Roberson 1956). Over the past three centuries, roughly 12 million km² of forest and woodlands have been cleared, and 5.6 million km² of grassland and pastures have been converted (Richards 1990). At the same time, cropland areas have increased by 12 million km², and some 18 million km² (equivalent to the size of South America) are under some form of cultivation (Ramankutty and Foley 1998).

With land conversion has come significant biodiversity losses as complex forest, grassland and wetland communities were converted into highly simplified cropping landscapes. In addition to the health effects of simplification and homogenization, land conversion affects human health in five primary ways:

i)   Change in the delivery of supporting and regulating services from natural habitat important for agricultural production;

ii) The loss of habitat for wild species, which contribute to diets in many parts of the world (reviewed in the chapter on nutrition);

iii) Increased interaction with disease host, vectors and reservoirs (discussed briefly here and reviewed in the chapter on infectious diseases);

iv) Loss of medicinal plants (reviewed in the chapter on traditional medicine);

v)   Cultural ecosystem services and mental well-being associated with interactions with nature and landscapes (see the chapter on mental health in this volume).

Most land conversion is currently taking place in tropical forest regions, home to some of the highest levels of biodiversity globally and a critical biome regulating global ecosystem services. Since the 1980s, 55% of new agricultural land in the tropics has come from the clearing of forests (Gibbs 2010). Forest and woodlands are important carbon sinks, they play an important role in the regulation of climate (Shvidenko et al. 2005), water flow and water quality (Shvidenko et al. 2005) and are important sources of fibre and fuel for numerous communities (Sampson et al. 2005).

Land use change, particularly deforestation for agriculture, is a leading contributor of carbon dioxide (CO_2), the greenhouse gas that is the primary contributor to climate change. An estimated 1.3 T 0.7 Pg C year^{-1} of CO_2 is emitted as a result of tropical land-use change (Pan et al. 2011), and land-use change accounts for 20–24% of all CO_2 emissions annually (IPCC 2014). Although there is currently little agreement on the net biophysical effect of land-use changes on the global mean temperature, its biogeochemical effects on radiative forcing through greenhouse gas (GHG) emissions was found to be positive (Working Group I Chapter 8; Myhre and Shindell 2013). The impacts of climate change are expected to both affect and be affected by the agricultural sector, with rising global temperature exceeding the thermal tolerance of certain crops (Bita and Gerats 2013), more erratic precipitation patterns (Rosenzwieg et al. 2001) and greater incidence of disease outbreaks (Rosenzwieg et al. 2001).

With the most fertile lands already used for farming, land conversion for agriculture increasingly brings marginal and/or fragile lands

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Box 3. Soil health and agricultural biodiversity

The importance of agricultural biodiversity in supporting soil health and associated regulating and supporting ecosystem services has been reviewed by Swift et al. (2004). The importance of diversity of soil biota and of the maintenance of all components of the soil food web, and of diversity within different levels has been described by Beed et al. (2011), Gliessman (2007) and Mäder et al. (2002). However, the amount of diversity that is needed or desirable is the subject of some debate and some authors have argued that, in functional terms, saturation is reached at fairly low levels of species diversity. There is growing evidence that natural and less intensive agricultural production systems have higher levels of diversity than those under intensive agriculture and that higher levels of diversity are associated with improved delivery of key ecosystem services. Swift et al. (2004) have noted the importance of maintaining total system diversity and of practices, such as conservation agriculture, and mulching, which ensure higher diversity levels in the soil.

under cultivation. Conversion of forested hillsides and the further expansion of arable farming into nutrient-poor tropical soils may lead to poor yields, with large losses in biodiversity (see Box 3 on soil health). It is expected that land conversion will continue to increase in some areas, particularly in biodiversity hotspots around the tropics where human population pressures are mounting (Myers 2000). This can also lead to increased incidence of infectious diseases, covered in a separate chapter in this volume. Other areas may see abandonment of marginal agricultural lands (Grau et al. 2004), and a forest transition with the return of significant areas of natural vegetation and biodiversity with land abandonment and replanting (Rudel et al. 2005).

3.1.2 Intensification and ecosystem services

Farmers are bringing more land under cultivation and intensifying land use on existing farmlands by removing fallow periods, hedgerows, ditches and green spaces, enlarging fields and expanding land under permanent cultivation (Stoate et al.

Box 4. Livestock intensification

As global incomes increase, diets increasingly shift from the protein derived from plant products to increased consumption of meat, dairy and eggs, adding pressure on farming systems to increase livestock production (Tilman et al. 2011). Global meat production is projected to more than double from 229 million tonnes in 1999/2001 to 465 million tonnes in 2050, while milk output is set to climb from 580 to 1043 million tonnes (FAO 2006). Already livestock production uses 30% of the earth's entire land surface, mostly permanent pasture but also including 33% of the global arable land used to produce feed for livestock (FAO 2006; Cassidy et al. 2013). While livestock makes an important contribution to food security, its increased consumption is also a contributing factor to the increase in noncommunicable diseases (NCDs) and can have negative impacts on biodiversity (as discussed in the chapter on nutrition in this volume).

Livestock feed crops (maize, soya) in low-diversity and high-intensity cultivation systems are a very inefficient use of resources and crop calories. For every kilogram of beef produced, 1 kg of feed is needed (USDA 2002). At present, 36% of calories produced by cropping systems is used for animal feed of which only 12% are ultimately used for human consumption (Cassidy et al. 2013). It has been estimated that if these calories were consumed by people directly, the current global food production system could feed an additional 4 billion (Cassidy et al. 2013), meeting our estimated population growth forecasts for 2050.

The conversion of land for pasture is a major driver of deforestation. For example, in Latin America, some 70% of former Amazonian forest has been turned over to grazing (FAO 2006). Widespread overgrazing disturbs water cycles, reducing replenishment of above-and below-ground water resources. Beyond land conversion, the livestock sector can also be deleterious to increasingly scarce water resources with negative implications for human health (McMichael et al. 2007). Animal wastes antibiotics and hormones, chemicals from tanneries, fertilizers and the pesticides used to spray feed crops contribute substantially to water pollution, eutrophication and the degeneration of coral reefs, while also posing health risks, such as antibiotic resistance (FAO 2006; Horrigan et al. 2002). The use of these products not only affects biodiversity but also has health consequences, for example, by affecting drinking water quality, increasing the risks for several types of cancer, undermining local fisheries – another important source of dietary protein – and contributing to endocrine disruption and reproductive dysfunction (Horrigan et al. 2002; see also chapter on freshwater in this volume).

2001; Wilby et al. 2009; Frison et al. 2011), as well as use of more agro-chemicals and inputs (see section 3.3.1). Although small in size, fragments of natural habitat within agricultural landscapes are important for the provision of a number of agricultural ecosystem services (Mitchell et al. 2013) and for maintaining wildlife habitats and corridors, which can contribute to sustainability and conservation. The supporting and regulating services upon which agriculture depends include pollination, pest control, soil health, water regulation and nutrient cycling, largely provided by associated biodiversity in and around production systems (Kremen et al. 2007).

It has been estimated that, based on current trends of greater agricultural intensification in richer nations and greater land clearing (extensification) in poorer nations, an estimated 1 billion ha of land may be cleared globally by 2050 (Tilman et al. 2011). However, according to FAO estimates, only about 70 million ha of additional land is likely to be used by 2050 (FAO/PAR, 2011). In contrast, if the crop demand in 2050 was met by moderate intensification focused on existing croplands in countries where potential exists, combined with the use of appropriate technologies, only some 0.2 billion ha would be needed.

The scale and nature of land conversion is also important to the continuing provision of ecosystem services. Many essential ecosystem services are delivered by organisms that depend on habitats that are segregated spatially or temporally from the location where services are provided, such as farmed fields (Kremen et al. 2007; Mitchell et al. 2013). Fine-scale green spaces such as hedgerows, ditches, green strips are critical habitats for important agricultural biodiversity such as bees, birds, arthropods and mammals, and a source of many of the ecosystems services important for agriculture (Ricketts 2004, 2008; Kremen et al. 2007, 2012; Kremen and Miles 2012; Horrigan et al. 2002; Mitchell et al. 2013). Management of organisms contributing to ecosystem services requires consideration not only of the local scale where services are delivered (i.e. farmed fields), but also the distribution of resources at the landscape scale, and the foraging ranges and dispersal movements of the mobile agents (Kremen et al. 2007). Two examples of the contribution of agricultural biodiversity to ecosystem services are pollination and pest and disease control.

3.2 Pollination

The importance of insect pollination for agriculture is unequivocal, and yet global pollinator populations are in significant decline (Potts et al. 2010) with potential consequences for pollination-dependent crop yields. Globally, 35% of crops depend on pollinators (Klein et al. 2007) with an additional 60–90% of wild plant species also requiring animal pollination (Husband and Schemske 1996; Kearns et al. 1998; Ashman et al. 2004). Pollination services also contribute to the livelihoods of many farmers. It has been estimated that in 2005, the total economic value of pollination worldwide was €153 billion, equivalent to 9.5% of the value of the world agricultural production used for human consumption. In terms of welfare, the consumer surplus loss was estimated at between €190 and €310 billion (Gallia et al. 2009).

Many of the crops for which pollination is essential, including fruits and vegetables, are important sources of micronutrients and vitamins (Eilers et al. 2011). Pollinated crops contribute 90% of the vitamin C, 100% of lycopene and almost all of the antioxidants β-cryptoxanthin and β-tocopherol, the majority of the lipid vitamin A and related carotenoids, calcium and fluoride, and a large portion of folic acid in our diets (Eilers et al. 2011). In terms of calories, approximately one third of the human diet comes from insect-pollinated plants (USDA 2002; Tscharntke et al. 2012). Many forage crops for livestock (e.g. clover) are also pollination dependent (see the chapter on nutrition for a case study on pollination).

For pollinated crop species, field size and distance to natural habitat edges is a strong predictor of fruit set (Klein et al. 2003; Ricketts et al. 2004, 2008). As hedgerows and green spaces have been eliminated from farming landscapes, and pesticide use has expanded, problems of ensuring adequate

pollination have increased. There is an increasing trade in honey bees to provide pollination services, although this is facing problems that appear to result from an unknown combination of habitat loss (Naug 2009), chemical use (neonicotinoids) (Maus et al. 2003) and disease resulting in colony collapse (reviewed in Ratnieks and Carreck 2010). Wild insect pollinators are often much more effective than honey bees but their delivery of this essential ecosystem service is also strongly compromised by habitat loss, land conversion and chemical usage.

3.3 Pest control

A major health concern associated with agricultural intensification is the increased use of pesticides. Among them, direct exposure to some pesticides have been associated with neurological, reproductive and genotoxic effects (Sanborn et al. 2007) and, in some cases, prolonged exposure to certain pesticides has been found to increase the risks for certain cancers, including non-Hodgkin lymphoma, leukaemia, brain and prostate cancers, among others (Bassil et al. 2007).

The simplification of landscapes through the enlargement of fields and loss of natural habitat areas also influences natural pest control services provided by associated biodiversity. These services help to reduce pest population numbers without the use of pesticides. Non-crop areas such as meadows, hedgerows and forest patches provide a habitat for a wide range of natural enemies of crop and animal pests and diseases (birds, aphids, etc.). Interspersion of natural habitats in the landscape matrix promotes the movement of natural enemies between crop and non-crop habitats, which is lost in landscapes dominated by arable cropland (Bianchi et al. 2006).

In a review of studies, Bianchi et al. (2006) showed that in 74% and 45% of cases, respectively, natural enemy populations were higher and pest pressure lower in complex landscapes versus simple landscapes. Pest predator activity was equally associated with herbaceous habitats, wooded habitats and landscape patchiness (Bianchi et al. 2006), suggesting that maintaining all three

habitat types are important for the provision of pest control services. In structurally complex landscapes, Thies and Tscharntke (1999) showed that parasitism was higher and crop damage was lower than in simple landscapes. Landscape diversity can also be an effective way to control non-native introduced crop pests (an emerging threat for many agricultural systems) through enhanced pest control services by native wildlife (Gardiner et al. 2009).

The value of diversity and the importance of maintaining natural prey/predator relations for pest control have been demonstrated in many crops (Hajjar et al. 2008). Gurr et al. (2003) list examples that range from the local field level to landscapes, and integrated pest management (IPM) programmes in Asia have shown that conserving arthropod diversity is a key ingredient of their effectiveness. Pretty et al. (2006) analysed 62 IPM projects in 21 countries and found that in 47 of them yields increased by an average of 42% while pesticide use declined by 71%.

Genetic diversity can also make a significant contribution (Finckh and Wolfe 2006) to pest and disease control. Large-scale deployment of mixtures of crop varieties in barley and rice have demonstrated that, even with relatively few components, improvements in both yield and yield stability can be achieved (Wolfe et al. 1981; Zhu et al. 2000). Further work by Jarvis and collaborators (e.g. Mulumba et al. 2012) has shown that diversity of traditional crop varieties in crops as diverse as banana, maize and bean improves the stability of production without a reduction in the crop productivity. Tooker et al. (2012) have described the use of genotypically diverse variety mixtures for insect pest management. The use of genetic diversity to reduce the impact of epidemics has been described by De Vallavieille-Pope (2004). The use of diversity-based approaches to pest management in Africa are also described in Abate et al. (2000).

Crop management practices can also influence the efficiency of pest control services. Intercropping and inclusion of non-crop strips within fields have been shown to increase the abundance

of spiders (important pest predators) by 33% (reviewed in Sunderland and Samu 2000), whereas management practices such as undersowing, mulching and reduced tillage were shown to enhance spider abundance by 80% (reviewed in Sunderland and Samu 2000). Temporal and spatial rotation of crops on fields is another important technique used to reduce the build-up of pathogens in soils and spread between plants (Abawi and Widmer 2000).

Reduced pest activity not only increases potential food production, but it may also reduce or eliminate the need for pesticides and reduce the presence of deleterious compounds associated with specific pests.

3.3.1 The use of pesticides and fertilizers in agricultural production

The negative effects of pesticides on human health, biodiversity and agricultural biodiversity have been well documented. Pesticides affect almost all living organisms and it has been estimated that more than 95% of herbicides and insecticides sprayed over agricultural fields reach a destination other than their target species (Tyler Miller 1994). Pesticides can be carried away by runoff water, seepage and leaching into ground-water, streams and aquatic environments, and through soil erosion. Through drift or evaporation, air can transport them for short and long distances, contaminating other areas, including wildlife (Cornell University 2001b; National Park Service 2014; Papendick et al. 1986). The following examples illustrate the effect of pesticides on agricultural biodiversity:

1. As persistent soil contaminants, pesticides negatively affect soil biota leading to lower organic matter content and reduced water retention, the latter reducing yields in drought years (Lotter et al. 2003). The reduction in soil-dependent ecosystem services, such as carbon and nitrogen cycling, leads to a situation of increased dependence on externally derived chemical inputs to support production – in fact, a negative feedback loop. The overall long-term effect of pesticides is a reduction in soil biodiversity (Johnston 1986). Pesticides

in the soil also reduce the symbiotic efficiency of nitrogen-fixing rhizobia and host plants. More specifically, the insecticides DDT, methyl parathion, and especially pentachlorophenol have been shown to interfere with legume–rhizobium chemical signalling. The environmental consequences are an increased dependence on synthetic nitrogenous fertilizers, reduced soil fertility, and unsustainable long-term crop yields (Fox et al. 2007).

2. Because of their indiscriminate mode of action, herbicides have a direct negative effect on plants that occur in and around agricultural production systems. These include crop wild relatives and plants used for integrated pest management strategies, such as the push – pull system. A number of pesticides have also been shown to have some direct harmful effect on plants, including poor root hair development, shoot yellowing and reduced plant growth (Walley et al. 2006).

3. It has been estimated that farmers in the United States (US) lose at least $200 million a year from reduced crop pollination because pesticides applied to fields eliminate about a fifth of honeybee colonies in the US and harm an additional 15% (Tyler Miller 2004). Henry et al. (2012) found that, even with very low levels of the pesticide thiamethoxam, a neonicotinoid insecticide, in the bee's diet a high proportion of bees (more than one third) suffered from orientation disorder and were unable to come back to the hive, putting the colony at risk of collapse (colony collapse disorder) (see also Whitehorn et al. 2012). The pesticide concentration was much smaller than the lethal dose currently used, and its application, together with clothianidin and imidacloprid, was restricted by the European Union in April 2013 (Wall Street Journal 2013).

The repeated application of many of the chemicals used as pesticides increases pest resistance, while its effects on other species can facilitate the pest's resurgence (Damalas and Eleftherohorinos 2011). This is true not only of fungicides, insecticides and bacteriocides but also of herbicides. The law of diminishing returns comes into force and requires increasing use of such pesticides with decreasing

beneficial effects and increasing detrimental effects on both the environment and human health.

The pesticide production industry is dynamic and able to develop, test and market an increasing range of chemical compounds, which have tended to become more specific and to have fewer deleterious side-effects. However, many pesticides remain generic with respect to the class of organism affected. There are now established international and national processes aimed at limiting the use of pesticides that have unacceptable negative effects on the environment or humans. The "Stockholm Convention on the Protection of Human Health and the Environment from Persistent Organic Pollutants (POPs)" came into force in 2004. It restricts and ultimately aims to eliminate the production and use of listed chemicals. This Convention also promotes the use of both chemical and non-chemical alternatives to POPs. Twelve chemical compounds – "the dirty dozen" – were on the Convention's original list of POPs. Nine of the 12 are pesticides (Gilden et al. 2010; UNEP 2005), including DDT (which is still used to control malaria). To date, ten more POPs have been added to this list and others are under review (UNEP 2013). Advances in agrochemistry have generally allowed pesticides to become more species-specific and to reduce their environmental impact. Moreover, the amount applied has declined in many cases, sometimes by 99% (Lamberth. et al 2013). The global spread of pesticide use, however, including the use of older or obsolete pesticides that have been banned in some jurisdictions, continues (Kohler and Triebskom 2013).

It is likely that most farmers use pesticides of some kind or other at some stage in their production (Alavanja 2009). Even many small- scale farmers in developing countries will use some pesticides and this can create major health problems through lack of appropriate equipment or knowledge, or through the use of outdated products. The US Environmental Protection Agency's (EPA) report on Pesticides Industry Sales and Usage (2006 and 2007 Market Estimates) reports that the amount of pesticide used worldwide was approximately 2.36 billion kg on average in 2006 and 2007, of which more than 0.5 billion kg (21%) was used

in the United States. Herbicides (including plant growth regulators) accounted for the largest portion of total use, followed by other pesticides, insecticides and fungicides. Although the total global consumption of pesticides increased in 2007 (US Environmental Protection Agency 2011), there is evidence that countries can make a significant difference through their legislation and regulations to the amounts of pesticide used. For example, Indonesia reduced expenditure on pesticides (an estimate of total amount used) from a high of US\$ 120–160 million in the period from 1980–1987 to US\$ 30–40 million in the following 5 years.

It has been estimated that as many as 25 million agricultural workers in the developing world, where programmes to control exposure are limited or non-existent (Alavanja 2009), experience unintentional acute pesticide poisoning each year (Jeyaratnam 1990). While the acute effects of pesticides are well documented in the literature, especially with respect to organophosphate poisoning (Sanborn et al. 2004), it is much less easy to assess the chronic effects of pesticide exposure. Sanborn et al. (2004 and 2012) conducted systematic reviews to establish whether chronic exposure to pesticides had adverse health effects. Many of the reviewed studies showed positive statistically significant associations between health problems and pesticide exposure. The continuing presence of pesticides in food, water and soil is also responsible for significant risks to health (U.S. Environmental Protection Agency 2007).

Depending on their nature, properties and mode of use, exposure to pesticides can have a wide range of negative health effects (Cornell University 2001a). These include the following:

• Reproductive effects: effects on the reproductive system or on the ability to produce healthy offspring;

• Teratogenic effects: effects on unborn offspring, such as birth defects;

• Carcinogenic effects: produces cancer in living animal tissues;

- Oncogenic effects: tumour-forming effects (not necessarily cancerous);

- Mutagenic effects: permanent effects on genetic material that can be inherited;

- Neurotoxicity: poisoning of the nervous system, including the brain;

- Immunosuppression: blocking of natural responses of the immune system responsible for protecting the body.

The direct negative effects of pesticides on biodiversity and human health are numerous but it should be recalled that there have also been very tangible benefits to human health from the use of pesticides and insecticides, such as in malaria control programmes. However, insecticide resistance in malaria vectors was also reported in 53 of 65 reporting countries around the world since 2010. The most commonly reported resistance is to pyrethroids, the most frequently used insecticide in malaria vector control (WHO 2014).

The development of resistance in disease-producing organisms, or in vectors of human disease, as a result of pesticide overuse is one example where health problems can be combined with ecological imbalance and the development of large pest populations. The use of herbicides in rural areas can also have associated negative effects by reducing the availability of many gathered foods and thus deprives communities of important sources of dietary diversity. The same is true of the negative effects of pesticides on pollinators and the availability of honey in rural areas. More generally, the use of pesticides as a part of simplified agricultural systems, while increasing the production of major staples, can lead to production systems that are more vulnerable to change and stress, resulting in much greater fluctuations in yield, which renders farmers and

rural communities liable to complete losses in production and loss of food security.

Fertilizers

The overuse of synthetic fertilizers has major negative effects on biodiversity, particularly freshwater and marine biodiversity and soil biota. It also has negative effects on human health, most obviously perhaps through pollution of groundwater and reduction in the availability of unpolluted fresh water. As with pesticides, there are points of interaction between loss of biodiversity and human health such as through the damaging effect of algal blooms and the increased frequency of toxic phytoplankton as described in the chapter on freshwater in this volume. The increasing size of marine dead zones also has a significant negative effect on the availability of fish for human consumption. While the application of synthetic fertilizers makes a significant contribution to improving overall food production and may be especially important in parts of Africa, for example, overuse has created major environmental problems in Asia. Large-scale synthetic fertilizer use is often associated with reduced adaptability and resilience in production systems and, in some stress situations, with reduced yield stability. Both synthetic fertilizers and pesticides can create negative feedback loops in which the reduced agricultural biodiversity associated with their use is accompanied by production problems associated particularly with loss of soil biota.

The negative effects of synthetic fertilizers on soil biota, soil acidification and groundwater pollution can be significant (Osborne 2011). Nitrogen that is not taken up by plants is transformed into nitrate, which is easily washed off the soil into watercourses or leached through soil into groundwater (Jackson et al. 2008; Barabasz et al. 2002). Nitrate levels above 10 mg/L in groundwater can cause acquired methaemoglobinemia in infants (also called "blue baby syndrome"), which leads to an overall reduced ability of the red blood cell to release oxygen to tissues, possibly leading to tissue hypoxia (Knobeloch et al. 2000; Self and Waskom 2013). High N fertilizer rates applied to arable, grassland and horticultural soils can also lead to the accumulation of nitrites and organic nitrogen compounds such as amines, nitro and nitroso compounds, including nitrosamines and nitrosamides (Barabasz et al. 2002).

Many studies have shown that mineral fertilization strongly affects both the number of microorganisms in the soil and the make-up of communities of soil microorganisms (Barabasz et al. 2002). Use of mineral fertilizers can also lead to increased heavy metal accumulation in soils, and potential health problems have been identified in connection with increased levels of cadmium, arsenic, lead and mercury. Eutrophication is also a major problem caused by the excessive inputs of phosphorus and nitrogen in lakes, reservoirs, rivers and coastal oceans (Smith and Schindler 2009, see also the Box on eutrophication in the chapter on freshwater).

3.4 Non-food crops

The demand for non-food crops has grown with the population and increasing prosperity. This has resulted in the conversion of larger areas of land for the production of (what some consider) "luxury" foods (e.g. coffee, tea, cacao), fibres (e.g. cotton), biofuels and oil (e.g. palm oil, rapeseed). Many of these crops grow exclusively in tropical climates (e.g. coffee, tea, cacao, oil palm) with production areas occurring almost wholly within areas identified as biodiversity hotspots (Myers et al. 2000), suggesting that production of such crops may have an environmental impact disproportional to its area (Donald 2004). The expansion of production of these crops in the twentieth and twenty-first centuries has come at great expense to local biodiversity (reviewed in Donald et al. 2004).

3.5 Impacts of agricultural intensification on human health

Agricultural intensification has involved the use of increasingly productive crop varieties and animal breeds, combined with the continually expanding use of chemical inputs, fossil fuel energy and water in both plant and animal production systems. The most important chemical inputs

have been pesticides of many different types and fertilizers. Fossil fuel energy inputs have included mechanization of cultivation and harvesting, and the use of more intensive animal production systems. Food transport and processing have also become increasingly important aspects of the overall food system with consequences both for human health and agricultural biodiversity.

Box 5. Case study: biofuels

Crops for industrial use, including biofuels, make up 9% of crops by mass, 9% by calorie content, and 7% of total plant protein production, diverting a considerable quantity of food away from human consumption (Cassidy et al. 2013). In 2000, biofuel production alone represented 3% of crop production and is estimated to have increased more than 450% (in terms of litres produced) between the year 2000 and 2010 (WWI 2009), suggesting that increasing areas of land are being dedicated to the production of intensively managed corn, vegetable oils and sugarcane (Cassidy et al. 2013). Based on biofuel statistics from 2010, ethanol production from maize in the United States and from sugarcane in Brazil alone now represents 6% of global crop production by mass and 4% of calorie production (FAPRI 2011). Although biofuels are meant to help reduce the dependence on carbon-dense energy sources and reduce carbon emissions to mitigate climate change, the production of food crops for biofuels can have additional negative impacts on human health associated with (i) intense production techniques (i.e. air quality from forest burning, high chemical use and contamination of waterways) and (ii) diversion of crop calories away from the food production system. In addition to biofuels, significant portions of cultivated land are dedicated to the production of fibres, in particular cotton, as described in the chapter on freshwater.

Box 6. Case study: vegetable oils

Vegetable oils are among the most rapidly expanding agricultural sectors (Clay 2004), and more palm oil is produced than any other vegetable oil (Carter et al. 2007). A native of West Africa, oil palm *(Elaeis guineensis)* is grown across more than 13.5 million ha of tropical, high-rainfall, low-lying areas, a zone naturally occupied by moist tropical forest, the most biologically diverse terrestrial ecosystem on earth (Corley and Tinker 2003, MEA 2005). Palm oil has some of the world's largest plantations, sometimes exceeding 20000 ha (Donald 2004), cut out of the tropical rainforests of Indonesia, Malaysia and increasingly in Latin America. This has resulted in extensive clearing and burning of carbon-rich forests and peat lands, contributing to biodiversity loss, poor air quality affecting respiratory health particularly in South-East Asia, and adding CO_2 to the atmosphere (Clay 2004). Examination of palm oil cultivation in contrast to shaded coffee, pasture and natural forest found that palm plantations supported extremely low levels of birds, lizards, beetles and ant communities (Power and Flecker 1998; Chung et al. 2000; Glor et al. 2001).

Per unit area, palm oil is the highest-yielding vegetable oil crop; the current global production of oil palm fruit is estimated at 97.7 million tons, produced from 10.7 million ha; production is increasing by 9% every year (Donald 2004). Palm oil now makes up about 21% of the world's production of edible oils and fats, second only to soybean oil. The oil is used in the manufacture of cooking oil, margarine, soap and cosmetics, and it has industrial uses. As a substitute for diesel, palm oil is less suitable than other vegetable oils owing to its high viscosity, lower energy density and high flash point (Agrawal 2007). However, oil palm gives high yields at low prices, and hence is likely to be important in meeting biofuel demand (Carter et al. 2007; Koh 2007).

Specialization in one or a select number of crop or animal species has reduced agricultural biodiversity, affecting ecosystem services and human health (Frison et al. 2011). The introduction of invasive alien species can also have negative impacts on biodiversity, terrestrial and aquatic agriculture, and related provisioning and regulating ecosystem services (Pejchar and Mooney 2009). As discussed in the chapter on freshwater, these impacts extend to human health. These trends can also affect the diversity of foods being produced for human consumption and alter agro-ecological processes (Kremen and Miles 2012 and references therein). Intercropping of species and agroforestry practices (the maintenance of perennials in fields) have been shown to enhance above- and below-ground associated biodiversity, soil quality, water-holding capacity, weed control, disease and pest control, pollination, carbon sequestration, and resilience to droughts and hurricanes (reviewed in Kremen and Siles 2012).

There is also concern that industrialized farming systems are vulnerable to the same disease risks as crop monocultures. The level of genetic diversity in livestock breeds has fallen dramatically over the past century as a result of intense selection. In cattle, the Holstein breed dominates production in the West and intensive sire selection is leading to rapid inbreeding rates with a few sons of sires and grandsires dominating US populations (Holstein Assoc. USA 1986). Over the past 100 years, approximately 28% of livestock breeds have become rare, endangered or extinct globally (Notter 1999). This is particularly worrisome as genetic diversity is required to meet current production needs in various environments, to allow sustained genetic improvement, and to facilitate rapid adaptation to changing breeding objectives (Notter 1999). Modern agricultural production systems decouple agriculture from the surrounding environment, controlling feed, water, temperature and disease in large industrial complexes, selecting for animals with very little environmental tolerance. In the interim, we will lose breeds with a range of environmental tolerances (Tisdell 2003). As climate change progresses, the future will not look like the present

and we will need genetic diversity to adapt to these changing conditions.

3.6 Alternative production pathways

The negative effects of modern intensive agriculture on the environment and human health, together with concerns about the unsustainable nature of many of the practices (e.g. with regard to water and phosphate use), the continuing failure to deal with malnutrition and the need to confront the challenges of climate change, have led to the identification of an increasing number of alternative approaches to agricultural production (e.g. Baulcombe et al. 2009; PAR/FAO 2011; FAO 2011; de Schutter 2010). The assessment that the food systems in place are no longer "fit for purpose" has been reflected in growing consumer concerns and the growth of civil society groups concerned about securing healthy and safe food production (Rosin et al. 2012).

Alternative approaches to ensuring sufficient production to meet human needs in environmentally safe ways are broadly based on enhancing the use of biological processes in agriculture. There are many alternative approaches and concepts variously identified as agroecology, ecological intensification or, more generally, as an ecological approach to agricultural production (Altieri et al. 1995; De Schutter 2010; FAO/PAR 2011). Ecological approaches are characterized by minimal disturbance of the ecosystem, plant nutrition from organic and non-organic sources, and the use of both natural and managed biodiversity to produce food, raw materials and other ecosystem services. This way, crop production not only sustains the health of farmland already in use, but can also regenerate land left in poor condition by past misuse (FAO 2011). This approach to agricultural production emphasizes the importance of maintaining natural ecosystem services and function in agricultural production systems rather than replacing them with external inputs.

There are a wide range of ecologically based options including conservation agriculture (Kassam et al. 2009), organic agriculture (Badgley et al. 2007),

integrated pest management (IPM), integrated plant nutrition systems, ecoagriculture (Scherr and McNeely 2007), sustainable crop production intensification (FAO 2009) and agroecology (Wezel et al. 2009). Many of these have already been deployed in large production areas although they are yet to be universally accepted or adopted, and each has its own community of advocates and detractors.

Ecological approaches to agricultural intensification make increased use of agricultural biodiversity and are expected to create conditions that will support the maintenance of biodiversity as a whole and improve human health, either directly or indirectly. Some of the features of such approaches with respect to agricultural biodiversity and to human health are illustrated in the section that follows.

4. Food production, food security and human health

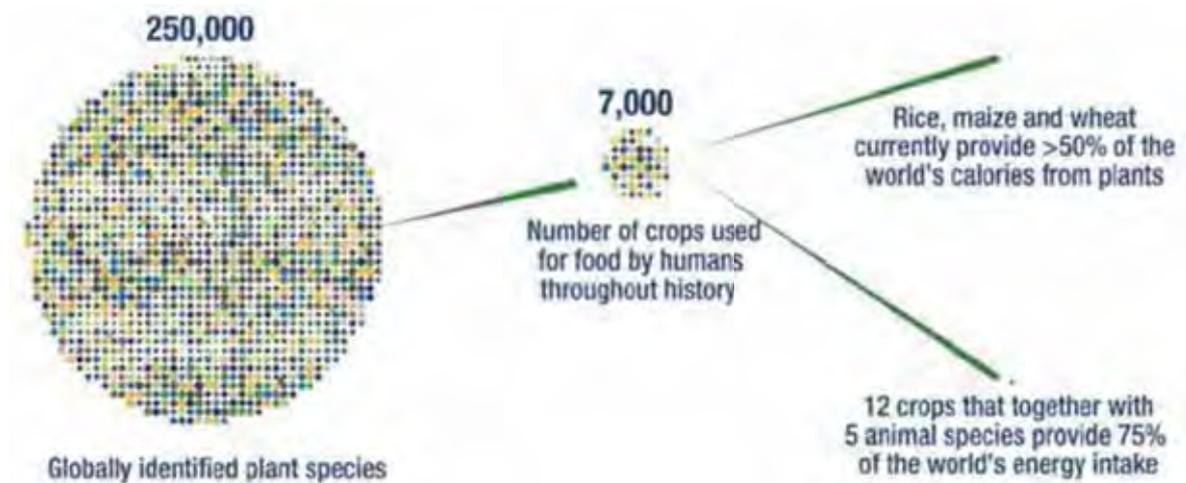## 4.1 Agricultural biodiversity and food production

Many barriers and challenges continue to hinder the optimum utilization and sustainable management of agricultural biodiversity, which have caused it to be relegated to a minor role in agriculture and health (Hunter and Fanzo 2013). This neglect of agricultural biodiversity continues to come at a great cost to national health-care budgets, the global environment and society in general (see chapter on nutrition). Globalization and the simplification of agriculture, population increase and urbanization, along with public policies that continue to provide perverse incentives for unsustainable food production, have changed patterns of food production and consumption in ways that profoundly affect ecosystems and human diets, and have led to increasingly dysfunctional food systems. High-input industrial agriculture and long-distance transport increase the availability and affordability of refined carbohydrates and fats, leading to an overall simplification of diets and reliance on a limited number of energy-rich foods (Figure 1). This has also resulted in a considerable disconnect

between diet and local food sources, a situation that threatens the continued existence of valuable agricultural biodiversity and the knowledge associated with it.

The development of widely adapted, highly uniform crop and livestock varieties has played a major part in the homogenization of agriculture. Such varieties or breeds can be grown and produced over very wide areas (many millions of hectares) owing partly to their broad adaptation and partly to the homogenization of agricultural production systems that can be achieved through chemical inputs and irrigation. The use of genetic modification and production of genetically modified organisms (GMOs) has added a dimension that has been the subject of substantial controversy (Letourneau and Burrows 2010; Costa-Font et al. 2010). The implications for human health of the widespread adoption of commercialized edible GMOs, including soy, maize and oilseed rape, is also disputed (summarized in De Vendômois et al. 2010 and references therein; Dona and Arvanitoyannis 2009). Certainly some of the practices associated with their use may have undesirable side-effects such as the widescale use of herbicides. However, others have suggested that GMO crop varieties reduce pesticide use and result in positive health benefits (Phipps and Park 2002). There are also concerns with respect to the unplanned spread of novel genes into wild crop relatives or to traditional varieties, especially in centres of crop diversity (Stewart et al. 2003). This unplanned spread could have significant negative consequences for existing patterns of within-species diversity, changing fitness levels of populations and varieties, and hence their potential long-term survival and evolution.

Shifts to monoculture or low diversity cropping systems in turn have led to the homogenization of global food production and the loss of regional and endemic crop types, while the adoption of global staple crops is changing people diet as many diets shift towards common starchy energy-dense foods crops in place of traditional crops or varieties (Padulosi et al. 2002; Malaza and Howard 2003; Adoukonou-Sagbadja et al. 2006; Smale et al. 2009). Such shifts have led to a global trend

FIGURE 1: The limited use of plant species diversity in agriculture

250,000

Globally identified plant species

7,000
Number of crops used for food by humans throughout history

Rice, maize and wheat currently provide >50% of the world's calories from plants

12 crops that together with 5 animal species provide 75% of the world's energy intake

Source: FAO, 1995

of increased quantities of food calories, proteins and fat for human consumption, but they are increasingly sourced from a handful of energy-dense foods (Khoury et al. 2014). Consequently, national food supplies worldwide became more alike in composition, correlated with an increased supply of several globally important cereal and oil crops, and a decline of other cereal, oil and starchy root species. The increase in homogeneity worldwide portends the establishment of a global standard food supply, which is relatively species-rich with regard to measured crops at the national level, but species-poor globally (Khoury et al. 2014).

Agricultural homogenization not only affects diets, but potentially the resilience of global food systems. Such cropping patterns make both local and global production landscapes vulnerable to wide sweeping pest and disease outbreaks. As landscapes become increasingly similar in the crop composition, pests and pathogens, including those that are invasive, have increasingly large and connected cropland areas to infect and infest – both through natural dispersal and through increasingly integrated transportation and trade pathways. This can be seen in the recent epidemics of virulent yellow wheat rust, *Puccinia striiformis* f. sp. *tritici* that have appeared in new areas, e.g. eastern USA (Chen 2005), South Africa (Boshoff

et al. 2002) and Western Australia (Wellings et al. 2003), as well as Central and northern Europe (Flath and Barthel 2002; Hovmoller and Justesen 2007). The vast and expansive spread of diseases affecting a small number of globally important crops can have important consequences for both local and global food supplies and human health (Hovmoller et al. 2008).

Such generalizations (Figure 1) mask the diversity of food crops, animal breeds, fish populations and genetic diversity that is still maintained and further developed by small-scale farmers, pastoralists and fisherfolk worldwide, and which is available and produced in many of the world's food production systems. Crop and livestock production systems that are often the target of agricultural development are in reality often elements of a larger landscape that comprises a broad range of wild, weedy and feral species that not only play critical roles in securing food production and ecosystem function but which may also contribute significantly to human diets, food security and health, such as many of the wild edible species found in and around aquatic agricultural systems or forests. Wildlife is consumed as bushmeat, and wild leafy and fruit species, and other edible species such as insects and mushrooms found in and around agricultural fields play an important role in feeding populations in many parts of

the world (PAR/FAO 2011). Despite potential health benefits of bushmeat consumption, as the nutrition chapter also indicates, health risks associated with its unsafe handling, storage and growing illegal trade must also be carefully considered (see also the chapter on nutrition in this volume). Agricultural intensification has also often upset the balance maintained by rural communities between sustainably managed natural areas and farmed areas, leading not only to reductions in uncultivated areas but also overexploitation of the resources that remain.

4.1.1 Mixed farming; crop and fish and agroforestry – increasing species diversity

Diverse production systems with a number of different productive components themselves confer multiple benefits. The forms that these can take are many and varied. For example, home gardens, which are characterized by high levels of species diversity in a relatively small space, are highly productive with multiple livelihood, health and biodiversity maintenance benefits (Galuzzi et al. 2010; Box 7 on home gardens). Diversity in livestock production has been shown to confer benefits through improved provision of nutrients, overall productivity, system resilience and income (Morton, 2007). The aquatic rice-based agroecosystems of South and South-East

Asia improve ecosystem function, nutrition and income in many different farming systems (Halwart 1998; Pullin and White 2011; see also Box 2). Integrating trees into agricultural environments helps to realize the full potential of agroforestry ecosystem function and provides marketable products (Garrity et al. 2010).

All alternative approaches to agricultural intensification based on increasing chemical inputs and uniformity of production systems involve increased use of agricultural biodiversity. This increased use takes two forms: (1) the use of different materials adapted to different agronomic practices and reduced inputs, and (2) the use of increased diversity at ecosystem, species and genetic levels (or at landscape, farm and field scales) (PAR/FAO, 2011), i.e. the use of more species, crop varieties, livestock breeds and wild populations. As De Schutter (2010) noted in his report to the UN Secretary General on the role of agroecology in food security, "These approaches involve the maintenance or introduction of agricultural biodiversity (diversity of crops, livestock, agroforestry, fish, pollinators, insects, soil biota and other components that occur in and around production systems) to achieve the desired results in sustainability and productivity." It has been estimated that traditional agricultural landscapes that are complex and rich in agricultural biodiversity still provide as much as 20% of the

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Box 7: Home gardens

Home gardens are estimated to support nearly 1 billion people in the tropics and contain remarkable diversity of food and other utilitarian species – up to a hundred or more species per garden – and offer great potential for improving household food security and alleviating micronutrient deficiencies (Heywood 2013). Efforts to promote nutritious biodiversity through home gardens have been the target of food security and nutrition interventions in many countries (Nielsen et al. 2013; Pudasaini et al. 2013), and may also provide animal products such as chickens, eggs and livestock as in the case of the homestead gardens promoted by Helen Keller International. Some studies have found that a child's nutritional status is associated with the presence of a home garden and that the garden's biodiversity, rather than its size, is the most important factor (Jones et al. 2005). In addition to enhancing food security and nutrition, the presence of home gardens in highly populated areas creates a pleasant and aesthetically pleasing environment, which may have broader health benefits, including mental health benefits, as well (Pushpakumara et al. 2012).

world's food supply (Heywood 2013). This may be a significant underestimate given that it has also been estimated that small-scale producers produce most of the world's food (Pretty and Barucha 2014).

4.2 Global food security, biodiversity and human health

With the growing demand of an expected 9 billion people by 2050, the world still faces tremendous challenges in securing adequate food that is healthy, safe and of high nutritional quality for all, and doing so in an equitable and environmentally sustainable manner (Pinstrup-Andersen 2009; Godfray et al. 2010; Tilman et al. 2011; Foley et al. 2011). Climate change, ecosystems and biodiversity under stress, increasing urbanization, social conflict and extreme poverty all make attaining this challenge difficult.

Despite progress in feeding a growing population, we still live in a world with a highly dysfunctional, and inequitable, food system, where there has been a failure to achieve global food security, in which we have been unable to feed a significant part of humanity adequately, and which continues to contribute to environmental and health problems, high species extinction rates, loss of genetic diversity, and land and ecosystem degradation (Rosin et al. 2012). One major issue is the apparent continuing lack of political will and moral imperative (Horrigan et al. 2002). This is reflected in such continuing problems as the scale of food waste. Of the total food produced, about 30% is lost through post-harvest losses on farms or in the process of marketing, distribution and consumption (Lundqvist 2008). There is clearly significant potential to improve the availability of food and reduce hunger through reducing these losses. In addition to the continued problems of hunger, micronutrient deficiencies undermine the growth and development, health and productivity of over 2 billion people (Micronutrient Initiative

2009). At the same time, according to recent estimates, over 2 billion people worldwide are overweight or obese (Ng et al. 2014).

We face a major global problem associated with the replacement of foods derived from biodiversity with high nutritional significance by globally marketed foods that are higher in energy but less dense in nutrients and other functional factors that often confer some degree of protection against disease. The result is an emerging "double burden"[5] of malnutrition and "hidden hunger"[6] in developing countries. Up to half a million vitamin A-deficient children go blind every year, half of them dying within a year of losing their sight; and iron deficiency is damaging the mental development of 40–60% of children in developing countries. The estimated cost of undernutrition to potential economic development is between US$ 20 and 30 billion annually (Shetty 2010, see also Chapter on nutrition within this volume).[7]

The Declaration of the World Summit on Food Security (FAO 2009) addresses the issue of investments in agriculture highlighting that efforts should focus more on sustainability by supporting sustainable agricultural production and practices aimed at conservation and improved use of the natural resource base and protection of the environment and enhanced use of ecosystem services. Some of the key aspects of improving food security identified by the World Food Summit where agricultural biodiversity is relevant are listed in Box 8 (FAO/PAR, 2011).

4.2.1 Climate change, food security and human health

FAO estimates that food production over the next 40 years will need to increase by about 70% in order to cope with increasing population and dietary demands for more animal-sourced foods. Over the same time frame, climate change is expected to cause significant reductions in not only crop

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[5] The Double burden of undernutrition and overnutrition.

[6] Hidden hunger – a lack of essential vitamins and minerals often results in "hidden hunger" where the signs of malnutrition and hunger are less visible in the immediate sense. See also chapter on nutrition in this volume.

[7] Shetty P. (2010) The challenge of improving nutrition: fact and figures. SciDevNet. http://www.scidev.net/en/health/the-challenge-of-improving-nutrition/features/the-challenge-of-improving-nutrition-facts-and-figures-1.html

Box 8. Key aspects of improving food security identified by the World Food Summit Declaration which particularly involve agricultural biodiversity

- Increase production including through access to improved seed and inputs; reduce pre- and post-harvest losses; pay special attention to smallholders.

- Implement sustainable practices, including responsible fisheries, improved resource use, protection of the environment, conservation of the natural resource base and enhanced use of ecosystem services.

- Ensure better management of the biodiversity associated with food and agriculture; support the conservation of and access to genetic resources, and fair and equitable sharing of the benefits arising from their use.

- Recognize that increasing agricultural productivity is the main way to meet the increasing demand for food, given the constraints on expanding the amount of land and water used for food production.

- Mobilize the resources needed to increase productivity, including research, and the review, approval and adoption of biotechnology and other new technologies.

- Enable all farmers, particularly women and smallholder farmers from countries most vulnerable to climate change, to adapt to, and mitigate the impact of, climate change.

- Support national, regional and international programmes that contribute to improved food safety and animal and plant health.

- Encourage the consumption of foods, particularly those available locally, which contribute to diversified and balanced diets.

- Address the challenges and opportunities posed by biofuels.

Reference: FAO/PAR 2011

production but also the nutritional content of foods, particularly in respect of production of C3 grains and legumes, which provide a large portion of the global population with their primary source of iron and zinc. Increasing CO_2 levels will lead to reductions ranging between 5% and 10% in the iron and zinc content of the edible portion of these crops, possibly increasing the burden of disease for these deficiencies that already cause a loss of 63 million life-years annually (Myers et al. 2014). Climate change is also expected to impact heavily on fish and livestock resources. Livestock

in particular will be impacted, especially in arid and semi-arid regions, including effects on pasture species composition and forage quality. Further, increasingly frequent and severe pest and disease attacks are expected. Bebber et al. (2013) highlight poleward movements of pests and pathogens to new areas from 1960 onwards. While soil-borne pathogens and diseases are likely to be more of a problem under increasing temperatures (Jaggard et al. 2010), Tirado et al. (2010) and Lake et al. (2012) also highlight the likelihood of climate change impacts on food contamination

and foodborne diseases through the increased incidence of existing pathogens or the emergence of new pathogens. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change[8] concluded that climate change is affecting all aspects of food security and agriculture, and that impacts on crop yields are already evident across several regions of the world.

Agricultural biodiversity, including utilization, and maintenance of plant genetic resources for crop improvement and diversification, is an important strategy in dealing with ongoing climate change and food security (FAO 2015). In addition to their nutritional potential, Foley et al. (2011) highlight important opportunities to improve crop yield and resilience, by improving the myriad neglected and underutilized species and conserving crop diversity as well as crop wild relatives. Bambara groundnut (*Vigna subterranea*) is well known for its drought tolerance and ability to grow in harsh and marginal environments, as are a number of minor millets commonly grown in South Asia. Ca̰nihua (*Chenopodium pallidicaule*), an underutilized Andean grain, has significant frost tolerance, while the perennial seabuckthorn (*Hippophaerhamnoides*) has considerable tolerance to abiotic stresses like frost and cold, assumed to be associated with the high levels of ascorbic acid and *myo*-inositol it contains (Padulosi et al. 2011; Yadav et al. 2015).

Crop wild relatives represent one of our most precious resources in trying to deal with climate change, while at the same time improving the nutritional quality of crops and food (Hunter and Heywood 2011). As well as containing genetic traits for enhanced nutritional quality, they also have novel pest resistance and tolerance to heat, drought and salinity, among other traits (Godfray et al. 2010; Hunter and Heywood 2011; Hodgkin and Bordoni 2012). Crop wild relatives have already provided many useful genes for crop improvement, which have been introduced to improve varieties through conventional breeding techniques in crops as diverse as wheat, potato, tomato and lettuce (Hajjar and Hodgkin, 2007). However, crop wild relatives, as well as other genetic diversity, cannot be taken for granted and they are currently under threat from changing climate (Jarvis et al. 2008; Lira et al. 2008; Hunter and Heywood, 2011).

Negative impacts on crop yields or when crops fail as a result of climate change may mean a greater role for wild food species for food security and nutrition in the future. Yet climate change is also likely to negatively impact on wild edible species themselves. A recent study (Carr et al. 2013) of wild plant and animal species of the Albertine Rift region of East and Central Africa combined climate change vulnerability and use assessments to identify those species utilized by communities

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Box 9. Agro-ecological resilience after Hurricane Mitch in Nicaragua

In October 1998, Hurricane Mitch hit Central America, causing damage worth at least US$ 6.7 billion. Over 10000 people died and 3 million were displaced or left homeless. In Nicaragua, a comparative study was carried out using participatory approaches, which involved farmers and local NGOs, on the levels of resistance to the hurricane of "sustainable" farms using a variety of sustainable land management practices, and neighbouring "conventional" farms that lacked those practices. On average, agro-ecological plots on sustainable farms had more topsoil, higher field moisture, less erosion and lower economic losses after the hurricane than the plots on conventional farms. The differences in favour of agro-ecological plots tended to increase with increasing levels of storm intensity, increasing slope and years under agro-ecological practices, though the patterns of resistance suggested complex interactions and thresholds.

(Holt-Gimenez 2002. See also the Chapter on disaster risk reduction in this volume)

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[8] http://www.ipcc.ch/report/ar5/

most likely to be negatively impacted by climate change. The study found that 14 amphibians (13% of those assessed), 17 birds (2%), 19 freshwater fish (3%), 24 mammals (7%), 33 plants (36%) and 25 reptiles (15%) of known importance for use, including food, were among those at greatest vulnerability to climate change impacts. For these reasons, better knowledge of how wild food species are likely to be impacted by climate change will be critical for both biodiversity conservation and developing sustainable use and livelihood strategies.

More biodiversity-friendly crop and food production mitigation strategies that might contribute to reduced methane and nitrous oxide emissions could include improved soil management practices, such as the enhanced use of mulching, cover cropping, conservation agriculture, more efficient N utilization, as well as improved rice cultivation and manure management practices (Reynolds and Ortiz 2010; Cribb 2010). Among other things, such strategies will require new crop varieties, including breeding of varieties with reduced carbon dioxide and nitrous oxide emissions, different crop combinations, and modified management systems and agronomic practices (Hodgkin and Bordoni 2012; Reynolds and Ortiz 2010).

5. Conclusions

The increase in food production achieved over the past decades has been accompanied by significant losses in agricultural biodiversity, as production systems (crop and animal) have become more uniform and dependent on externally derived chemical inputs. The loss of agricultural biodiversity has been associated with reductions in ecosystem service provision, often accompanied by negative impacts on human health. It is clear that agricultural biodiversity can make significant contributions to improving food security, nutrition and human health, and will play an essential role in achieving sustainable food production and improving the productivity needed to meet the challenges of climate change. The chapter points to a number of areas of work that can help to improve the contribution of

agricultural biodiversity to food security and human health. These are listed below:

1. There are still significant knowledge gaps in relation to the optimum use and deployment of agricultural biodiversity in production systems. The ways in which agricultural biodiversity can improve ecosystem-regulating and-supporting services is still poorly understood in terms of how to achieve real benefits in different production systems. This will involve a substantial programme of integrated transdisciplinary research, which fully involves producers, and links the production of improved crop and livestock materials to the adoption of agronomic practices that support biological functions in production systems.

2. The importance of diversity-rich production systems and diversification is widely recognized in respect of their contribution to food security, sustainability, adaptation to change and human health. However, the ways in which such approaches can be adopted with direct benefits to producers who are committed to uniform non-diverse approaches has not been clearly established. This will involve taking account of biological, social, economic and political dimensions, and of recognizing both producer and consumer concerns.

3. Even when practices that provide food security, health and diversity benefits have been identified (such as alternatives to the use of pesticides or of reducing the pollination deficit through improved pollinator diversity), there remain economic, policy and other barriers to the adoption of such practices, especially at the national level. These need to be identified and alternatives adopted. It will be especially important to investigate ways in which the full economic value of the use of agricultural biodiversity can be measured and rewarded.

4. A number of international policies and instruments have been developed to take account of the importance of agricultural biodiversity. However, there remain significant challenges in achieving full recognition of its importance in, for

example, climate change adaptation agendas[9] and the global food security debates of the Committee on World Food Security (CFS). A key objective of international policy efforts should be to ensure the enhanced availability of agricultural biodiversity to users.

5. Sustainable development goals and targets, and the post-2015 Development Agenda provide an important global entry point to better recognition of the ways in which agricultural biodiversity and health co-benefits can be maximized. The goals of ending hunger, malnutrition, increasing agricultural productivity and incomes, ensuring sustainable and resilient food production systems, and maintaining genetic diversity provide a framework for developing a compelling agenda on the value of the improved use of agricultural biodiversity.

6. The growing concerns of consumers about food production approaches and the demand for environmentally friendly approaches that provide adequate rewards for rural communities and safe food provide important entry points for exploring the contributions that agricultural biodiversity can make to these wider social objectives.

9   The recent adoption of guidelines on the integration of genetic diversity in climate change adaptation planning by the FAO Commission on Genetic Resources for Food and Agriculture is a beneficial development.