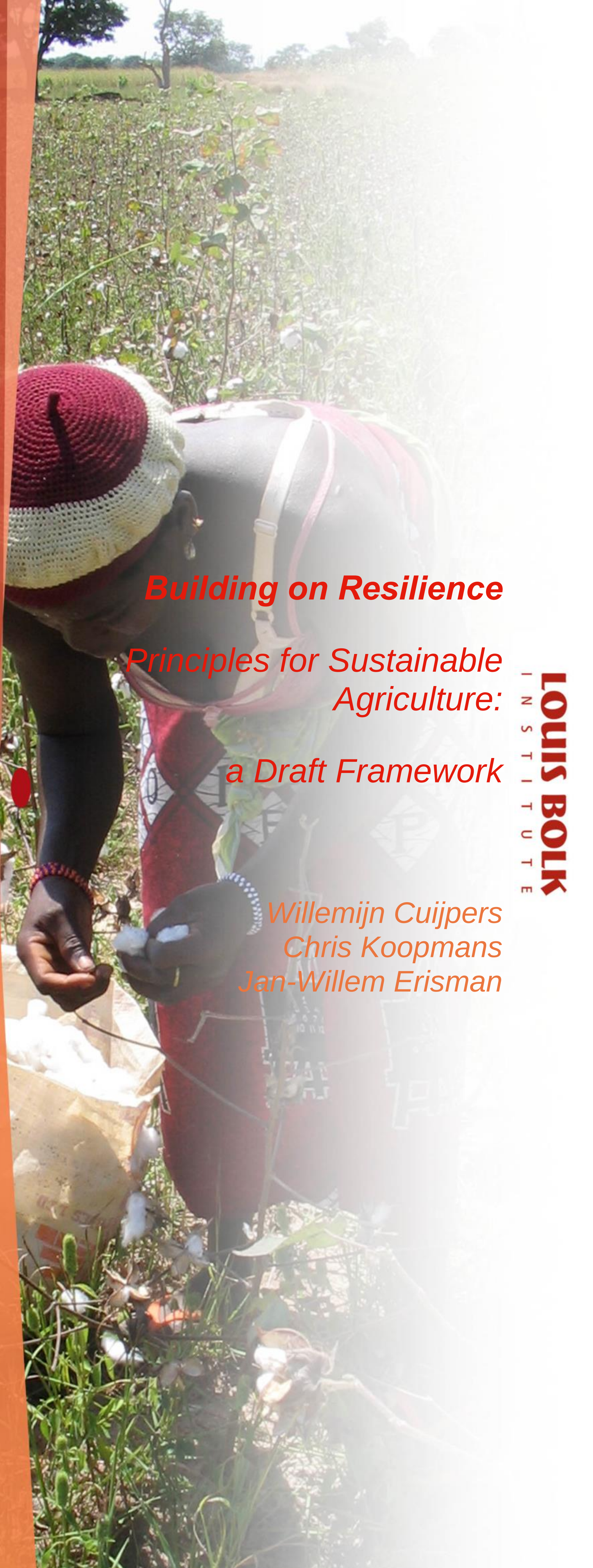

Building on Resilience

Principles for Sustainable Agriculture: a Draft Framework

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Preface

This paper introduces and explores the possibilities of a concept that may bridge apparent divergences within a sustainable agriculture approach. Sustainable agriculture concepts may depart from different paradigms, varying from securing global and local resource availability, to maintaining functional integrity of farming systems. Likewise, many different terms have been suggested to address the sustainability of farming systems. Discussions on sustainability may result in apparent contrasting views on intensification versus extensification and land-sharing versus land-sparing. In order to develop more sustainable ways of cultivation, creativity and out-of-the-box thinking is necessary, and no agricultural technology can *a priori* be labelled as being good or bad. For each situation, the soil, crops, farmers, landscapes and product chains are different and pose different challenges and possibilities for increasing sustainability. In this paper, we will depart from the concept of resilience, and from this base we will start to explore principles of sustainable agriculture.

Resilience is the capacity of a system to undergo disturbances, and at the same time maintain its functions. More resilient ecosystems are able to absorb larger disturbances without changing in fundamental ways. Resilient systems are able to adapt, to renew, to self-organize and to learn from change and disturbance. Ecological resilience plays a key role in the sustainability of farming systems. When loosing resilience, vulnerability increases, and the system is not able to exert its functions anymore as soon as disturbances occur. Not only production is lost, but also regulating and supporting functions, that are necessary for sustainable use of resources for future generations within the boundaries of one earth. Ecological resilience is the principle that connects both the production function of agricultural systems, and the regulating and supporting functions that are needed to sustain production for future generations.

This report has been written as a background paper for WWF-Netherlands, in order to provide input for the development of a vision on sustainable agriculture. As one of the largest nature conservation organisations, WWF's main focus is on protecting specific key areas and priority species. Agriculture has been identified as one of the main drivers of biodiversity loss, and as such influences WWF's mission and reach. The focus of this paper is on the development of global (high-level) guidance on sustainable agriculture via a set of agricultural principles. The scope of the assignment is restricted to land-use activities that encompass the production of crops and livestock, including pastoralism, but excluding wild foods and aquaculture. The focus is on the ecological aspects of sustainability, as social-ethical and economic aspects are captured in a higher level vision on sustainable land-use.

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Willemijn Cuijpers, Chris Koopmans and Jan-Willem Erisman

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Summary

Agriculture plays a dominant role in global land use. Agriculture not only occupies a great deal of the earth' surface, but also modifies natural ecosystem functioning. Land transformation has resulted in loss and fragmentation of habitat in many different ecosystems. Changes in land-use are one of the main drivers of global biodiversity loss. Both natural ecosystems and agricultural ecosystems are important providers of ecosystem services. Although external inputs in farming systems do partly replace natural ecosystem services, sustaining agricultural production levels on the long term depends on the maintenance of these natural ecosystem services. Loss of natural services, through loss of nutrient cycling, decreased water storage, increasing erosion, decreasing disease suppression and decreasing pollination will negatively affect production levels.

Restoring these functions is necessary in view of future trends and challenges. Estimates of the global food demand by 2050 predict the need for an increase in food production with 70 percent or more. As possibilities for expansion of agricultural land are limited, sustainable intensification of agriculture has to take place. Changes in diet could greatly affect the possibilities for feeding a larger global population, as well as diminishing the amount of food waste. Supporting the role of smallholders is essential in securing more food, as yield gaps are most pronounced in smallholder farming. Current agriculture is highly dependent on non-renewable energy sources, for manufacturing inorganic fertilizers, field machinery and transport. The necessary increase in global food production should facilitate a shift towards less dependency on non-renewable energy, by maximizing nitrogen fixation and recovery of nutrients. Global depletion of mineral reserves of phosphates and essential micronutrients should be slowed down in order to safeguard future food production.

The notion of sustainable agriculture has gradually developed from the 1960s onward, resulting in a wide array of terms and definitions. The sustainability paradigm as defined in Agenda 21 addresses three areas of sustainability: ecological, social and economic, that could be integrated by the principle of good governance. This paper mainly focuses on key factors of ecological sustainability, as other domains are captured in a higher level vision of sustainable land-use. The framework for developing principles of sustainable agriculture is based on the concept of agroecosystem resilience. Resilience is the capacity of a system to undergo disturbance and maintain its functions and controls. Agroecosystems need resilience in order to cope with change and disturbances. Resilience protects farming systems against loss of production, and secures future production by maintaining the regulating and supporting ecological functions of the farming system. For many ecosystem processes, the soil is the central regulatory centre. A healthy soil has not only the right physical and chemical properties, but harbours a wide diversity of soil organisms, that support a variety of functions. Starting from a resilient and healthy 'living soil', other principles can be deduced. Both below-ground and above-ground biodiversity provide different functions needed to sustain ecosystem services like nutrient cycling, water storage, erosion prevention, disease suppressiveness, pollination, climate regulation and animal health and well-being.

1 The effect of agriculture on habitat loss, biodiversity and ecosystem services

Agriculture plays an important role in global land use. Future development of global land use has to take into account the one planet boundaries. From the understanding that biodiversity is vital for human livelihoods, and habitat loss is a major driver of biodiversity loss, it becomes necessary to understand the relationship between agriculture, habitat loss, biodiversity, and ecosystem services. Although biodiversity is also considered as part of the ecosystem services, it is addressed separately in the following part, as it is a major focus of conservation policy.

1.1 The scope of agriculture's land use

At present, agriculture occupies about 38% of the Earth's terrestrial surface: croplands covering 1.53 billion hectares (12% of the Earth's ice-free land) and pastures covering another 3.38 billion hectares (26%). This land use comprises those areas on Earth that are most suited for farming. The remaining part of the terrestrial surface is covered to a large extend by deserts, mountains, tundra's, cities and ecological reserves (Foley, 2011). When exploring the possibilities to expand the area of pastures into new (and for pasture suitable) areas, current land-use of these areas is mainly forests, especially in sub-Saharan Africa (88 percent) and Latin America (87 percent) (Steinfeld et al., 2006). Global estimates of land suitability for cropland expansion conclude that although there is a cropland 'reserve' of 120%, mainly in tropical South America and Africa, much of this land is under forests or in protected areas (Ramankutty et al., 2002) The further expansion of pastures and arable land into natural ecosystems will have huge ecological consequences.
Global food production is influenced by allocation of crops to direct food production for human consumption, and indirect food production as animal feed. It is estimated that, of all crops produced globally, 62% is allocated to direct human food production, 35% to animal feed and 3% to bioenergy, fibers and seed. Many ecosystems are directly dominated by humanity, and most of the functioning and structure of Earth's ecosystems cannot be understood without recognition of human influence (Sanderson et al., 2002; Vitousek et al., 1997). In 1995, more than 1.1 billion people were living within the Earth's 25 biodiversity 'hotspots'. The 25 hotspots identified are high in species endemism and low in pristine vegetation (<30% remaining), appointing them as high-priority terrestrial ecosystems for conservation. Additionally, three areas of tropical forest (Upper Amazonia/Guyana Shield, the Congo Basin, and the New Guinea/Melanesian Islands) are identified as the most pristine of all terrestrial ecosystems, with a high degree of species endemism. In 1995, nearly 75 million people were living within these three major tropical wilderness areas (Cincotta et al., 2000). The Millennium Ecosystem Assessment states that more than 45% of 100 000 protected areas have more than 30% of their land area under crops (Scherr and McNeely, 2008). However, the influence of agriculture extends beyond the modification of the Earth's ecosystems through land transformation and impacts on biodiversity. Agriculture has also modified the ecosystem services on which humanity depends. Provisioning ecosystem services deliver food, fodder, fuel and pharmaceuticals. Regulating and supporting services are necessary to sustain production and prevent land degradation. Cultural services provide humankind with aesthetic, spiritual and educational values. Agricultural systems are

both generators and receivers of ecosystem services. The Millennium Ecosystem Assessment (MA) found a deterioration of many of these natural services that are essential to the functioning of agricultural systems (MA, 2005A). Future agricultural production will have to focus explicitly on ecologically sensitive management systems, while at the same time securing food production. Agricultural transformation has to be ‘doubly green’, to meet the twin challenges of food security and environmental sustainability (Foley, 2011; World Bank, 2008).

1.2 The effect of agriculture on habitat loss

Land transformation has resulted in loss and fragmentation of habitat in many different ecosystem types. Habitat fragmentation has additional consequences for biodiversity and ecosystems beyond the loss of habitat area alone (Sanderson et al., 2002). In the past 300 years land transformation for agricultural expansion and timber extraction have caused a net loss of ~700 to 1100 million ha of forest. Highly managed forests, such as timber and oil-palm plantations, have replaced natural forests and cover at present ~190 million ha worldwide (Foley et al., 2005). The expansion of global agricultural land area during the 1980s and 1990s occurred primarily in developing countries. Total agricultural land (croplands, pastures and temporary agriculture) in developing countries increased by 629 million ha, while in the same period developed countries lost 335 million ha. Forest-rich tropical countries like Brazil, Indonesia and Malaysia have responded quickly to increasing demands for crops such as sugarcane, soybeans and palm oil. In 2012, Indonesia and Malaysia together delivered 85% of global production of palm oil. Brazil is the largest producer of sugarcane (38% of global production), and second largest producer of soy (26% of global production) (FAOSTAT, 2013). Acreage conversion for soy (24.9 million ha in 2012) and sugarcane (9.4 million ha) in Brazil is expected to react to changing demands for soy (as a result of United States corn ethanol production) and sugarcane (as a biofuel feedstock). Sugarcane estimates are rather homogeneous, but estimates for soy acreage vary considerably. Acreage increase is expected to be higher in regions of ecological importance, like the Amazon border (Hausman, 2012). The environmental impacts of this expansion of tropical croplands will vary substantially, depending on the types of land being cleared and cultivated. Analysis of agricultural expansion in the tropics revealed a net increase in agricultural land of more than 100 million ha during the 1980s and 1990s. Rice, maize, soybeans and oil palm showed the most dramatic increase, while areas of millet, cassava, groundnuts and beans remained steady. More than 55% of this new agricultural land came from intact forests. An additional 28% of new agricultural land came from disturbed forests. Disturbed forests have previously been affected by shifting cultivation, logging, fuel wood collection, or other forms of gradual degradation. Shrubland conversion (including cerrado, savannas, woodlands, shrublands and grasslands) was responsible for most of the remaining expansion. The sources of new agricultural land are not equal for all tropical regions. In South America and East Africa, shrublands are substantial sources of new cropland. In West-Africa and South Asia, disturbed forests are the main source, while in forest-rich regions in Latin America, Central Africa and South-East Asia intact forests are cleared for new agricultural land. In Latin America, cattle pastures accounted for ~42 million ha expansion of agricultural land, while sugarcane and soybeans were responsible for the majority of cropland increase (~5 million ha) in South-America. Africa has less cropland than other regions, and major crops are often planted in subsistence farming systems, including sorghum, maize, millet, cassava, groundnuts, rice, coffee and yams. In Southeast Asia, tree plantations cover a large portion of total agricultural land. The area under tree plantations increased from 11 million to 17 million ha between 1980 and 2000. In the 1990s oil palm was responsible for 80% of this expansion. The origins of new plantations in this critically important area vary from agricultural lands to disturbed and intact forests (Gibbs et al., 2010).

1.3 Agriculture's impact on biodiversity

Global biodiversity is rapidly declining, as a complex response to various human-influenced changes in the global environment. Over the past few hundred years, species extinction rates increased by as much as 1,000 times background rates that were typical over Earth's history. Some 12% of bird species, 23% of mammals, and 25% of conifers are threatened with extinction and even higher levels of threat (52%) are found in the cycads, a group of evergreen, palm-like plants. Resilience and adaptability of domesticated species is eroded by a substantial reduction in genetic diversity. Biodiversity contributes directly to the provisioning, regulating and supporting ecosystem services that sustain human well-being. The Millennium Ecosystem Assessment states that there is also "established but incomplete evidence that reductions in biodiversity reduce ecosystem resilience or the ability of an ecosystem to recover from a perturbation" (MA, 2005A). Gradual biodiversity loss can move ecosystems towards tipping points, were resilience is lost and sudden 'surprises' can result in irreversible ecosystem degradation.

The five most important drivers of changes in global biodiversity are changes in land use, atmospheric CO_2 concentration, nitrogen deposition, climate, and biotic exchanges (deliberate or accidental introduction of organisms to an ecosystem). Scenarios of biodiversity change in 10 terrestrial biomes for the year 2100 reveal that changes in land-use is the most severe driver of biodiversity change, through the impact on habitat availability and consequent species extinction. Most land-use changes will occur in tropical forests and temperate forests of South America, while least land-use change is expected in arctic and alpine biomes, and in northern temperate forests. Habitat modification is modest in desert and boreal forest, and intermediate in savannas, grasslands and Mediterranean ecosystems. Not all biomes are equally affected by all drivers, and biomes will differently react to changes in different drivers as well. It is expected that all biomes will experience the same change in CO_2 concentration, but nitrogen deposition will be largest in the northern temperate zones. Temperature is expected to change most dramatically at high latitudes (arctic and boreal zones), least in the tropics, and intermediate in other biomes, while changes in precipitation are highly uncertain. Biotic exchange is directly linked to human activity (Sala et al., 2000).

Grasslands and savannas are the most water-limited biomes, with mixtures of different plant types (C_3 and C_4 plants), that are expected to receive the highest impact of elevated CO_2 on biodiversity. Elevated CO_2 levels increase water-use efficiency of so-called C_4 species, thus giving them a competitive advantage over C_3 species. Temperate forests, boreal forest, arctic and alpine biomes are expected to receive the largest impact from increased nitrogen deposition, as they are naturally the most nitrogen-limited biomes. Biodiversity in deserts and tropical forests are expected to respond least to nitrogen deposition, as plant growth is strongly limited by water and phosphorus respectively. Climate change is expected to have the largest effect in biomes characteristic of extreme climates, although all biomes will be sensitive. Small changes in temperature and precipitation in arctic, alpine, desert and boreal forest will result in large changes in species composition and biodiversity. The sensitivity of biomes for biotic introductions will be least in the severe environment of arctic and alpine ecosystems. Also, the high diversity of tropical biomes provides resilience towards successful biotic introduction. Biomes that have long been isolated such as southern temperate forests and Mediterranean biomes are expected to be most sensitive to biotic exchange (Sala et al., 2000). Conservation of biodiversity is essential as source of biological resources, for maintenance of ecosystem services and for maintenance of resilience. These benefits of biodiversity have to become reflected in resource management and decision-making, in order to slow down the current rate of biodiversity loss (MA, 2005A).

Box 1.1: Trade-offs of habitat and biodiversity loss: wild food access and availability

Although the bulk literature on food security deals with cultivated foods, wild foods are key to many agricultural communities and provide a significant proportion of the global food basket. They are important sources of micronutrients, and critical suppliers of vitamins during seasonal lean periods. Wild foods are not just taken from their natural environment, but actively managed and maintained, ranging from intentionally sowing plant species, enriching forests with fruit and medicinal trees, to transplanting species to home gardens. Wild foods provide a ‘hidden harvest’, being a resilient source of both food and earnings. Many of these species are found in agricultural fields. Well-known sources of wild foods are paddy fields; in Thailand farmers harvest wild herbs, insects and vines; in Bangladesh paddies are sources of greens and fish, and in Cambodia, wild fish provides up to 70% of protein intake. Wild foods are particularly important to landless poor and other vulnerable groups. Compared to cultivated plant species, wild foods provide an enormous diversity. A study of 12 indigenous communities across both industrialized and developing countries, showed a mean use of 120 wild species per community, rising to 315 species for Karen farming communities in Thailand. This great diversity may play a critical role as buffer against food stress caused by climate change (Bharucha and Pretty, 2010). In many agricultural landscapes, wild foods decline through homogenisation of landscapes and loss of local ecological knowledge. Expansion of intensive agriculture applying herbicides directly threatens wild plant foods in fields. In areas of malnutrition and hunger, wild foods are threatened by unsustainable harvesting methods. Local ecological knowledge, indigenous access and harvesting rights and scientific knowledge on sustainable yields of plant and animal species should be combined to provide a framework for sustainable wild food management.

1.4 Agriculture's impact on ecosystem services

1.4.1 Nature as provider of ecosystem services

Farming systems depend on a suite of ecosystem services provided by natural ecosystems. Supporting and regulating services provided by nature include genetic biodiversity providing the raw material for breeding crops and livestock, vegetation cover in upstream watersheds affecting the amount, quality and stability of the water supply to downstream agricultural systems, crop pollination by wild pollinators, and natural enemies that move into agroecosystems from natural vegetation. Biological control of pest insects in agroecosystems is an important ecosystem service that is often supported by natural ecosystems. Non-crop habitats provide the necessary shelter and food resources to sustain populations of natural predators and parasitoids. Pollination is another important ecosystem service provided by natural habitats. Another essential ecosystem service is the provision of sufficient quantities of clean water, as agriculture accounts for about 70 percent of global 'blue' water use. Perennial natural vegetation plays an important regulating role in the capture, infiltration, retention and flow of water on a landscape level (Power, 2010).

1.4.2 Agriculture as provider of ecosystem services

Agricultural ecosystems provide humans with food, forage, fuels and pharmaceuticals that are essential to human well-being. These ecosystem services are usually called provisioning services, and have been regarded as the single most important role of farming (Scherr and McNeely, 2008). Farmers influence the capacity of the farming system to deliver ecosystem services. But farms not only sustain provisioning services (food, feed, fuel or pharmaceuticals) but also provide supporting, regulating and cultural services. Supporting and regulating ecosystem services are mostly biologically regulated. Soil management is a key factor in many of the provisioning and supporting ecosystem services provided by farming systems. Maintaining a healthy soil is an important strategy for many supporting and regulating services: water infiltration and -retention, resistance to erosion, nutrient cycling and retention, and disease suppressiveness (Powlson et al., 2011). Farmers actively manage soil health to secure future production, by enhancing regulating and supporting services of soils.

1.4.3 External inputs replacing ecosystem services

In the process of agricultural intensification, farmers have replaced much of the regulating and supporting ecosystem services that originally were provided for by soil biota, by human external inputs. Decomposing functions of soil organisms have been replaced by inorganic fertilisers, disease suppressive functions of soil organisms and natural biodiversity have been replaced by chemical crop protection agents and the function of 'ecosystem engineers' like earthworms in building soil structure has been diminished by tillage. (Giller et al, 1997). These external inputs have decreased farmers dependency on natural ecosystem processes and biodiversity. They have been drivers of the enormous production increase that agriculture has seen in the last century. And they have also made soil health and sustaining a 'living soil' of less concern for farm management. However, as on-farm soil biodiversity gradually spirals down, resilience is negatively affected, until a tipping point is reached where soil degradation occurs. At that point production levels can only – if possible – be re-established at very high costs.

1.4.4 Loss of ecosystem services caused by agriculture

Agricultural ecosystems around the world vary tremendously in structure and function. They include annual crop monocultures, perennial orchards, grazing systems, arid-land pastoral systems, tropical shifting cultivation systems, smallholder mixed cropping systems, paddy rice systems, tropical plantations (like oil palm, coffee, cacao), agroforestry systems and species-rich homegardens. Although a gradual change towards intensification of agriculture has taken place, agricultural systems are still very diverse. This variety of agricultural practices results in different adverse effects on regulating and supporting ecosystem services provided by natural ecosystems (Power, 2010). Loss of natural habitat and biodiversity loss occurs in most agricultural systems. But the extent to which agricultural systems negatively influence supporting and regulating ecosystem services differs greatly.

Loss of nutrient cycling Agriculture has both on a global and on a local scale profound effects on biogeochemical cycles and nutrient availability in ecosystems. Nitrogen (N) and phosphorus (P) are most limiting for biological production in both natural and agricultural ecosystems. As a result of fertiliser applications, the amount of N and P in the biosphere has greatly increased, with complex, often harmful effects on natural ecosystems (Power, 2010). Excessive nutrient loading associated with nitrogen and phosphorus fertilisers has resulted in groundwater pollution, increased nitrate in drinking water, eutrophication (a process in which excessive plant growth depletes oxygen in water), acidification of freshwater and terrestrial ecosystems, large and at times toxic algal blooms, and ‘dead zones’ in coastal marine ecosystems (MA, 2005b). Nitrogen deposition is one of the main drivers of biodiversity change (Sala et al., 2000). Ecological resilience of wetlands is slowly decreasing as a result of nutrient loading, which may result in sudden catastrophic shifts from a state where they retain nutrients, to one in which they release nutrients or emit the greenhouse gas nitrous oxide (Carpenter et al., 2005) Restoring ecosystem services can be supported by soil nutrient management strategies, including prevention of nutrient losses, enhancing nutrient storage and buffering, and increasing nutrient efficiency of agroecosystems.

Changing water flow and decreased storage Agriculture modifies the plant species composition and below-ground root structure, the production of litter, the extent and timing of plant cover, and the composition of the soil biotic community: factors that influence to a major extent the water infiltration and retention in soil. The intensity of agricultural production and management practices affect both the quantity and quality of water in agricultural landscapes (Power, 2010). Around 66% of all water withdrawn for direct human use is attributed to agriculture. Increasing irrigation efficiency results in smaller amounts of this water returning to downstream watersheds and rivers, and higher ‘consumptive use’ resulting in a flow to the atmosphere through evaporation or transpiration. Transfer of water between river systems can also reduce downstream water availability for some basins. These changes have altered water regimes, with substantial declines in discharges in some of the world’s largest rivers, including the Yellow, Indus, Nile, Ganges and Rio Grande

(Gordon et al., 2010). Wetlands are particularly challenging ecosystems in relation to agricultural water management. Both nearby and further afield changes to hydrology can have major effects of wetlands that are dependent on either groundwater or surface water and direct rainfall (Gordon et al., 2010). By 1985, an estimated 56-65% of inland and coastal marshes had been drained for intensive agriculture in Europe and North America, 27% in Asia, 6% in South America and 2% in Africa (MA, 2005b) Poor soil and water management, and the unsuitability of many soils for irrigation, have resulted in salinization and land degradation extending over all the continents. Irrigation has resulted in the accumulation of salts in the rooting zone of arable land, as high rates of evapotranspiration draw soluble salts from deep layers of the soil profile. The water and salt balance has also changed in regions where dryland agriculture – growing crops without irrigation in areas with less than 300 mm rainfall per year – is practiced after forest clearance (Rozema and Flowers, 2008) According to the FAO, the total global area of salt-affected soils was 831 million hectares at the turn of the century. Although it is generally assumed that saline soils occur under arid and semi-arid climates, these soils are found in various climatic zones (Rengasamy, 2006). Clearing of woody vegetation for pastures and crops can also lead to salinization. Forest provide important regulating ecosystem services by consuming rainfall, limiting groundwater recharge, and keeping groundwater tables low enough to prevent salt from being carried upward through the soil. Salinization seriously hampers agricultural production, and finally results in the abandonment of agricultural land. Intensification of agriculture has also increased pressure on inland water ecosystems through pesticide leakage from cultivated lands (MA, 2005).

Increasing erosion Soil erosion is a natural geological phenomenon, that has created the vast fertile soils of alluvial flood plains and loess plateaus around the world. However, the accelerated soil erosion, exacerbated by human perturbations, is a destructive process. It depletes soil fertility, degrades soil structure and reduces the rooting depth of plants (Lal, 2003). As a result, the diversity of plants, animals and microorganisms is diminished. Ultimately, the resilience of the entire ecosystem is threatened (Pimentel and Kounang, 1998) Global assessments of the influence of erosion and deposition on carbon dynamics have had contrasting outcomes. Recent analysis of soil erosion based on watershed-scale processes, considers soil erosion as a net carbon sink, not a source (Van Oost et al., 2007).

Water erosion, wind erosion, chemical erosion and physical erosion play different roles in different biomes, and vary in the extent to which they are attributed to agricultural management. It is estimated that approximately 75 billion tons of fertile soil are annually lost from global agricultural systems (Pimentel and Kounang, 1998) Water erosion, either causing loss of topsoil, or causing terrain deformation by rills and gullies, is by far the most important type of soil degradation, affecting about 1100 M ha worldwide (56% of the total area affected by soil degradation). Around 225 M ha is so degraded by water erosion, that it is no longer suitable for agriculture (Oldeman, 1992). Water erosion selectively removes the fine organic particles from the soil, leaving behind large particles and stones (Durán Zuazo and Rodríguez Pleguezuelo, 2008). Deforestation is the most important cause (43%), followed by overgrazing (29%) and agricultural mismanagement (24%). Wind erosion, characterised by either loss of topsoil, terrain deformation or overblowing, is most pronounced in arid and semi-arid zones, usually on coarse textured soils with a limited vegetative cover. Global extent of soils affected by wind erosion is around 550 M ha (28% of total degraded area). Wind erosion is mainly caused by overgrazing (60%), followed by agricultural mismanagement (16%), over-exploitation of the vegetative cover for domestic use (16%) and deforestation (8%). Chemical soil degradation occurs either through loss of nutrients and/or soil organic matter on ~240 M ha worldwide (representing 30% of degraded soils in South America) or through salinization, which is the most dominant type of chemical soil degradation in Asia. Chemical soil degradation is mainly caused by agricultural mismanagement (56%) and deforestation (28%). Physical soil degradation affects 'only' 83 M ha of soils (4% of the soil degraded area), and is characterised by compaction, sealing and crusting. Nearly 33 M ha is located in Europe, where the main causal factor is agricultural use of heavy machinery. Sealing and crusting is often a result of cattle trampling and insufficient vegetation cover, and is mainly found in Africa and Asia. Waterlogging is mainly caused by human intervention in natural drainage systems, and is mainly found in Central and South America. Physical soil degradation is mainly caused by agricultural mismanagement (80%) and overgrazing (16%) (Oldeman, 1992).

Land which is covered by plant biomass, living or dead, is protected and will experience reduced soil erosion. Vegetation is the main component of ecosystem biomass, followed by belowground microbial biomass. Maintenance of vegetation is one of the main principles to prevent soil erosion. In forested areas, a minimum of 60% forest cover of the landscape is necessary to prevent soil erosion and landslides. Another factor influencing the susceptibility to erosion is soil structure. Soils with medium to fine texture, low organic matter content, and weak structural development are most easily eroded. Principles for preventing soil erosion should enhance soil organic matter contents (Pimentel and Kounang, 1998).

Decreasing disease suppression and pollination Many farming systems have sought to eliminate wild species from their lands in order to reduce the negative effects of pests, predators and weeds. (Scherr and McNeely, 2008). Some farming systems like home gardens may be notably exceptions to this rule, where usual distinctions between 'wild' and 'cultivated' species become blurred. In intensive farming systems, crop protection with agrochemicals has resulted in pesticide residues in surface and groundwater, degrading water provisioning services and continuing biodiversity loss. Biodiversity loss includes loss of non-target species, natural enemies and pollinators, not only affecting natural habitats, but decreasing agroecosystem resilience.

Changing climate Land transformation contributes ~20% to current anthropogenic CO_2 emissions, and more substantially to increase in greenhouse gases methane and nitrous oxide. Analysis of global CO_2 concentrations has shown that for thousands of years CO_2 concentration was more or less stable at 280 ppm. From 1800 onwards it has increased exponentially, until current 360 ppm (Vitousek, 1997). The increase has predominantly been caused by two human activities: land use and fossil fuel burning. The global release of soil organic carbon from agricultural activities has been estimated at 800 Tg C yr^{-1} (T = tera = 10^{12}) Soil biological degradation, by decrease of soil organic carbon, is an important factor leading to C emission from soil to atmosphere (Lal, 1997). Increased CO_2 represents the most important human enhancement to the greenhouse effect. It will

affect species differentially, and likely will drive substantial changes in species composition and dynamics of all terrestrial ecosystems (Vitousek, 1997) Changes in land use and land cover, mainly driven by agriculture, may also influence climate through changes in evapotranspiration. There is increasing concern about potential effects of land cover changes on agriculture, through adverse effects on the African and Asian monsoons (Gordon et al., 2010).
Animal husbandry is one of the major sources of ammonia and methane emissions. About 14% of global GHG emissions consists of methane, and about 2/3 of the methane is produced by enteric fermentation of ruminants and losses through manure management (IPCC, 2007).

2 Future trends and challenges

2.1 Meeting the global food demand

Despite the enormous agricultural production increase over the last few decades, it is estimated that nearly 870 million people, or one in eight, are suffering from chronic undernourishment (Godfray et al., 2010a). Although on a global level caloric intake has increased with ca. 380 kcal per person per day between 1970 en 2000, some sub-Saharan countries have declined further from an already very low per capita food consumption level (Kearney, 2010) Global population growth is predicted to decelerate and reach over 9 billion people in 2050 (Godfray et al., 2010b). At the same time, a nutritional transition is taking place. It is expected that people who are initially undernourished, will move through a phase where more grains, roots, tubers and pulses are consumed. In the following phase, the latter are substituted by energy-rich foods like meat, and foods with high concentrations of vegetable oils and sugars. Estimates for global food demands by 2050 indicate a further increase in daily caloric requirements of about 340 kcal per person per day (Kearney, 2010). It is estimated that there will be a need to raise food production by some 70 percent (IFAD, 2011). From 2000-2030, global cereal production is predicted to increase with 50 percent and global meat production with 85 percent (World Bank, 2008). From these projections it can be concluded that agricultural production levels have to increase substantially in order to meet future food demands. As the scope for agricultural expansion has been reached, agricultural intensification is urgently needed. (Tittonell, 2013)

Reducing the consumption of meat offers the possibility to feed more people with the same amount of land, due to the inherent low efficiency of converting feed into meat. Ruminants (cattle, sheep and goats) are less efficient in converting forage into useful products than monogastrics (pigs and poultry). Energy conversion efficiency for meat production ranges from 11% for chicken meat, to 9% for pork, and 3% for beef. Protein conversion efficiency ranges from 20% for chicken, to 10% for pork and 4% for beef. Cattle are the least efficient converters, caused by their high basal metabolism, large body mass, and long gestation and lactation periods (Smil, 2002). Reducing the consumption of meat and increasing the proportion of meat that is derived from the most efficient sources creates possibilities to feed more people sustainably (Godfray et al., 2010b). Global food transitions to eating less meat would have enormous consequences for both land use and climate (Stehfest et al, 2009).

2.2 Supporting the role of smallholders

Although rapid urbanization is occurring globally, at present the majority of the people in the developing world live in rural areas: ~55% of the total population, or 3.1 billion people. In 2005 it was estimated that 1.4 billion people lived in extreme poverty, and 70% of them, about 1 billion people, were living in rural areas. South Asia, with the greatest number of poor rural people, and sub-Saharan Africa, with the highest incidence of rural poverty, are most affected by poverty and hunger. Agriculture plays a vital role in most developing countries. It is estimated that over 80 percent of rural households farm to some extent, and typically the poorest households rely most on farming and agricultural labour (IFAD, 2011). It is estimated that at present, smallholders produce about half of the food in the world. Of total world production of cereals, coarse grains, roots and tubers, pulses and oil crops, ~2.8 billion tonnes are produced in developing countries, against ~1.8 billion in developed countries. It is also estimated that small to medium family farms account for about three quarters of total production in developing countries (Tittonell, 2013). Smallholder agriculture may provide an important route out of poverty, but then it has to be highly resilient: meeting the twin goals of being both productive and sustainable. Addressing smallholder agriculture is also essential when challenging the future demand for food, as yield gaps are most pronounced in smallholder farming. New approaches to increasing productivity of smallholder farming should also be more accessible than traditionally to rural women, who play critical roles in smallholder agriculture (IFAD, 2011)

2.3 Reducing waste

It is estimated that 30 to 40% of food in both developed and developing countries is lost to waste, although in different parts of the food chain and through different causes. In the developing world main losses occur after harvest, through inadequate on-farm storage and lack of food chain infrastructure. In contrast, in the developed world dramatic losses occur at retail and home stages of the food chain. Different strategies are needed to tackle the two types of waste. In developing countries, postharvest storage technologies can be improved, and better functioning markets and transport infrastructure is needed. In developed countries, domestic strategies for reducing food loss are more difficult to change, as it is intimately linked with consumer behaviour. Consumers have become used to food with high cosmetic standards, and retailers discard many edible, yet only slightly blemished products (Godfray et al., 2010b)

2.4 Reducing dependency on non-renewable energy

Global crop production has substantially increased in recent decades. Considering all 174 crops tracked by FAO, Foley et al. (2011) estimate that global crop production increased by 56% between 1965 en 1985 and by 20% between 1985 en 2005. As average yields of major food crops increased by a factor two over the last 50 years, the total amount of external nitrogen fertilizer input increased sevenfold, while the amount of phosphorus increased 3.5-fold (Foley et al., 2005). Current worldwide use of fertiliser nitrogen is about 100 Tg nitrogen per year (Erisman et al., 2008). Both nitrogen and phosphorus are expected to increase another 3-fold by 2050 unless there is a substantial increase in fertiliser efficiency (Tilman et al., 2002) Current agriculture is highly dependent on non-renewable energy sources. About 70% of the total amount of energy in one kernel of corn is derived from fossil fuels. About 30% of the energy needed for feeding a person in the developed world is used in manufacture of inorganic fertilisers, 19% for field machinery and 16% for transport. Feeding 9 billion people in 2050 with current agricultural production means would require 113,000 Million barrels of oil per year (without considering natural gas feedstock), which would exhaust global oil reserves in about 12 years (Tittonell, 2013).

Most agricultural soils are not sufficiently fertile to sustain plant production without regular addition of nutrients: either recovered and recycled through farmyard manure or crop residues, naturally produced by nitrogen fixing legumes, or manufactured as inorganic fertilisers (Dawson and Hilton, 2010). The main focus has traditionally been on three macronutrients: nitrogen (N), phosphorus (P) and potassium (K). Calcium, sulphur (S) and magnesium are more general available, though on some soils application of these macronutrients is necessary (Dawson and Hilton, 2010). As K and S are not anticipated to be limiting, N and P are critical because of their finite and depleting nature. Depletion occurs through the energy sources currently needed for the production of inorganic ammonia N and through the limited stock of global phosphate rock reserves. In order to safeguard future food production, both fertiliser N and naturally fixed N are likely to be required (Dawson and Hilton, 2010) Estimates of the potential of leguminous nitrogen fixing plants to account for a substantial part of the nitrogen needed for global food production show considerable variation. Based on crop rotations with leguminous green manures between normal cropping periods, it has been calculated that it should be possible to feed the current world population without mineral nitrogen fertiliser and without expansion of agricultural lands (Badgley et al., 2007). These calculations are based on many premises, and others conclude that natural N fixation can generate only the food to support 3.1-4.2 billion people (Connor, 2008).

2.5 Preventing depletion of mineral reserves

Modelling of phosphorus balances suggest a global phosphorus depletion in grasslands and a reduction in rock phosphate reserves by 36-64% in 2100 (Power, 2010). Closing nutrient cycles for phosphorus will significantly influence possibilities for sustaining future crop production. Micronutrients like boron, iron, copper, manganese, molybdenum and zinc are required in small quantities, but are equally essential for plant growth. A micronutrient that is not essential for crop production, but very essential for livestock and humans is selenium. Large-scale deficiencies of selenium occur in parts of Asia and Africa. During the past decade, soil micronutrient deficiencies have been attributed mainly to zinc, and to a lesser extent to boron and molybdenum. Zinc deficiencies are widespread in Asia, sub-Saharan Africa and north-western South America. Many important interactions exist between macro and micronutrients. A high availability of phosphate may restrict the availability of iron, zinc and copper for crops. Shortages of micronutrients may severely hamper plant production. The micronutrient molybdenum for example, is essential for nitrogen fixation by legumes. Although deficiencies of micronutrients in agricultural soils may be replenished with mined minerals, some mineral reserves are disappearing at an alarming rate. Mineral reserves of zinc are expected to last for only 21 years, while zinc deficiencies are already occurring in food chains in large part of the world. Also selenium reserves are being depleted very fast. De Haes et al. (2012) urgently call for a less one-sided focus on NPK fertilisation alone.

3 Development of concepts of sustainable agriculture

The notion of sustainable agriculture has gradually developed from the 1960s onward, leading to calls for an ‘evergreen’ or ‘doubly green’ revolution in the 1990s, and a very diverse range of terms in the last decades, from ‘low external input agriculture’ to ‘conservation agriculture’, ‘sustainable intensification’, ‘evergreen agriculture’ and ‘diversified farming systems’ (IFAD, 2011). The idea of agricultural sustainability essentially “centres on food production that makes the best use of nature’s goods and services while not damaging these assets. (…) Agricultural sustainability does not, therefore, mean ruling out any technologies or practices on ideological grounds (…) provided they improve productivity for farmers, and do not harm the environment” (Pretty et al., 2006). Many different terms are being used to address the level of sustainability of different farming systems and technologies. No single farming system or technology is however one hundred per cent sustainable, in all aspects of ecological, economic and social sustainability, at any given location on Earth. In order to develop more sustainable ways of cultivation, creativity and out-of-the-box thinking is necessary, in which no agricultural technology can be *a priori* determined to be ‘good’ or ‘bad’. The following table, which is by no means complete, shows some of the concepts of sustainable agriculture that have been developed over the last few decades.

Table 3.1: General principles related to different concepts of sustainable agriculture.

Sustainable Agriculture Concepts	Principles	References
Diversified Farming Systems	Farming practices and landscapes that intentionally include functional biodiversity at multiple spatial and/or temporal scales in order to maintain ecosystem services that provide critical inputs to agriculture, such as soil fertility, pest and disease control, water use efficiency, and pollination.	Kremen et al., 2012
Ecoagriculture Landscapes	Mosaics of areas in natural/native habitat and areas under agricultural production. Agriculture, biodiversity and ecosystem services are seen as interdependent. Rural communities are critical stewards of biodiversity and ecosystem services.	Scherr and McNeely, 2008
Sustainable Intensification	Intensification of resources, using natural, social and human capital assets, combined with the use of best available technologies and inputs (best genotypes and best ecological management) that minimize harm to the environment. Resource-conserving technologies are Integrated Pest Management, Integrated	Pretty, 2008

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Sustainable Agriculture Concepts	Principles	References
	Nutrient Management, Conservation Tillage, Agroforestry etc.	
Conservation Agriculture	Conservation Agriculture is defined as minimal soil disturbance (no-till, NT) and permanent soil cover (mulch) combined with rotations.	Hobbs et al., 2008
Organic Agriculture	Organic agriculture is a production system that sustains the health of soils, ecosystems and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Organic agriculture combines tradition, innovation and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved.	IFOAM (www.ifoam.org)
Direct-seeding Mulch-based Cropping Systems	A form of Conservation Agriculture, Direct seeding mulch-based cropping systems are characterised by ideally no-tillage, soil surface protection through mulch from crop residue, crop rotation, keeping the soil permanently covered.	Affholder et al., 2010
Evergreen Agriculture	Evergreen agriculture is defined as the integration of particular tree species into annual food crop systems. The intercropped trees sustain a green cover on the land throughout the year to maintain vegetative soil cover, bolster nutrient supply through nitrogen fixation and nutrient cycling, generate greater quantities of organic matter in soil surface residues, improve soil structure and water infiltration, increase greater direct production of food, fodder, fuel, fiber and income from products produced by the intercropped trees, enhance carbon storage both above-ground and below-ground, and induce more effective conservation of above- and below-ground biodiversity.	Garrity et al., 2010

4 Principles for sustainable agriculture – A draft framework

There are many diverging views and opinions on the future of agriculture, sustainable land use, habitat conservation and biodiversity management. Conflicting views sometimes result in emotional debates that miss the opportunity to learn from one another and discourage creativity and out-of-the-box thinking. The following input for a common framework aims to find general denominators and principles for a sustainable agriculture perspective, rather than pointing out single solutions as 'good' or 'bad'. The framework hopes to connect rather than polarize different views, resulting in common building blocks for sustainability, in particular sustainable agriculture.

4.1 Three areas of sustainability

The sustainability paradigm as defined in Agenda 21 addresses three areas of sustainability: ecological, social and economic. In order to integrate these three domains effectively, good governance is necessary, which could be regarded as a fourth principle. Ecological sustainability can be seen as the key building block, providing the base for all living organisms. For humanity, social and economic sustainability are equally necessary, as well as the overarching principles of good governance. In this paper on agricultural sustainability, we will mainly focus on key factors of ecological sustainability for agriculture.

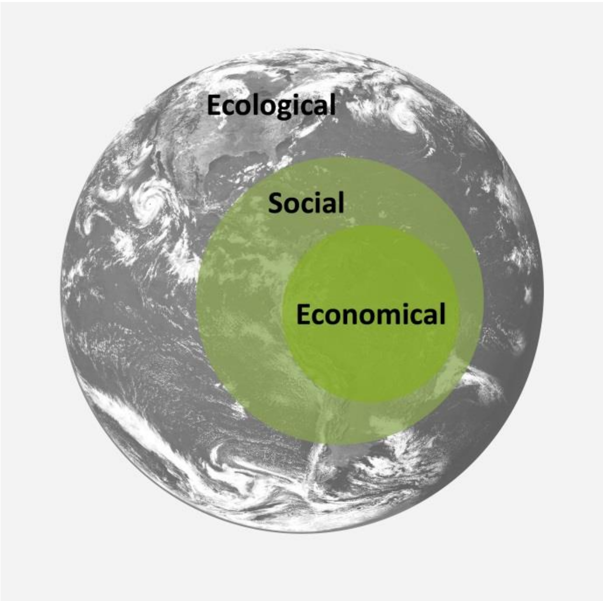

Figure 4.1: Three areas of sustainability. From the global perspective, ecological sustainability is the overarching principles. On field level, social an economical sustainability are equally important.

4.2 The framework: agroecosystem resilience

Although different definitions of resilience exist (Carpenter et al., 2001), in this paper we will refer to the widely employed definition of Gunderson and Holling (2001), defining resilience as "the capacity of a system to undergo disturbance and maintain its functions and controls". Resilience is measured by the magnitude of disturbance a system can tolerate, without losing its functions and moving to a different system state. More resilient ecosystems are able to absorb larger disturbances without changing in fundamental ways. Resilient systems contain those components that are needed for renewal and reorganization. They can cope, adapt, or reorganize without losing the provision of ecosystem services (Folke et al., 2002). Essential aspects of resilience are the degree to which a system is capable of self-organization and the learning and adaptive capacity, or ‘adaptiveness’ of the system in response to disturbance (Carpenter et al, 2001)

Ecological resilience plays a key role in the sustainability of agroecosystems. When resilience of agroecosystems is lost, vulnerability increases, and the system is not able to exert its functions anymore as soon as disturbances occur. Not only production is lost, but also regulating and supporting functions, that are necessary for sustainable use of resources for future generations within the boundaries of one earth. Ecological resilience is the principle that connects both the production function of agricultural systems, and the regulating and supporting functions that are needed to sustain production for future generations.
Ecological resilience is a well-known concept for ecologists, originating from the understanding of the dynamics of natural ecosystems (Holling, 1973). All ecosystems are exposed to gradual changes in external conditions. Sudden shifts to alternative states may occur when a natural ecosystem becomes more fragile by loss of resilience. Studies on natural ecosystems, including lakes, coral reefs, oceans and forests, have shown that prevention of gradual changes is more important than prevention of disturbances, as especially these smooth changes imply loss of resilience (Scheffer et al., 2001). In agricultural systems, examples of smooth changes that can be the silent onset of catastrophic shifts, are slow loss of organic carbon in soils, or increases in nitrate levels in wetlands. When reaching critical tipping points, soils become severely degraded and restoration may no longer be possible, resulting in land abandonment and conversion.

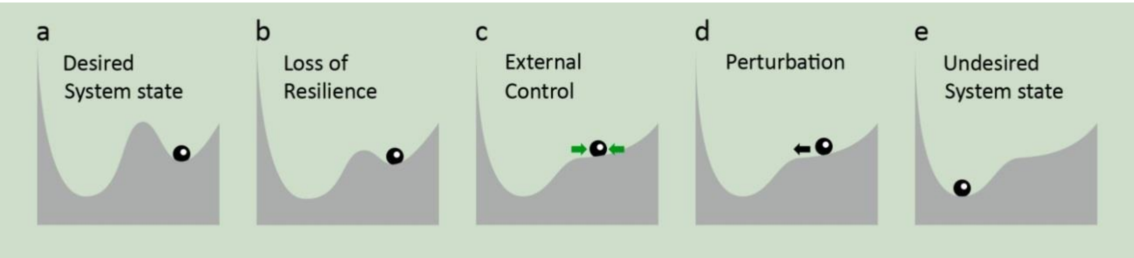

Figure 4.2: Resilience landscapes, showing the gradual loss of resilience upon soil degradation. In ecosystems, multiple equilibrium states exist. (a) highly resilient, biodiverse soil system; (b) gradual loss of resilience through narrowing crop rotations and loss of associated soil organisms; (c) complete loss of resilience: high amount of external control needed to keep the desired system state; (d) sudden perturbation, e.g. the introduction of a soil-borne pathogen; (e) flip over to an undesired alternative system state, with diseased plants and lower production levels.

4.3 Soil health and resilience linked to biodiversity

All agroecosystems share a common base and foundation: a healthy soil. Healthy soils are the necessary prerequisite of sound farming systems. A healthy soil has a high resilience: it is able to maintain its functions and controls in view of external changes, stress and disturbances. A healthy soil also provides a myriad of ecosystem functions, such as nutrient cycling, water buffering, water transport and purification, carbon storage and buffering, resistance to erosion and compaction and provision of biodiversity and habitat functions. For a healthy soil, principles can be defined that contribute to a high resilience of the different ecosystem functions that soils provide.

For many ecosystem processes, the soil is the central regulatory centre. The traditional focus on soil productivity has largely been directed towards physical and chemical properties of soils. During the last few decades, agriculture has increasingly replaced many of the biologically regulated functions of soil by human external inputs. A number of ecosystem services has become more controllable by replacing them by external inputs. Agricultural management has also diminished soil biodiversity, leading to loss of ecosystem functions and soil degradation. The concept of soil health typically addresses the biological component of soils. This biological diversity becomes increasingly important in maintaining the different ecological functions of soil when addressing agricultural sustainability. High levels of soil biodiversity per se are no guarantee that soil resilience is secured, although it is sometimes postulated as an insurance against ecosystem malfunctioning under stress (Brussaard et al., 2007). The presence of different functional groups is important, and the level of 'redundancy' among soil organisms within a functional group has been related to the resilience as well.

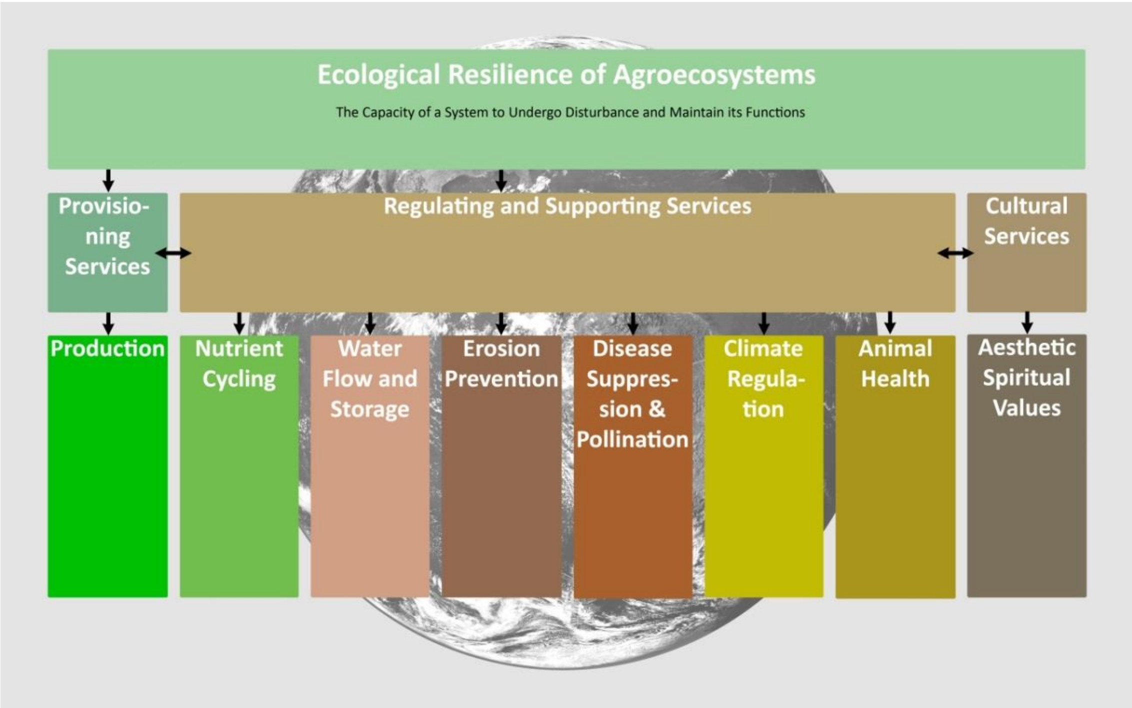

Figure 4.3: Ecological resilience of agroecosystems is the foundation for resilience in all types of ecosystem services: provisioning, supporting, regulating and cultural. Resilience provides a concept in which both production is secured and in which supporting and regulating functions are cared for, that are necessary for stewardship for future generations.

5 Principles for ecological resilience of agroecosystems

The dominant focus of agroecosystems has been on provisioning ecosystem services: the production of food, fodder and fuel. This has resulted in loss of regulating and supporting services of agroecosystems themselves, and of the services provided by natural ecosystems surrounding them. It has resulted in loss of biodiversity, and in loss of natural habitat through land conversion.

In order to meet the challenge of feeding a growing world population, while remaining within the boundaries of one earth, the production function of agroecosystems has to be enhanced. Leading principle in the development of sustainable agroecosystems is resilience. Resilience of production itself is obtained by working towards resilience of all major regulating and supporting services. The most basic resource for each farming system is the soil. Starting from a resilient and healthy soil, other principles can be deduced. In building soil health and resilience, biodiversity is an important aspect. Below-ground biodiversity is able to provide the different functions needed to deliver ecosystem services like nutrient cycling, water storage, and erosion prevention. Below-ground diversity is in turn related to diversity in above-ground vegetation cover and organic materials supplied to the soil. Guiding principle towards building resilience in different ecosystem services, is the role of a ‘living soil’, in which soil organisms provide the basic mechanisms of resilience building.

5.1 Stimulate nutrient cycling

A healthy soil is able to decompose organic materials and deliver nutrients to plants, but also to retain nutrients and prevent unnecessary losses through leaching or run-off. Plants and plant roots are part of the ‘living soil’, and can contribute to fix nitrogen and decrease dependency of mineral nitrogen fertilisers.

Principles

- Prevent nutrient losses
- Stimulate nutrient storage and buffering
- Increase nutrient-use efficiency

5.1.1 Prevent nutrient losses

Agroecosystems are characterized by relatively open nutrient cycles. Inherent nutrient losses take place through offtake by harvest, but additional losses occur through leaching, run-off, volatilization and soil erosion. Cover crops and reduced tillage may reduce nitrogen loss through leaching and erosion. Organic amendments (manure, compost, crop residues, green manures) will stimulate the diversity of decomposing organisms in soil, in contrast to mineral fertilizers. This diversity of soil organisms is thought to be a main factor in providing soil resilience. However, careful matching of crop demand to the slower nutrient release from organic amendments is necessary in order to obtain a high level of nutrient-use efficiency (Tilman et al., 2002). Inadequate storage of manure and slurry are important sources of nutrient losses in agricultural systems. Preventing losses of carbon (methane) and nitrogen to the atmosphere, and loss of nitrogen to the subsoil can increase on-farm nutrient cycling.

5.1.2 Stimulate nutrient storage and buffering

Soil organic matter plays a central role in both nutrient storage as well as buffering nutrient concentrations. Conversion to agriculture from natural ecosystems often leads to rapid fall of organic matter contents of soils. Although the functional community in soil which is responsible for decomposition of organic matter has a high level of “redundancy” compared to other ecosystem services, gradual loss of soil organic matter contents will finally have far-reaching consequences for soil resilience. Soil degradation results not only in less possibilities to cope with changing environmental circumstances, but keeps many households in poverty traps as it prevents farmers reaching the genetic potential of crop varieties (Swift et al., 2004). In sub-Saharan Africa, it is estimated that 70% of farmland is prone to soil degradation. When soil resilience is lost, crops do not respond to fertilizers, while nitrogen-fixing legumes are unable to grow. Huge amounts of manure are needed to restore soil fertility to original levels, being no realistic option for African smallholders that generally have no or only a few livestock. In order to find workable solutions, local and scientific knowledge and technologies have to be combined in ecological intensification strategies. Multiple strategies to restore degraded soils in the Sahel include use of specific shrubs (inedible for livestock), to provide alternative organic matter inputs and mulching. They are combined with planting basins, appropriate crop varieties and small amounts of mineral P-fertilizer to make harvest possible in the first year of soil rehabilitation (Tittonell, 2013).

5.1.3 Increase nutrient-use efficiency

Nitrogen-use efficiency of agroecosystems can be enhanced by crop rotations that include nitrogen fixing leguminous plant species. The potential of nitrogen fixing plants is underutilized in many cropping systems. Nutrient losses through leaching may be prevented by associations of main crops with deep-rooted, secondary crops. Crop associations in conservation agriculture usually entail a main crop (often a cereal) and a secondary crop (often a legume with a deep rooting system). The main principle of conservation agriculture is the maintenance of a mulch layer of crop residues on the soil surface, usually in combination with minimum tillage. For example, in case of cotton production, cotton may be combined with velvet bean as a cover crop. Other conservation agricultural systems involve planting of cotton into a mulch layer resulting from a combination of a cereal and a cover crop grown in rotation with cotton. Recent research on conservation agriculture reports maize grain yields of nearly 5 t ha-1 after 3 years of maize-pigeon pea intercrops without fertilizers, compared with yields lower or equal than 1 t ha-1 for maize monocropping with or without fertilizers (Tittonell, 2013). In some areas, micronutrients may limit crop production, and use of additional mineral fertilizers may improve general nutrient-use efficiency.

Nutrient use efficiency is usually no key factor in conventional plant breeding programs, as selection is usually carried out under circumstances with high inorganic fertilizer use (Lammerts van Bueren et al., 2011). However, in nutrient poor circumstances, crops with a more elaborate rooting system will produce better than crops that are selected for nutrient rich circumstances. In a low phosphorus environment, crops with stronger associations with mycorrhizal fungi will perform better than crops that grow well under high phosphorus conditions (Sanginga et al., 2000) Functional diversity of so-called “elemental transformers” in soil also play a role in nutrient-use efficiency. Redundancy among this functional group is probably smaller than in case of decomposers. Examples of these soil-organisms are nitrogen fixing bacteria and mycorrhiza. As specific mycorrhiza strains facilitating phosphorus uptake by plants are lost, consequences of phosphorus depletion of soils for production levels may become more severe. Use of mineral fertilizers, soil fumigation and fungicide applications may degrade the natural mycorrhiza community in agroecosystems, and decrease resilience.

Box 5.1: Gender division of labour: no-till and weeding

Despite clear ecological benefits of farm management options that decrease nutrient losses, social sustainability should be genuinely considered. One of the major constraints to farmers’ adoption of conservation agriculture are labor requirements. Minimum or no-till systems require higher amounts of labor for weeding and adoption may result in a transfer of the labor burden from men, traditionally in charge of land preparation, to women, traditionally in charge of weeding. Although such a system may be ecologically sound, social sustainability may be lacking (Baudron et al., 2009).

5.2 Regulating water flow and enhancing storage

A healthy soil is capable of providing enough water for crop growth, and enhances the rooting depth of plants. A ‘living soil’ also provides deep burrows, necessary for a good water infiltration capacity, and a soil structure that is able to conserve water in times of drought.

Principles

- Improve water infiltration capacity
- Improve water retention by soils
- Enhance rootability of soils
- Increasing water-use efficiency
- Maintain water quality

5.2.1 Improve water infiltration capacity

Plant cover and plant litter influence the water infiltration capacity of soils and water retention. A reduction of ground cover, in time or space, increases the amount of run-off, diminishes infiltration and increases the risk of erosion. The macrofauna moving between litter layers and deeper soil layers influences the water infiltration capacity and water holding capacity of soils. Some groups of engineers make stable, deep burrows that allow for rapid water infiltration, while others enhance soil porosity and rootability. However, in some agroecosystems the soil engineers responsible for macropores are unwanted: in irrigated rice fields, farmers consider earthworms as the greatest pests. Soil tillage negatively influences the abundance and diversity of these soil engineers.

5.2.2 Improve water retention by soils

The adoption of plough tillage has had highly detrimental effects on soil structure in tropical soils, resulting in a dramatic loss of ecological resilience, and manifested as low levels of soil moisture being available to plants. There is increasing awareness that soil quality, in terms of both soil structure and soil fertility, is often a more limiting factor to crop growth than water, even in semi-arid tropical agroecosystems, requiring an integrated soil and water management approach (Rockström, 2004).

5.2.3 Enhance rootability of soils

In determining the resilience to hydro-climatic shocks (like droughts and floods) of semi-arid and dry sub-humid tropical agroecosystems, the dynamics of the hydrological system are more important than water quantity per se. Slow processes in agroecosystems are particularly important in securing long-term resilience. These 'slow factors' include building up of organic matter contents, development of soil structure and rooting depth. These all contribute to higher resilience of the soil ecosystem.

5.2.4 Increasing water-use efficiency

On a landscape scale, upstream agricultural management influences ecosystem services of downstream aquatic systems. The conventional focus of agricultural water management has largely been on blue water (river, lake and groundwater), irrigation withdrawing 70% of managed blue water resources. Limited attention has been given to the direct use of green water (transpiration flow) in rainfed agriculture, encompassing 97% of water-scarcity prone smallholder agriculture in sub-Saharan Africa. Farming system innovations in rainfed agriculture, like water harvesting and conservation farming aim to increase water-use efficiency at field scale. Effects on the larger watershed or river basin scale have received much less attention. This becomes also clear when reviewing water conservation policies. Adoption of more efficient irrigation technologies like drip irrigation, reduces valuable return flows and limits recharge of aquifers. Drip irrigation is important for greater water productivity and food security, but does not necessarily save water when considered from a basin scale (Ward and Pulido-Velazquez, 2008).

Box 5.2: Supporting biological processes to increase yields: the System of Rice Intensification

The System of Rice Intensification (SRI) was developed in the 1980s in Madagascar. The system shows that the supporting biological processes can have positive results on yields, with little or no dependence on mineral fertilisers or pesticides. SRI methods can raise average rice yields to twice the present world average of 3.7 t ha-1 and much higher when improved or hybrid varieties are used. The basic principles are careful transplanting of very young seedlings, spacing plants widely rather than densely, and providing soil aeration intermittently during vegetative growth, stimulating both aerobic and anaerobic microorganisms in soil (Uphoff, 2003).

The System of Rice Intensification is an example of improvements in irrigation systems, that do not necessarily involve the use of external inputs, but instead make better use of local resources (Box 5.2).

5.2.5 Maintain water quality

Water quality in ground- and surface water downstream production sites should be maintained by management practices that minimize leaching of nutrients (nitrate, phosphates) and plant protection products. Plant protection products, including metabolites, can have detrimental effects on aquatic ecosystems. Many ecosystem processes are disrupted by use of plant protection agents or herbicides. Minimum use can be stimulated by paying more attention to aboveground biodiversity, both of crops and predators (see also paragraphs on disease suppression).

5.3 Prevention of soil erosion

A resilient soil has the capacity to resist wind- and water erosion, through sufficient soil organic matter, a good soil structure, the presence of plant roots, and the protecting cover of living or dead plant materials. This prevents soil degradation and finally land abandonment.

Principles

- Enhance soil protection by plant cover
- Minimize soil disturbance by tillage
- Maintain soil organic matter levels

5.3.1 Enhance soil protection by plant cover

Plant cover protects the soil against erosion by reducing water runoff and increasing water infiltration. Plants shelter and fix the soil with their roots, and reduce the impact of raindrops with their canopy. Vegetation can also act as a physical barrier, altering sediment flow at the soil surface. The way the vegetation is spatially distributed along slopes determines to a great extent the possibility of decreasing sediment runoff. In the long term, vegetation also increases the soil-aggregate stability and cohesion. Studies on highly erosion resilient native shrub vegetation in Mediterranean ecosystems have shown that canopy cover plays a key role in reducing runoff and soil loss, while litter cover beneath plants is fundamental for erosion control during intense rainfall. Croplands are particularly sensitive to erosion, because of frequent cultivation of the soils and recurrent removal of vegetation before planting. When cropland is left without vegetation between plantings, erosion becomes more severe. Also in perennial cropping systems, erosion can be considerable. Almond orchards where the undergrowth is frequently removed, experience high erosion rates, in contrast to Olive orchards grown under semi-natural conditions with an understorey of annual plants. Erosion can be significantly reduced by the use of plant strips running across the hillslope (Durán Zuazo and Rodríguez Pleguezuelo, 2008).

Soil cover can also be obtained by mulching. Crop residues can provide mulches after harvest, and cover crops (legumes or non-legumes) can be specifically grown to provide a mulch. Mulch layers intercept the impact of raindrops, enhance water infiltration and reduce soil loss by erosion. Surface crop residues, anchored or loose, protect the soil from wind erosion. Surface mulch also helps reduce water losses from the soil by evaporation and helps to moderate soil temperature. This is a very important factor in tropical and subtropical environments, but a hindrance for temperate climates, due to delays in soil warming in spring and delayed germination. A cover crop and the resulting mulch also helps reduce weed infestation through competition and by inhibiting weed germination through light interception (Hobbs et al., 2008) Direct-seeding mulch-based cropping systems (DMC) are being increasingly promoted in tropical agriculture, but have mainly been adopted by large-scale mechanized farmers, and seldom by resource-poor farmers in the developing world. DMC modifies the use of farm resources that are often managed at community level, like crop residues. Collection of mulching materials may require labour which is not directly offset by a reduction in labour required for weeding. DMC may also involve the application of herbicides to decrease the amount of labour required for weeding, but many resource-poor farmers do not have means to obtain these inputs (Affholder et al., 2010).

Box 5.3: Evergreen Agriculture

Many sustainable management options embrace the idea of permanent vegetation cover. One example is Evergreen Agriculture, a type of agroforestry system that is characterised by maintenance of a green cover throughout the year, through direct and intimate intercropping of trees within annual crop fields. In Zambia this system has been developed with maize and cotton as annual crops, in combination with Faidherbia albida, indigenous nitrogen fixing acacia trees, as a permanent canopy. This tree species has a unique growth habit, called ‘reverse leaf phenology’. Faidherbia goes dormant and sheds its leafs during the early rainy season, at the time when field crops are being established. Leaves regrow at the end of the rainy season. The unusual phenology makes it highly compatible with food crops, since it does not compete for light, nutrients or water during the growing season. In Zambia, maize yields in the vicinity of Faidherbia trees averaged 4.1 t ha-1, compared to 1.3 t ha-1 nearby but beyond the tree canopy, both systems with zero inorganic fertilisers (Garrity et al., 2010).

5.3.2 Minimize soil disturbance by tillage

No tillage is a key characteristic of Conservation Agriculture. Conservation Agriculture maintains a permanent or semi-permanent organic soil cover, which can be a living crop or dead mulch, as a protection against water and wind erosion. The soil micro-organisms take over the tillage function and soil nutrient balancing. Deep-rooting cover crops in combination with no-till help to promote biological soil tillage and relieve compaction. Zero or minimum tillage and direct seeding are important elements of Conservation Agriculture. The adoption of no-till worldwide is ~95 million ha, with the US having the largest area under no-till (25 Mha), followed by South America, particularly Brazil (24 Mha) and Argentina (18 Mha) (Hobbs et al., 2008).

5.3.3 Maintain soil organic matter levels

Soil organic matter is an important factor in determining soil structure and sensitivity to erosion. Vegetation removal is normally followed by a period in which the soil has sufficient organic matter to maintain its ecosystem functions, enabling it to recover from damage, and being sufficiently resilient. Soils rich in organic matter, such as those in many rainy regions, are more resilient than soils with low organic matter content, such as those predominating in arid and semiarid areas. Soil organic matter facilitates the formation of soil aggregates and increases soil porosity, thus improving soil structure. (Durán Zuazo and Rodríguez Pleguezuelo, 2008). Soil organic matter synthesis and decomposition is determined by the same decomposer community that is responsible for decay of plant litter. In the conversion of land to agriculture, decomposition of soil organic matter provides nutrients for plant growth. Soil tillage stimulates the breakdown of soil organic matter, and may promote crop yields after conversion. However, when soil organic matter is not replenished by organic amendments to the soil, organic matter contents may gradually fall down, influencing not only erosivity, but also soil structure, water holding capacity and nutrient delivery. Once organic matter is depleted, productivity declines both because of degraded soil structure and the depletion of nutrients contained in organic matter. Soils that suffer from severe erosion may produce 15-30% less than uneroded soils (Durán Zuazo and Rodríguez Pleguezuelo, 2008).

Box 5.4: Multiple uses of farm resources

In most agroecosystems crop residues have multiple uses. Rice straw is not only be used for thatching, mat-making and fodder, but husks are used for fuel, and leaves are prepared into relishes (Howard, 2003). The maintenance of vegetation cover on agricultural soils may very well compete with other uses of crop residues. In many developing countries, cooking and heating depend on the use of crop residues as fuel. It has been estimated that ~60% of crop residues in China and ~90% of crop residues in Bangladesh are stripped from the land and burned for fuel (Pimentel and Kounang, 1998). The single allocation of crop residues to vegetation cover and soil organic matter building, may strongly affect gender relations, as women may be deprived of their sources of fodder and fuel. This emphasizes the need of local solutions that are supported by a strong participatory and gender-sensitive approach.

5.4 Enhance suppressiveness to diseases and pests and stimulate pollination

A healthy soil contains natural enemies that are able to suppress soil-borne diseases. Resilience is also enhanced by a high above-ground diversity, both in cultivar varieties, and in natural vegetation. The latter provides a habitat for natural enemies of pests, and for pollinators.

Principles

- Maintain high biodiversity of cultivar varieties
- Employ crop rotation in time and/or space
- Provide habitats for natural enemies and pollinators
- Maintain soil organic matter levels
- Enhance soil biodiversity

5.4.1 Maintain high biodiversity of cultivar varieties

Compared to natural ecosystems, the decreased genetic diversity in the plant cover of a monoculture crop also implies a higher susceptibility to diseases and pests. Maintaining a high variety of cultivars is essential in providing a resilient genetic base for plant health. Improving local farmers' knowledge on selection and breeding may increase the capacity of farming systems to adapt to change. Local farmers are more aware of those selection factors that are critical to production in marginal environments. Conventional breeding programs may overlook local farmers' knowledge on breeding and variety selection, especially when this knowledge is gender-based. An example is the case of Rwanda, where women produce an exceptional high amount of more than 600 varieties of beans, and where 65% of protein intake and 30% of caloric intake is provided by beans. Local production zones are very diverse, extending from 1000-2200 m. Seed managers, usually women, target mixtures of bean varieties to different cropping niches and modify them according to soil type, season or intercropping pattern (Sperling, 2001). This high interspecies variety strongly supports agroecosystem resilience. In many cases however, the genetic uniformity of crops has lead to increased vulnerability. In the US, 60-70% of the bean area is planted with only 2-3 bean varieties, and 53% of the cotton area is planted with 3 varieties (Altieri, 1999).

5.4.2 Employ crop rotation in time and/or space

Enhancing plant biodiversity of agroecosystems through mixed cropping systems, floral undergrowth or adjacent wild vegetation may foster resilience. Specialized herbivorous arthropod species generally reach higher abundance in monocultures than in diversified systems. Insect communities in agroecosystems are stabilized by the presence of vegetational architectures that support natural enemies. The more continuous availability of microhabitats and food sources in annual polycultures supports natural enemy populations. In perennial crop systems, stands with a rich floral undergrowth exhibit lower incidence of insect pests.

5.4.3 Provide habitats for natural enemies and pollinators

Adjacent wild vegetation may in some cases support invasion of insect pests when this vegetation is botanically related to the crop, but will also provide alternate food and habitat to natural enemies. These alternate vegetation structures may allow naturally occurring biological control organisms to maintain higher population levels on alternative hosts or prey and persist in agroecosystems throughout the year, also when the primary crop is not present. The presence of certain weeds also plays an ecological role by providing niches for a complex of beneficial arthropods that suppress pest populations (Altieri, 1999). Simplification of the agroecosystem combined with the use of broad-spectrum insecticides decreases the diversity of natural enemies and non-target beneficial organisms, undermining resilience.

5.4.4 Maintain soil organic matter levels

Soil health provides the basis for a healthy crop, that is less susceptible to diseases and pests. Soil suppressiveness to soil-borne diseases is largely mediated by the presence of soil biota, although chemical and physical soil characteristics may affect the resistance of plants. Part of this resilience is based on the decomposer community in soil and based on competition between pathogens and decomposers for food and space. This is especially true for those pathogens that are susceptible to a high level of competition between soil micro-organisms that are part of the decomposer community. Resilience of this ecosystem function will be high as long as the decomposer community is stimulated by sufficient fresh organic matter inputs.

5.4.5 Enhance soil biodiversity

More difficult to enhance is resilience towards specific soil-borne diseases, as this type of resilience will depend on the presence of relatively few hyper-parasites or predator species, with little redundancy within this functional group. Agricultural management practices that diminish soil biodiversity (e.g. through fumigation or broad-spectrum fungicides) may irreversibly damage this type of resilience, as introduction of predator species is both expensive and difficult to realize.

5.5 Climate

A healthy soil can act as a carbon sink, when organic matter contents of soils gradually increase. Permanent perennial vegetation cover with woody plants or trees can increase carbon sequestration.

Principles

- Maintain soil organic matter levels
- Include perennial and woody vegetation in agro-ecosystems

Changes in land use by clearing natural vegetation and conversion to agricultural systems have major implications for the balance of gas emissions and global climate. Dramatic changes occurring in the atmosphere at present are due to the steady increase in the amount of CO2 and several other trace gases like CH4 and N2O. Soils contribute to the amounts of atmospheric trace gases by acting as sources and sinks, and soil organisms are mostly responsible for this functioning. Clearing natural vegetation generally implies large increases in CO2 output, by degradation of soil organic matter reserves. Regrowth usually can’t balance this enormous breakdown. Some agroecosystems are characterized by high output of methane, such as paddy rice cultivation and intensive animal husbandry. These changes in gas emissions are linked to alterations in soil structure and shifts in the dominant functional groups in the soil community, e.g. from aerobic to anaerobic organisms, including methanogenic and methanotrophic bacteria.

5.6 Animal health and well-being

Livestock is a very important component of the livelihoods of at least 70% of the world's rural poor, including ~200 million pastoralists, ~700 million mixed farmers, and ~100 million landless livestock keepers. Particularly for poor and landless farmers, livestock is an important factor in household income (Anderson, 2003). Animal health, susceptibility to disease, and animal well-being are important factors determining the resilience of farming systems. Animal health determines the very source of livelihood for pastoral communities. Animal health is related to type, quality and quantity of fodder, the presence of appropriate surroundings and shelter, supporting the natural species-specific behaviour, maintaining a balanced stocking density, and providing a broad genetic base for animal breeding. An important factor in health and behaviour of domestic animals is the quality of the husbandry and the human-animal interaction (Hemsworth and Coleman, 1998).

Principles

- Providing enough fodder of good quality
- Providing appropriate surroundings and shelter
- Maintaining a balanced stocking density
- Providing a broad genetic base for breeding
- Good stockmanship (husbandry and positive human-animal interaction)

5.6.1 Providing enough fodder of good quality

In order to provide animals with optimal health conditions, both quantity and quality of fodder should be in accordance with the animals' need. Providing animals with a diet that resembles their natural diet will support their health. Dietary diversity will also increase animal health and resilience, as it provides a greater diversity of macro- and micronutrients. Grasslands that contain a greater variety of herbs may support the prevention of disease in cattle and increase the animal's natural resistance. Breeds that are adapted to local available resources reduce the farmer's dependency on external supplies and increase the health of a herd.

5.6.2 Providing appropriate surroundings and shelter

The surroundings of animals should support a diverse array of needs: from providing clean water and a variety of foods, to providing daylight, shelter and protection against climate conditions, to spaces to rest and recover. Farmers can minimize stress and optimize animal health' by providing them with species-appropriate surroundings and enrichments. An example is the provision of litter, or additional forages such as roughage, which may prevent boredom and stress in animals (Bestman and Wagenaar, 2012).

5.6.3 Maintaining a balanced stocking density

Many crop-livestock systems and extensive grazing systems are based on multiple-use common property regimes. When pressure on land increases, traditional free range communal grazing systems may shift to more intensive husbandry practices. Systems of multispecies herding, combining cattle with small ruminants, may particularly enhance the use of marginal lands and crop residues. In order to prevent degradation of rangeland, stocking rates should be adapted to the carrying capacity of the land. However, high variability of rainfall in regions like sub-Saharan Africa, makes sustainable stocking densities very variable (Pulina et al., 1999). Stocking densities that structurally exceed the carrying capacity of the land, will require large inputs of fodder from other regions. This may imply shifts in soil fertility from one region to another, leading to depletion of nutrients in some regions of the World, and problems with eutrophication and over-fertilization in others. Regarding stocking density in housing systems, all animals in the herd should have the ability to move freely, and to perform behaviour as resting, lying and rising, eating, drinking and foraging. All animals should also have the possibility for social contact and social behaviour (Bartussek, 1999). If stock density is managed adequately, animals are protected from harming each other and disease pressure is lower, preventing both the spread of animal diseases and zoonosis.

5.6.4 Providing a broad genetic base for breeding

A broad genetic base for animal breeding is necessary to maintain the health within a herd or population of domestic animals. Rural farmers in marginal areas need animal genetic resources that are capable of performing a wide variety of functions, providing flexibility, resistance and diversity to the farming system. Animals provide a diversity of livelihood functions, including not only cash income from sales of animals and their products, but also as means of saving, insurance, transport, inputs for crop production, and to capture benefits from common property rights, like nutrient transfer through foraging on common lands. The most important animal genetic resources in marginal areas are local breeds, adapted to relatively unfavourable environments, which can thrive on low external input type management. In these cases, ‘improved’ breeds may involve higher risks, due to lack of adaptive potential and resilience. Selection of proper animal genetic resources requires involvement of the farmers and farming community, who can identify and address their specific needs and requirements (Anderson, 1993).

5.6.5 Good stockmanship (husbandry and human-animal interaction)

The health and welfare of domestic animals is integral to the knowledge, skills, abilities and attitude of the stockman. Good stockmanship encompasses affinity and empathy with livestock, dedication, patience, and keen observational skills. Good stockmanship brings a unique quality in animal husbandry and may compensate for deficiencies in the farming system. It has a balancing and compensating effect on behaviour, hygiene, health and well-being (Hemsworth and Coleman, 1998; Bartussek, 1999).

6 Conclusions

In the previous chapters, the concept of resilience has been used as a base to define principles of sustainable farming practices. Although this may initially result in a technical list of ideal ‘preferred practices’, field situations will be much more complex, and far from the ‘ideal’ situation. The principles lined out in the previous chapters could be regarded as a means towards moving in the direction of more resilient systems, rather than being fixed and pre-determined goals in themselves.

Farming systems should enhance resilience in order to be able to cope with change. Resilience can be viewed upon from different levels. The soil as the central regulatory center provides a valuable starting point from which to develop a broader understanding of resilience on farm level. Not only production, but many other ecological functions are dependent on soil health. Biodiversity at different levels is supporting resilience in soils, crops and animals. Rethinking farming systems in terms of resilience, without *a priori* rejecting solutions on ideological grounds, can overcome differences in approaches to sustainable agriculture, and bridge the gap between highly productive agriculture and conservation goals.

References

Affholder, F. D. Jourdain, D.D. Quang, T.P. Tuong, M. Morize and A. Ricome, (2010). **Constraints to farmers' adoption of direct-seeding mulch-based cropping systems: A farm scale modeling approach applied to the mountainous slopes of Vietnam.** Agricultural Systems 103: 51-62.

Altieri, M.A., (1999). **The ecological role of biodiversity in agroecosystems. Agriculture, Ecosystems and Environment** 74: 19-31.

Anderson, S., (2003). **Animal genetic resources and sustainable livelihoods.** Ecological Economics 45: 331-339.

Bartussek, H., (1999). **A review of the animal needs index (ANI) for the assessment of animals' well-being in the housing systems for Austrian proprietary products and legislation.** Livestock Production Science 61:179-192.

Bestman, M. and J-P Wagenaar, (2012). **Health and welfare in organic laying hens in The Netherlands.** Agriculture and Forestry Research, Special Issue No. 362: 156-159.

Badgley, C., J. Moghtader, E. Quintero, E. Zakem, M.J. Chappell, K. Avilés-Vázquez, A. Samulon and I. Perfecto, (2007). **Organic agriculture and the global food supply.** Renewable Agriculture and Food Systems 22(2): 86–108.

Barrios, E., (2007**). Soil biota, ecosystem services and land productivity.** Ecological economics 64: 269-285.

Bharucha, Z. and J. Pretty, (2010). **The roles and values of wild foods in agricultural systems.** Philosophical Transactions of The Royal Society B 365: 2913-2926.

Brussaard, L., P.C. de Ruiter, G.G. Brown, (2007). **Soil biodiversity for agricultural sustainability.** Agriculture, Ecosystems & Environment 121: 233-244.

Carpenter, S, B. Walker, J.M. Anderies and N. Abel, (2001). **From Metaphor to Measurement: Resilience of What to What?** Ecosystems 4: 765-781

Cincotta, R.P., J. Wisnewski and R. Engelman, (2000). **Human population in the biodiversity hotspots.** Nature 404: 990-992.

Connor, D.J., (2008). **Organic agriculture cannot feed the world.** Field Crops Research 106: 187–190.

Dawson, C.J. and J. Hilton, (2011). **Fertiliser availability in a resource-limited world: Production and recycling of nitrogen and phosphorus.** Food Policy 36: S14-S22.

Durán Zuazo, V.H. and C.R. Rodríguez Pleguezuelo, (2008). **Soil-erosion and runoff prevention by plant covers. A review.** Agronomy for Sustainable Development 28: 65-86.

Erisman, J.W., M.A. Sutton, J. Galloway, Z. Klimont and W. Winiwarter. (2008). **How a century of ammonia synthesis changed the world.** Nature Geoscience 1: 636-639.

FAOSTAT, (2013). **FAO database.** Available at: http://faostat3.fao.org/faostat-gateway/go/to/download/Q/QC/E. (accessed 15 November 2013).

Foley, J.A., R. DeFries, G.P. Asner, C. Barford, G. Bonan, S.R. Carpenter, F.S. Chapin, M.T. Coe, G.C. Daily, H.K. Gibbs, J.H. Helkowski, T. Holloway, E.A. Howard, C.J. Kucharik, C. Monfreda, J.A. Patz, I.C. Prentice, N. Ramankutty and P.K. Snyder, (2005). **Global Consequences of Land Use.** Science 309: 570-574.

Foley, J.A., N. Ramankutty, K.A. Brauman, E.S. Cassidy, J.S. Gerber, M. Johnston, N.D. Mueller, C. O'Connell, D.K. Ray, P.C. West, C. Balzer, E.M. Bennett, S.R. Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockström, J. Sheehan, S. Siebert, D. Tilman and D.P.M. Zaks, (2011). **Solutions for a cultivated planet.** Nature 478: 337-342.

Folke, C., S. Carpenter, T. Elmqvist, L. Gunderson, C. S. Holling, and B. Walker, (2002). **Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformations.** AMBIO 31(5): 437-440.

Garrity, D.P., F.K. Akinnifesi, O.C. Ajayi, S.G. Weldesemayat, J.G. Mowo, A. Kalinganire, M. Larwanou and J. Bayala, (2010). **Evergreen Agriculture: a robust approach to sustainable food security in Africa.** Food Security 2: 197-214.

Gibbs, H.K., A.S. Ruesch, F. Achard, M.K. Clayton, P. Holmgren, N. Ramankutty and J.A. Foley, (2010). **Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s.** PNAS 107(38): 16732-16737.

Giller, K.E., M.H. Beare, P.Lavelle, A.-M.N. Izac and M.J.Swift, (1997). **Agricultural intensification, soil biodiversity and agroecosystem function.** Applied Soil Ecology 6: 3-16.

Godfray, H.C.J., I.R. Crute, L. Haddad, D. Lawrence, J.F. Muir, N. Nisbett, J. Pretty, S. Robinson, C. Toulmin and R. Whiteley, (2010a). **The future of the global food system.** Philosophical Transactions of the Royal Society B 365: 2769-2777.

Godfray, H.C.J., J.R. Beddington, I.R. Crute, L. Haddad, D. Lawrence, J.F. Muir, J. Pretty, S. Robinson, S.M. Thomas and C. Toulmin, (2010b). **Food Security: The Challenge of Feeding 9 Billion People.** Science 327: 812-818.

Gordon, L.J., C.M. Finlayson and M. Falkenmark, (2010). **Managing water in agriculture for food production and other ecosystem services.** Agricultural Water Management 97: 512-519.

Hausman, C., (2012). **Biofuels and Land Use Change: Sugarcane and Soybean Acreage Response in Brazil.** Environmental and Resource Economics 51(2): 163-187.

Hemsworth, P.H. and G.J. Coleman, G.J., (1998). **Human-Livestock Interactions. The Stockperson and the Productivity and Welfare of Intensively Farmed Animals.** Cab International.

Hobbs, P.R., K Sayre and R. Gupta, (2008). **The role of conservation agriculture in sustainable agriculture.** Philosophical Transactions of The Royal Society B. 363: 543-555.

Holling, C.S., 1973. **Resilience and stability of ecological systems.** Annu. Rev. Ecol. Syst. 4: 1-23

Howard, P., (2003). **The Major Importance of 'Minor' Resources: Women and Plant Biodiversity.** Gatekeeper Series no. 112. International Institute for Environment and Development, London.

International Fund for Agricultural Development, (2011). **Rural Poverty Report 2011: New realities, new challenges: new opportunities for tomorrow's generation.** International Fund For Agricultural Development (IFAD), Rome.

IPCC, 2007. **Climate Change 2007: Synthesis Report.** Intergovernmental Panel on Climate Change, Geneva.

Kearney, J., (2010). **Food consumption trends and drivers.** Philosophical Transactions of The Royal Society B 365: 2793-2807.

Lammerts van Bueren, E.T., S.S. Jones, L. Tamm, K.M. Murphy, J.R. Myers, C. Leifert and M.M. Messmer, (2011**). The need to breed crop varieties suitable for organic farming, using wheat, tomato and broccoli as examples: A review.** NJAS 58: 193-205.

Millennium Ecosystem Assessment, (2005a). **Ecosystems and Human Well-being: Biodiversity Synthesis.** World Resources Institute, Washington, DC.

Millennium Ecosystem Assessment, (2005b). **Ecosystems and Human Well-being: Wetlands and Water Synthesis.** World Resources Institute, Washington, DC.

Oldeman, L.R., (1992). **Global Extent of Soil Degradation.** In: ISRIC Bi-Annual Report 1991-1992. ISRIC, Wageningen, pp.19-36.

Pimentel, D. and N. Kounang, (1998). **Ecology of Soil Erosion in Ecosystems.** Ecosystems 1(5): 416-426.

Power, A.G., (2010). **Ecosystem services and agriculture: tradeoffs and synergies.** Philosophical transactions of The Royal Society B. 365: 2959-2971.

Powlson, D.S., P.J. Gregory, W.R. Whalley, J.N. Quinton, D.W. Hopkins, A.P. Whitmore, P.R. Hirsch and K.W.T. Goulding, (2011). **Soil management in relation to sustainable agriculture and ecosystem services.** Food Policy 36: S72-S87.

Pretty, J.N., A.D. Noble, D. Bossio, J. Dixon, R.E. Hine, F.W.T. Penning de Vries and J.I.L. Morison, (2006). **Resource-conserving agriculture increases yields in developing countries.** Environmental Science & Technology 40(4): 1114-1119.

Pulina, G., E. Salimei, G. Masala and J.L.N. Sikosana, (1999). **A spreadsheet model for the assessment of sustainable stocking rate in semi-arid and sub-humid regions of Southern Africa.** Livestock Production Science 61: 287-299.

Ramankutty, N., J.A. Foley, J. Norman and K. McSweeney, (2002). **The global distribution of cultivable lands: current patterns and sensitivity to possible climate change.** Global Ecology and Biogeography 11(5): 377-392.

Rengasamy, P., (2006). **World salinization with emphasis on Australia.** Journal of Experimental Botany 57(5): 1017-1023.

Rockström, J., C. Folke, L. Gordon, N. Hatibu, G. Jewitt, F. Penning de Vries, F. Rwehumbiza, H. Sally, H. Savenije and R. Schulze, (2004). **A watershed approach to upgrade rainfed agriculture in water scarce regions through Water System Innovations: an integrated research initiative on water for food and rural livelihoods in balance with ecosystem functions.** Physics and Chemistry of the Earth 29: 1109–1118.

Rozema, J. and T. Flowers, (2008). **Crops for a Salinized World.** Science 322: 1478-1480.

Sala, O.E., F.S. Chapin, J.J. Armesto, E. Berlow, J. Bloomfield, R. Dirzo, E. Huber-Sanwald, L.F. Huenneke, R.B. Jackson, A. Kinzig, R. Leemans, D.M. Lodge, H.A. Mooney, M. Oesterheld, N.L. Poff, M.T. Sykes, B.H. Walker, M. Walker and D.H. Wall, (2000). **Global Biodiversity Scenarios for the Year 2100.** Science 287: 1770-1774.

Sanderson, E.W., M. Jaiteh, M.A. Levy, K.H. Redford, A.V. Wannebo and G. Woolmer, (2002). **The Human Footprint and the Last of the Wild.** BioScience 52(10): 891-904.

Sanginga, N., O. Lyasse and B.B. Singh, (2000). **Phosphorus use efficiency and nitrogen balance of cowpea breeding lines in a low P soil of the derived savanna zone in West Africa.** Plant and Soil 220: 119–128.

Scheffer, M., S. Carpenter, J.A. Foley, C. Folke and B. Walker, (2001). **Catastrophic shifts in ecosystems.** Nature 413: 591-596.

Scherr, S.J. and J.A. McNeely, (2008). **Biodiversity conservation and agricultural sustainability: towards a new paradigm of 'ecoagriculture' landscapes.** Philosophical Transactions of the Royal Society of Biological Sciences 363: 477-494.

Smil, V., (2002). **Worldwide transformation of diets, burdens of meat production and opportunities for novel food proteins.** Enzyme and Microbial Technology 30: 305-311.

Stehfest, E., L. Bouwman, D.P. van Vuuren, M.G.J. den Elzen, B. Eickhout and P. Kabat, (2009). **Climate benefits of changing diet.** Climatic Change 95: 83-102.

Steinfeld, H., P. Gerber, T. Wassenaar, V. Castel, M. Rosales en C. de Haan, (2006**) Livestock's long shadow: environmental issues and options.** FAO, Rome.

Swift, M.J., A.-M.N. Izac and M. van Noordwijk, (2004). **Biodiversity and ecosystem services in agricultural landscapes—are we asking the right questions?** Agriculture, Ecosystems and Environment 104: 113–134.

Tilman, D., K,G. Cassman, P.A. Matson, R. Naylor and S. Polasky, (2002). **Agricultural sustainability and intensive production practices.** Nature 418: 671-677.

Tittonell, P.A., (2013). **Farming Systems Ecology: Towards ecological intensification of world agriculture.** Inaugural lecture upon taking up the position of Chair in Farming Systems Ecology at Wageningen University on 16 May 2013.

Uphoff, N., (2003). **Higher Yields with Fewer External Inputs? The System of Rice Intensification and Potential Contributions to Agricultural Sustainability.** International Journal of Agricultural Sustainability 1(1): 38-50.

Van Oost, K., T.A. Quine, G. Govers, S. de Gryze, J. Six, J.W. Harden, J.C. Ritchie, G.W. McCarty, G. Heckrath, C. Kosmas, J.V. Giraldez, J.R. Marques da Silva and R. Merckx, (2007**). The Impact of Agricultural Soil Erosion on the Global Carbon Cycle.** Science 318: 626-629.

Vitousek, P.M., H.A. Mooney, J. Lubchenco and J.M. Melillo, (1997). **Human Domination of Earth's Ecosystems.** Science 277: 494-499.

Ward, F.A. and M. Pulido-Velazquez, (2008). **Water conservation in irrigation can increase water use.** PNAS 105(47): 18215-18220.

World Bank, (2008). **World Development Report 2008: Agriculture for Development.** World Bank, Washington DC. 366 pp.

Zhang, W., T.H. Ricketts, C. Kremen, K. Carney and S.M. Swinton, (2007). **Ecosystem services and dis-services to agriculture.** Ecological Economics 64: 253-260.