Chapter 2
The Diversity of Living Organisms: The Engine for Ecological Functioning

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The diversity of living organisms has long been the mainstay of agricultural activity and its innovations. However, since the late nineteenth century, particularly in industrialized countries, increases in yields have been based on radically new technologies which deny the biological reality of agriculture and end up artificializing environments. This greatly intensified agriculture is primarily based on fossil fuels (mainly petroleum). It now finds itself at an impasse because of its impacts on ecosystems and the dramatic increase in the prices of inputs and energy. Social inequalities and massive rural exoduses that it has caused are further reasons for concern. Scientists, politicians and NGOs have striven, mainly over the last 20 years, to come up with alternative approaches for developing countries to overcome these energy, economic and environmental crises, and in order to ensure food security for the most vulnerable populations. There is now a widespread conviction that these countries must develop the capacity to ensure sustainable food security. The intensification of their production is therefore essential but has to be based on new approaches. Often grouped under the all-encompassing term ‘agroecology’, these new approaches rely on both the most modern advances in agricultural sciences and the traditional know-how of rural populations.

Paths to ecological intensification today mainly depend on biological diversity. They appear promising not only in terms of yields and economic efficiency but also in terms of sustainability, especially in vulnerable areas (Pretty et al. 2011). We find ourselves in a context of ecosystems with radically altered functioning. Large biological cycles are no longer able to provide services and sufficient renewable resources to meet our needs. And, most worryingly, biodiversity is

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eroding away at an alarming rate. Given this situation, we propose in this book ways of producing more biodiversity, by doing more than just preserving our resources, in fact by explicitly cultivating them. Ecological intensification must produce biodiversity, in all environments ranging from industrial production to small family farms.

This chapter aims to show that the evolution of cultivated biodiversity, i.e., agrobiodiversity, is inseparable from the history of agriculture and of the life sciences.

1 Diversity and Unity of Living Organisms: The Successive Revolutions of the Biological Sciences

If interest in the diversity of living organisms—and ecological thinking—goes back to antiquity, the term 'biodiversity' itself is of very recent origin. Scientific ecology has really developed along with other biological disciplines in the second half of the twentieth century. The idea that almost all of the resources we use are directly dependent on the activity of living organisms from the very origins of life, and that human activities have a major impact on their renewal, received widespread international exposure at the Rio Summit in 1992.

1.1 The Concept of Diversity Explored Over the History of Science

Compared to other sciences, biology is in its infancy. Chemistry was already present in prehistory: thanks to fire, discovered 800,000 years ago, metals and metal-working were mastered early on (gold and silver in 7000 BC, bronze in 5000 BC, iron in 2500 BC). The first physicist-astronomers, on the banks of the Tigris and Euphrates, described the rules of cyclical astronomical phenomena (diurnal, lunar, annual) 5,000 years ago. Greek mathematicians mastered abstraction to establish theorems we still cannot prove today. But it was not until 1854 that G.A. Thuret described gamete fertilization for the first time even though farmers had been using sexual reproduction by practicing empirical selection for 12,000 years.

Aristotle (384–322 BC) is considered the founder of ecology and botany, and to his pupil Theophrastus we owe the first *History of Plants* (320 BC). But it was not until the seventeenth century that naturalists began to identify and classify species, and it is Linnaeus (1707–1778) who devised the binomial system of nomenclature that designates each plant by a generic and specific name.

In the nineteenth century, species were fixed once and for all for naturalists. Charles Darwin (1809–1890) published his groundbreaking *The Descent of Man, and Selection in Relation to Sex* in 1871, in which he laid the foundations of the theory of evolution. Meanwhile, Gregor Mendel (1822–1884) had described the laws of heredity. Published after his death, his work was rediscovered in the early twentieth century, revealing through Mendelian genetics, a law common to all living organisms. In 1918, Ronald Fisher used the laws of heredity to establish the theoretical basis of evolutionary biology which has led to numerous applications in plant breeding.

The revolution in molecular biology, which began with the discovery of DNA—and thus of the profound unity of all living things—by James D. Watson and Francis Crick in 1953, contributed to the considerable development of genetics of today (Box 1). Paradoxically, this revolution has led us to revise and expand the concept of the diversity of living organisms beyond the strict specific diversity.

Box 1. The genome, a computer program of living organisms or a toolbox?

The genome has often been compared to a computer program.
The development of amplification techniques for cell proliferation and gene analysis* opened up significant opportunities for genome analysis. With genetic engineering and clonal propagation, it became possible to build and multiply customized genotypes. These techniques have led to the development of new medical treatments (diabetes, vaccines, antibiotics, etc.). In agriculture, the seed sector and the agrochemical industry have transferred specific characteristics into varieties using gene transfer: resistance to herbicides, various forms of the Bt toxin, etc. But the applications of genetic engineering in plants mainly use molecular markers for genetic selection. Indeed, transgenic varieties—even setting aside the controversies surrounding them—do not always express the genes that are transferred to them. Why does then transgenesis not lead to more applications, and to what extent the comparison of the cell with a computer has done a disservice to biology? This is the question posed in 2011 by the philosopher and physician Henri Atlan in his book *Le vivant post-génomique. Ou qu'est-ce que l'auto-organisation ? (The Post-Genomic Living Organism. Where is the Self-Organization?)* He poses the question asked by a growing number of biologists and addressed by Thomas Heams, molecular biologist, in a *Monde* op-ed on 22 September 2012: '[comparing DNA to a computer program] has been the topic of a vast research programme since the 1950s, that of molecular biology and its thousands of genes, first studied one by one, culminating in large sequencing programs, including that of the human genome, at the turn of the millennium', an issue that extends into the current vogue of synthetic biology. Today, 'genetics is drowning in data'. We take recourse (yet again) to computers to try to bring some coherence in systems biology that is struggling to emerge: 'Apart from a few pioneering studies, multiscale syntheses (from the molecule to the organism) have not been forthcoming.' (Heams 2012).

Thus, are not scientists going down the wrong path in according a major programming role to DNA?

Recent studies militate towards a paradigm shift: the genome, far from being a program 'written in advance', is rather a toolbox that each cell could use with more or less degrees of freedom (Cohen et al. 2009; Ruault et al. 2008). This new 'post-genomic' vision, which emphasizes the 'self-organization of living organisms' (Atlan 1999, 2011) and is consistent with the Darwinian theory of evolution, offers an alternative to the technological approach to decryption: 'By restoring cellular disorder to its proper place in biological explanation, one need not seek non-existent programs [...]. Would we expect to understand the climate using an atlas of all the clouds and all the raindrops on Earth?' (Heams 2012).

*In 1993, K. Mullis was awarded the Nobel Prize in chemistry for the invention of polymerase chain reaction (PCR).

Thanks to new scientific and technological methods, the rate of new scientific discoveries has been accelerating since the 1970s. Our knowledge of evolution has grown by leaps and bounds and we now realize the key role of living organisms in the history of our planet and of mankind.

On a geological time scale, it was the life of cyanobacteria that created a breathable atmosphere, patiently accumulating oxygen for several billions of years. This led to an evolutionary revolution by opening the door to aerobic organisms. It is the diversity of living organisms that has shaped our planet by allowing the accumulation of metal ores through oxidation. They are also responsible for the vast sedimentary formations of limestone and shale, and for coral reefs. Finally, the very same diversity of living organisms is at the origin of deposits of coal, oil, natural gas and phosphates—veritable storehouses of energy or chemicals.

Nowadays, biodiversity is considered in its temporal dimension, as a dynamic process. It is an ever-evolving system, from the point of view of the species as well as of the individual. The mean half-life of a species is estimated to be 1 million years and a full 99 % of species that have lived upon Earth are now extinct.

Biodiversity is also considered through its spatial component: it is not distributed evenly on Earth (Box 2). Flora and fauna differ depending on various criteria such as climate, altitude, soil or intervention by man or by other species. At the local or regional level, it evolves within ecosystems, which are associations between a given biophysical environment, the habitat and populations of living organisms—the biotic community—in perpetual co-evolution.

As our knowledge grows of the dynamics of interactions between species or populations of species within ecosystems and of the multiple functions of production, regulation and services they provide shows that the diversity of living organisms is indeed the engine of ecological functioning.

Box 2. Areas of megabiodiversity (hotspots)

Today, there are estimated to be over 8.7 million living species on Earth. They are not evenly distributed: thus, in 1988, the American primatologist Mittermeier discovered that four 'megadiversity' countries—Brazil, Indonesia, Madagascar and the Democratic Republic of Congo—accounted for, just by themselves, two-thirds of primate species on the planet (Mittermeier and Goettsch Mittermeier 2005). With his colleagues at Conservation International, Mittermeier expanded his research to other species. In 1997, 17 countries were recognized as megadiverse because they each host at least three thousand species of endemic vascular plants.

'Hotspots' of biodiversity are locations where the largest concentrations of plant and animal species, often endemic, are found. They are mainly concentrated in the tropics: the Amazon Basin, the Congo Basin, Madagascar, islands of Melanesia and of the East Indies, Amazonian foothills of the Andes, coral reefs, and forests of Borneo and New Guinea.

The concept of megabiodiversity applies to these hotspots at the national level and are usually demarcated by political boundaries. Thus the Amazon region extends over six countries: Bolivia, Brazil, Colombia, Ecuador, Venezuela, and Peru (French Guiana makes France their neighbour!). Costa Rica and Mexico in America; China, India, Indonesia, Malaysia, Nepal and the Philippines in Asia; Kenya, the Democratic Republic of Congo, Madagascar and South Africa in Africa joined these six countries in Cancun in 2002 to form the 'Group of Like-Minded Megadiverse Countries'. This group serves as a mechanism for consultation and cooperation so that these countries' interests and priorities related to the preservation and sustainable use of biological diversity can be promoted. France, through its overseas *departments*, is also part of the movement.

It is worth noting that the biologically megadiverse countries are also those where cultural forms (language, arts, etc.) abound in greatest numbers.

1.2 Biodiversity on the International Stage

The term 'biodiversity' was born in 1986 due to heightened concerns about the extinction of species and due to a growing perception of its role as an engine in the planet's functioning.

In June 1992, the Rio de Janeiro Summit brought these concerns onto the international stage. Biological diversity was viewed as 'the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystems' (Convention on Biological Diversity, CBD 1992). The Convention on Biological Diversity (CBD) became available for adoption at the Rio Summit. Today, it has been signed by 193 countries committed to the conservation of biological diversity, its sustainable use, and fair and equitable sharing of benefits arising from the use of genetic resources. A comprehensive work was undertaken to highlight three levels of understanding the diversity of living organisms in terms of their social, economic, cultural or scientific importance:

- ecosystems and habitats which (i) host high diversity or large numbers of endemic or threatened species, or encompass wilderness areas, (ii) are necessary for migratory species and (iii) are representative, unique or associated with key biological processes;
- threatened species and communities; wild species related to domesticated or cultivated species which are of medicinal, agricultural or economic interest; species of interest to research, such as indicator species;
- genomes and genes of social, scientific or economic importance.

In (1996), the Conference of the Parties of the CBD held in Buenos Aires recognized 'the special nature of agricultural biodiversity, its features, and problems needing distinctive solutions'. Man and his agricultural activities are indeed at the heart of these ecosystems.

The concept of agrobiodiversity was thus born, defined as 'the set of components of biological diversity in relation to the production of goods in agricultural systems'. It encompasses the genetic resources of plants, animals and microorganisms (programmed biodiversity), genes, species and ecosystems necessary to maintain the functions, structures and key processes of agricultural systems (associated biodiversity), in particular the pollinators, parasites, symbionts, pests and competitors. Agrobiodiversity has a critical socio-economic and cultural dimension because it is heavily influenced by human activities and management practices. Local and traditional knowledge, cultural factors, participation processes and tourism are also taken into account (Conference of the Parties 2000).

Our understanding of agrobiodiversity has changed: we now put the interactions between organisms and their functional relationships at the heart of the agronomic approach. We consider the cultivated plot as a dynamic system and integrate cultivated areas into the landscape. Agrobiodiversity is not only the genetic resources of domesticated plants and animal species or gene stocks to keep available for their improvement and future adaptation. It is also the diversity of all species 'auxiliary' to crops, aerial or soil-based, in and around the plot. In the agroecosystem, man too is very much present through his interventions, production activities, and his cropping practices. He programmes a part of the diversity, one that he cultivates or raises (plants and animals). But in an integrated approach, he must henceforth take into account, the 'other' side too, i.e., species that share this space with crops, irrespective of whether they are 'useful' or 'harmful'. In addition, since the space is not compartmentalized, there exist flows between agrobiodiversity and 'natural' biodiversity through numerous interfaces and interactions.

How does one manage such a diversity? How to enrich, optimize, guide—in one word 'cultivate'—this diversity? A further step forward was taken with the Millennium Ecosystem Assessment (MEA 2005), a monumental undertaking by over 1,300 experts from around the world. In arriving at an assessment of the planet's resources and spaces, they have helped us understand the importance of local customs and cultures in the maintenance of biodiversity and the many services it provides.

2 A History Closely Linked to Man's

It is now established that agriculture arose simultaneously in several centres, on all continents, about 12,000 years ago. It marked the transition from man's use of natural plant and animal resources—hunting and gathering over vast spaces—to the domestication of useful species, i.e., their multiplication and cultivation on cleared and demarcated plots. The descendants of plants that had different favourable usage characteristics (food, medicines, fibres, transmission, production cycles, harvesting, storage, etc.) were grown through seeds or cuttings. The dawn of agriculture also corresponded with the settlement of a portion of human populations and a new division of labour between farmers and non-farmers. Agriculture also made them probably aware of the necessity of managing resources in a limited space, and thus encouraged them to innovate in production techniques in these very first stages of 'intensification'.

2.1 The Origins of Agrobiodiversity

Anthropologists have drawn attention to the role of traditional communities in the conservation of agricultural diversity. Women in particular play a very important role through their detailed knowledge of plants and the myriad criteria by which they choose and exchange them: behaviour depending on soil; altitude; sunshine and rainfall; yield and ease of being processed; pest and disease resistance; organoleptic and aromatic qualities; emotional, social and aesthetic values; etc.

This is why in regions where some species have originated or diversified, there is a staggering variety of cultivars: seven recognized species and 5,000 varieties of potatoes still cultivated in the Andes (FAO 2008a), 92 names of rice varieties listed with the Hanunóo in the Philippines (Conklin 1957), etc.

Selecting plants like this, according to very varied criteria, enables continuous genetic hybridization, including with wild relatives. Indeed, this is the basis of the adaptation of crops and their renewal.

Peasant communities have drawn from the genetic diversity of species for over six hundred generations. They first domesticated them, then organized production into 'cropping and livestock systems' and, finally, improved their performance through increasingly focused work on the selection of varieties or races. By specializing the production, first the farmers, then agronomists and scientists, and finally the seed industry, have ended up maintaining a 'gene pool' of crops and livestock.

2.2 The Great Voyages of Exploration and Redistribution of Cultivated Species from the 15th to the 19th Century

Even though species and varieties have travelled at all times, their movements accelerated in an unprecedented way in the fifteenth century. The history of the cultivated plants commonly found today begins in 1453 with the great navigational explorations, when the fall of Constantinople led Europeans to leave Turkey and undertake sea journeys to obtain food commodities that they needed (Volper 2011).

With the discovery of America, the range of useful plants in Europe became considerably enlarged. Tomatoes, maize, beans and potatoes were introduced to Europe in the sixteenth century. The English, French, Dutch, Spaniards, Portuguese and Danes all stepped up their efforts to successfully 'acclimatize' these new species, which soon changed profoundly the landscape of European agriculture. But many species collected were not always cultivable in European climates, and the territories conquered in the tropics were instead asked to grow them. Thus sugar cane, native to New Guinea and grown in the Pacific, was spread across the New World. This species is typical of the colonial era. In fact, to satisfy their passion for sugar, the colonial powers disrupted international trade, imposing appalling terms on their new possessions: the so-called 'triangular trade' (Europe, Africa and the New World). The same pattern was repeated for other large strategic tropical productions—cotton, coffee, cocoa, rubber, oil palm, etc.—which led to frenzied commercial competitions around these commodities.

The European industrial revolution in the nineteenth century accelerated the pressure on crops, increasing the need for raw materials and new markets. Europe turned to Africa and Southeast Asia and, at the beginning of the twentieth century, embarked on major undertakings for the exploitation of agricultural potential of their colonies.

Botanical gardens, in particular the National Museum of Natural History in Paris (and the colonial garden it set up in nearby Nogent-sur-Marne) and the Royal Botanic Gardens at Kew in the United Kingdom, played a role in the acclimatization of species. Colonial enterprises headquartered in the home countries started expanding in size and reach from 1925 onwards. Colonial exhibitions attracted investors who in turn relied on the professionals: the tropical agronomists. And so, with the intensification of production, was born tropical agronomy, based on the scientific knowledge of the time, i.e., tested in temperate industrialized countries. Agricultural systems in the former colonies, even after they gained independence, remained profoundly and lastingly marked by these developments.

During this time, the seeds travelled and were exchanged (Box 3). Genetics arose as a major component of agricultural intensification, especially for improving productivity and for combating the many crop diseases and pests.

Box 3. Origins of a few iconic tropical crops

Cocoa, discovered by Christopher Columbus in Nicaragua, was introduced to Europe by Cortez in 1528 to his king, Charles V of Spain. Initially, the preserve of the elite, its consumption became popular only in the twentieth century. The primary producers of cocoa today are Côte d'Ivoire, Ghana and Malaysia.

Coffee, which is of Ethiopian origin, was introduced to Europe in 1615, 5 years after tea. It soon gained a following there and spread widely. The history of its cultivation is long and convoluted. It is now produced by nine major countries including Brazil, Colombia, Indonesia, and Vietnam (Ethiopia is in sixth place).

The **rubber tree** and its latex became known to Europeans with the discovery of America. Yet it was only in the eighteenth century that it attracted any real interest with the first industrial applications and the first processes, developed in 1790. It is the automotive industry which, in the late nineteenth century, caused global production to explode, mainly due to the development of the vulcanization process. Native to the Amazon, it is now produced in Asia, with Thailand, Malaysia and Indonesia accounting for three quarters of global production. Rubber cultivation provides 44 % of the world's production of elastomer and is grown on 10 million hectares maintained by millions of smallholders. Eighty percent of the 10 million tonnes of natural rubber they produce is used in the automotive industry.

The **banana**, discovered in India by Alexander the Great, also existed in China at that time. In 650, Islamic conquerors imported it into Palestine and to the island of Madagascar. From there, traders carried it all over Africa. In 1402, Portuguese sailors planted it on the Canary Islands. A Portuguese monk brought it to the island of Santo Domingo in 1516. It did not take long before it became popular throughout the Caribbean and Central America: in the eighteenth century, more than three million banana trees were growing on Martinique. The banana is the third biggest tropical fruit crop, with about 15 % of production being exported and 85 % being consumed locally, especially in the poorest countries of Africa, Latin America and Asia. Over a thousand banana varieties currently exist. Staple food in many tropical countries, locally consumed banana plays a major role in food security.

The **oil palm** originated in West Africa, where its consumption in food probably dates back over 5,000 years. In 1959–1960, the government of Côte d'Ivoire launched a major development programme for industrial and village plantations of selected oil palm varieties. But African production, while flourishing at the beginning, has been overtaken by the explosion of production in Asia in a market dominated today by Malaysia, Indonesia, Nigeria and Thailand. The primary oilseed crop in the world, the oil palm has become a strategic crop for many tropical countries. With a production of 42 million tonnes in 2008, it represents more than a third of global production of vegetable oils. Its rapid expansion, like that of rubber, often at the expense of the primary forest, has raised new research questions.

2.3 Agricultural Revolutions and Genetic Resources in Europe in the 20th Century

Since the Neolithic age, agriculture has experienced some major technical revolutions (Mazoyer and Roudart 2002). These have included use of flood rivers in antiquity, the advent of irrigation systems, the development of complex cropping systems such as triennial crop rotations with fallow in the Middle Ages and animal draught cultivation. More recently, in the seventeenth century, animal feed, mechanization and organic manure arrived on the agricultural scene. This dominant model persisted in France until the early twentieth century, even in the period leading up to the Second World War, whereas the United States began the modern agricultural revolution as far back as the 1930s.

It should however be noted that in France, the Vilmorin-Andrieux family of seed merchants published a catalogue describing and comparing wheat varieties as far back as 1850. By cross-breeding wheat and *Aegilops*, they played a pioneering role in plant breeding. In 1873, Henry de Vilmorin (1843–1899) started improving wheat varieties through systematic and reasoned cross-breeding and, 10 years later, marketed the first wheat variety originating from a genealogical selection.

The last phase of modernization and industrialization of agriculture has greatly increased yields and lowered production costs in industrialized countries. Between the two World Wars, the goal was to better integrate agricultural production into market economics and improve farmers' living conditions. Increasingly powerful mechanization, the development of agrochemicals and agrifood industries and genetic advances have enabled this transformation of agriculture. High yields have been accompanied with extraordinary increases in labour productivity but also, unfortunately, in energy consumption. By modernizing itself, agriculture has become dependent on fossil fuel resources.

The pesticides industry has developed, thanks to research in organic chemistry during the two wars. Military research had already perfected combat poison gases which, after the war, were used against insects. In the 1950s, insecticides such as DDD and DDT were used in large quantities in preventive medicine (mosquito disinfestation against malaria) and agriculture (elimination of the Colorado potato beetle). The use of these products then experienced very strong growth, making them virtually indispensable to most agricultural practices. This dramatic intensification was based on the idea that agricultural production could be beneficially reduced to chemical flows, and that all that was necessary was to complement what nature had difficulty providing. From 1945 to 1985, the consumption of fertilizers and pesticides doubled every 10 years. Pesticides proved to be a powerful means for increasing agricultural yields and for helping ensure an abundance of food while limiting deforestation. But the use of synthetic fertilizers, herbicides, insecticides and fungicides has artificialized agroecosystems by homogenizing the soil at the trophic level. These synthetic products have accumulated in soils and waters and have destroyed, along with pests, many useful species necessary to maintain agroecosystem balance.

Genetics has contributed greatly to the development of this intensive agriculture. Geneticists have relied on the richness and diversity of cultivated varieties from around the world to find characteristics that can provide ever increasing yields in a non-limiting nutritive context and to fight against various agricultural pests. In 1933, the first hybrid maize from cross-breeding came to market in the United States. Today these high-yielding varieties allow compounded year-on-year gains of more than 1 % over long periods.

To improve crop species, geneticists study their history, their origins and the role of farmers in their selection. Surveys are organized, private and public collections of genetic resources are created, and seed companies arrange to exchange samples.

The intensification of agriculture has had the rapid effect of reducing considerably the number of cultivated species and varieties. This has led a concerned scientific community to scramble to preserve their genetic resources. The first collection of material obtained from surveys was created by Russian geneticist Vavilov (1887–1943), following botanical and agronomic expeditions to help support the theory on the origin of cultivated plants. It had 250,000 accessions in 1940, of which 30,000 for wheat. Today, it has 400,000. There are now many gene banks around the world, with the Svalbard Global Seed Vault in Norway being probably the best known. In addition to these major banks, a few small treasures of genetic material are being maintained and enriched by enthusiastic and concerned producers (Box 4).

Vavilov developed the concepts of 'centres of origin' and 'zones of domestication' of a given species, where genetic intermixing is the richest. These concepts, still in vogue today, were further advanced and refined by numerous studies on the phylogeny of different cultivated species with the help of the tools of molecular biology. The history of 'complex species' and the role mankind and populations have played in their selection and dissemination have been studied by geneticists with the help of ethnobotanists, joined nowadays by linguists and anthropologists.

The ‘programmed biodiversity’ of agroecosystems is thus stored in gene banks since the advent of genetics, even though the ideas and modes of preservation and conservation of ‘useful’ genetic diversity have changed over time.

2.4 The Green Revolution

After the Second World War, the colonies took the path of independence and development. But even though by then industrialized countries had adopted intensive agriculture, its transfer to developing countries did not prove so simple, mainly because of its dependence on inputs.

The Green Revolution was thus born out of a political will to transform agriculture in developing countries (FAO 1996; Griffon 2006, 2011). Modelled on the systems in industrialized countries, its main goal was intensification and the use of high-yield cereal varieties. It was orchestrated by international agricultural research centres and large foundations associated with major American universities.

The Green Revolution was based on three factors: use of high-yield varieties, use of inputs—fertilizers and pesticides—and irrigation in areas at risk of water stress. This profound transformation of agriculture has led to increased energy costs in developing nations, but not in the same measure as in industrialized countries because mechanization has remained ultimately limited. This revolution was also based on a massive support from public policies, both for infrastructure investments as well as for price guarantees and technical training. Its beginnings can be traced to Mexico in 1943, where the government, with support from the Rockefeller Foundation, achieved a dramatic increase in wheat production. Self-sufficient in 1951, the country became an exporter the following year, even though during the same period its population grew significantly.

Norman Borlaug, who developed the high-yield wheat varieties in the Office of Special Studies (OSS), Mexico City, and then disseminated them in Asia, is considered the father of the Green Revolution. His work earned him the Nobel Prize for Peace in 1970. The Rockefeller Foundation endeavoured to spread the idea of the Green Revolution by helping set up new international research centres in the world: CIMMYT (Centro Internacional de Mejoramiento de Maiz y Trigo), succeeded the OSS in Mexico in 1963, and IRRI (International Rice Research Institute) was established in the Philippines in 1960. The latter was instrumental in helping spread the use of high-yield rice varieties in Asia.

The Green Revolution, undeniably successesful in Asia—though less obviously so on other continents—has long seemed to be the most effective model of development in developing countries. India is the most cited example: it has increased wheat production ten-fold and that of rice three-fold. Areas of chronic hunger have turned exporters, but under conditions in which sustainability remains challenged due to the requirements the varieties grown have for water, fertilizers and pesticides.

The externalities of the Green Revolution have also gradually emerged: social, with a massive rural exodus; and environmental, with widespread soil degradation, misuse of pesticides and subsequent pollution, and the homogenization of cultivated varieties. This homogenization has led to a large loss of traditional knowledge and agricultural biodiversity, most notably in local cultivars. Concerns have also emerged about the resilience of these varieties to the emergence of new pathogens.

The spectre of genetic erosion is now haunting the varieties of the countries of the South. To address these concerns, seed banks have been established, modelled on the International Plant Genetic Resources Institute (IPGRI), now Bioversity International.

In fact, many developing countries have drawn little or no benefits from the advantages expected from modern agriculture and have seen no wealth flow from it. The reasons cited most often are unfavourable soils and climate, and lack of water, financial capital and appropriate training. To these can be added the unfavourable political, economic and legal environments in a number of countries. Imbalances caused by the protection of certain markets, most notably the massive subsidies given to industrial agriculture in rich countries, also share the blame. In the case of Africa, the dynamics of intensification were abruptly halted by the period of structural adjustment in the 1980s.

3 Documented Risks of Erosion of Agrobiodiversity

Many studies have attempted to assess the general effects of pressures on biodiversity. But biodiversity, as we have mentioned, is a dynamic process, wherein agriculture plays a special role. In this book, we are particularly interested in the biodiversity of agroecosystems.

The difficulty of quantifying diversity depends on the level we approach it at: allelic, specific or ecosystemic (Le Roux et al. 2008). Documenting changes in diversity is just as difficult and controversial as quantifying it in the first place. The figures quoted below are mainly drawn from the Millennium Ecosystem Assessment (MEA 2005) and FAO. The latter was made responsible in 1999 to assess periodically the state of Earth's plant genetic resources for food and agriculture in the world. Its brief is to propose action plans to the international community, guided by the international Commission on Genetic Resources for Food and Agriculture. In 1996, a global action plan was drawn up and to date 170 countries have adopted it. According to the Second Report on the State of Plant Genetic Resources for Food and Agriculture in the World (Commission on Genetic Resources for Food and Agriculture 2010), the main reason for the erosion of genetic diversity is the replacement of local varieties by modern varieties, a trend that has accelerated in the last 50 years. Other causes, such as environmental degradation, urbanization, and land clearing through deforestation and bush fires are also highlighted.

The need for relevant indicators that can be reliably defined and acquired has made them the topic of research programmes and international negotiations.

3.1 Agriculture, the Planet's Most Important Landscape

Today, of Earth's entire surface of about 51 billion hectares (including the oceans) an estimated 12 billion hectares (land and water) are bioproductive in the sense that they create a certain amount of organic matter each year through photosynthesis. The landmass covers 14.9 billion hectares, of which 70 % is directly subject to human activity. Photosynthesis also exists in deserts and most parts of the ocean, but is spread out too thinly for its products to be exploited by man (Ecological Footprint Atlas 2009).

Ten percent of the landmass area, i.e., around 1.5 billion hectares, is cultivated land, of which one–third is dedicated to livestock feed. Added to this area are 3.4 billion hectares of pastures (consisting of 1.4 billion hectares of improved grasslands and 2 billion hectares of natural pastures and rangelands) and 4 billion hectares of forest cover (including 1.4 billion hectares of primary forests). Farmers have therefore shaped a very large part of our planet over the centuries.

The number of farmers in the world is estimated at 2.3 billion,[1] i.e., almost one quarter of the world's population and half its workforce. A large majority of these farmers is in developing countries; in developed countries, farmers represent only 2–3 % of the population. The World Bank (2008) considers that in the least developed countries (LDCs), two-thirds of jobs remain directly linked to agricultural activity. Most of these countries are in sub-Saharan Africa, where agriculture employs 65 % of the workforce and accounts for nearly a third of GDP growth.

3.2 A World Heritage Under Threat

According to the FAO (2010), about 7,000 *plant species* have been grown for consumption over the span of human history, with other sources putting this number much higher (it must be noted that for plants, we speak of complex of species rather than of individual species). For nearly 12,000 years, the large diversity of varieties maintained or domesticated by man have provided him food, fibres, material and energy. It has ensured the survival and development of human populations inspite of pests, diseases, climatic fluctuations, droughts or other hazards.

[1] Most of the figures mentioner here are from Millennium Ecosystem Assessment. See also: Convention on biological diversity, 2008. Biodiversity and agriculture—Protecting biodiversity and ensuring food security, www.cbd.int (retrieved: 29 November 2012).

Yet, today, only about thirty species meet 95 % of human and animal food needs. Four of them—rice, wheat, maize and potato—satisfy more than 60 % of food energy needs. The loss of diversity within cultivated species is also widespread, as illustrated by the case of the apple (Box 4).

Box 4. From industrialization and erosion because of standardization to diversification by farmers: the case of the apple in France

Known and appreciated since ancient times, the apple experienced spectacular growth in the nineteenth century, with France playing a major role*. André Leroy, a famous French nurseryman of the early part of that century, described 527 well-differentiated varieties in his catalogue. And plant breeders did the rest: there are today nearly six thousand varieties worldwide.

Between the two World Wars, urbanization led to the disappearance of many town orchards and small producers. More distant producers were then tasked with producing more fruit with increased tolerance to transport and which could remain fresher for longer periods. In this way, a large number of varieties fell by the wayside.

After the Second World War, grubbing-up premiums were offered to farmers for replacing their apple orchards with intensive agriculture. In 1960, the official catalogue of species and varieties was created by the Permanent Technical Committee for Selection. It drew up the list of varieties that could be marketed. Only one French apple was listed as Class I and could become part of modern distribution supply chains. The other varieties (11,000 worldwide) were no longer cultivated except only occasionally by a few small producers who slowly succumbed to economic pressure.

Faced with such a significant loss of heritage, pomological associations were created by enthusiasts in the late 1970s. One of them, the Pomological Association of Upper Normandy**, conducted a census in France: there are 37 conservatory orchards growing 987 apple varieties. Two hundred of these varieties are used, half of them as 'table fruit'.

*See http://www.lapomme.org (retrieved: 4 April 2013).

***Association pomologique de Haute Normandie*, http://www.aphn.net/ (retrieved: 4 April 2013).

About 35 *animal species* have been domesticated for agriculture and food production. Their intraspecific diversity is reflected in the many indigenous breeds. These chosen breeds are well-suited to local conditions because of their resistance to climatic stress, diseases and parasites, or because of their adaptation to specific agroecosystems. However, according to *The State of the World's Animal Genetic Resources for Food and Agriculture* (FAO 2008b), 20 % of livestock breeds, i.e., around 1,500 of the 7,600 races in the world, could disappear forever in the near future due to inability to adapt, inbreeding, unsustainably small populations, etc.

Even though *aquatic biodiversity* plays a vital role in human livelihood, it is currenly under threat from overfishing, resource depletion, destructive practices, the introduction of exotic species, and habitat destruction and degradation. In 2008, an estimated 1,731 species or groups of aquatic species (finfish, shellfish, molluscs, etc.) were commercially fished, many of which are destined to disappear before the middle of this century. With the trawlers going further out into the oceans and becoming better equipped, the FAO estimates that about one fish species in three is threatened with extinction. Only pisciculture can compensate for the expected drop of fished quantities. *Aquaculture* is one of the food production sectors experiencing the fastest growth. More than 360 species of fish, invertebrates and plants are grown in the world, most only since the last 100 years or so.

Two agroecosystem compartments are particularly vulnerable to the effects of intensive agriculture: (i) the soil and (ii) the habitats of auxiliary species of crops. It is this biodiversity—whose importance we are only now realizing—which is emphasized in the concept of agrobiodiversity. Because it is poorly understood and because we have an incomplete grasp of its functioning, it is particularly difficult to estimate its erosion.

Soil biodiversity reflects the variability among living organisms. It ranges from micro-organisms (e.g., bacteria, fungi, protozoa and nematodes) to the larger meso-fauna (e.g., acari and springtails) to the more familiar macro-fauna (e.g., earthworms and termites). Plant roots can also be considered soil organisms in view of their symbiotic relationships and interactions with other soil components. These diverse organisms interact with one another and with the various plants and animals to ensure the ecological functions of the soil through trophic exchanges, information flows, etc. In this way, they contribute to the provision of ecosystem services essential for life.

Microbes and invertebrates form the group of species which are the most numerous on the planet (World Conservation Monitoring Centre, WCMC 1992). It seems impossible to inventory them, given the difficulty in even quantifying the number of species. It is now estimated that there are about 10–50 million undescribed species of microbes and invertebrates. Food and agricultural production depends on multiple interactions with this 'hidden' biodiversity, whose functional role has been completely ignored by intensive agriculture. Bees, butterflies and other insects pollinate fruits and vegetables. Microorganisms form symbioses with the roots of cultivated plants and some fungi, or with animal organisms whose intestines they inhabit and whose assimilation functions and health they help regulate. They allow livestock ruminants—bovines, ovines and caprines—to assimilate cellulose. They help conserve and enhance protein in foods, especially through fermentation. Microorganisms and invertebrates are essential for breaking down dead matter and for the recycling of organic matter in soils. They can even be used as biological control agents. They are thus indeed at the heart of the ecosystems' basic operating mechanisms.

3.3 Ecosystems and Habitats Under Pressure

Natural forests are a source of income for many of the poorest countries, representing more than 10 % of GDP for some of them. One billion people make their living directly from them. They are also the most important reserves of terrestrial biodiversity. Despite this crucial economic role, the loss and degradation of tropical forests continues at an alarming rate of more than 10 million hectares per year. The loss of forest diversity imperils its future valorisation in terms of medicines, foodstuffs and raw materials, and it jeopardizes the well-being of many populations since it impacts the very basis of their livelihood. The use of forest plantations can meet some of these needs (timber, fuel wood) by sparing natural forests, but it cannot recreate the complex biodiversity of natural forest ecosystems.

At the *agroecosystem* level, the industrialization of agriculture generally results in the dissociation of crops and livestock through the specialization of farms and a homogenization of landscapes. This very important aspect is discussed further below (see 'Effects of the evolution of landscapes').

Finally, at the landscape scale, the phenomena of *biological invasion* (Box 5) also comes into play. More widespread today than ever before because of the globalization of trade, they are now considered by the UN as one of the major causes of the loss of biodiversity, along with pollution, the ecological fragmentation of ecosystems, hunting, fishing and the overexploitation of certain species. Reductions in the number of individuals of endangered species in particular has a very significant impact on their intraspecific diversity.

Box 5. Invasive species and biodiversity in island environments: example of the French Antilles

The French Antilles (also known as the French West Indies) have a climate conducive to extreme weather events such as cyclones. In addition they run the risk of volcanic activity. During the colonial period, massive clearing and overexploitation of forests took place and this was followed by a period of intensive agricultural production with heavy pesticide use. Its biodiversity thus underwent great stress (Sastre et al. 2007). Like other tropical islands, the islands of the French Antilles too host a unique biodiversity. But because of their insularity and pressures of rapid population growth and development, these ecosystems have become particularly vulnerable.

The destruction of natural habitats has led to the disappearance of most of the dry forests for purposes of urbanization and agriculture. Overexploitation of resources has exacerbated the situation. Thus, parrots of the Lesser Antilles have been hunted to extinction in Guadeloupe and Martinique, even though these two islands once had the largest number of these iconic species and even though mountain forests, one of their preferred habitats, yet remain.

Invasive alien species are another threat, in both natural and cultivated ecosystems:

- Rodents (black rat, brown rat, gray mouse) have been impacting agricultural production for several centuries.
- More recently, the 'cassava ant' has run over all of Guadeloupe within a few decades, causing significant damage to crops and gardens. Pesticides that are used to control it are known for their toxicity and persistence.
- The giant African snail (*Achatina sp.*) amazed residents by the speed of its colonization in the 1990s and the damage it caused. However, as on other oceanic islands, a relative equilibrium has been established, with a strong overall decrease in population and damage that is now localized and/or episodic.
- Many plant species have been introduced, some of which have become a problem for crops.
- Emerging pests threaten crops or livestock: *Ralstonia solanacearum*, tomato bacterium; black cercosporiosis, fungus attacking banana; Senegalese tick, vector of cowdriosis, etc.

In addition, some current agricultural practices threaten biodiversity: excessive use of fertilizers and pesticides, limited water resources, land clearing, etc.

'Biological' agriculture is a promising path to diversification and is partly already being practiced in Creole gardens. The horticultural sectors (fruit and vegetables) and some major crops such as sugar cane are gradually taking this path by adopting the so-called 'organic' practices of agroecology. In close collaboration with research, most sectors, in particular the banana sector, have adopted programmes for sustainable production, especially through the use of functions of agricultural biodiversity as a whole*. These paths are explored in detail in this book's later chapters.

*As part of the 'Antilles Sustainable Banana Plan', launched in 2008 by the Ministry of Agriculture at the initiative of the Union of Groups of Banana Producers (UGPBAN) and banana producer groups, the Tropical Technical Institute (IT^2), Cemagref and CIRAD are developing solutions to combat diseases of the banana and develop tools for sustainable banana production in the French Antilles.

For further information: Feldmann et al. (2007).

3.4 *Effects of the 'Modernization' of Agriculture on Biodiversity*

3.4.1 Effects of Agricultural Practices

According to a collective INRA study (Le Roux et al. 2008), there exist no statistics or suitable indicators to assess the environmental costs of agricultural practices, especially on the interactions between organisms. The few indicators that do exist are limited to the extent of the plot or are for periods that are too short. This group of experts referred to some two thousand bibliographical references—concerning mainly temperate crops—for analyzing existing knowledge on the relationships between agriculture and biodiversity.

To estimate the effects of agriculture on agroecosystems, experts have to study mechanisms at various levels: the entirety of agricultural practices at the plot scale; the impact of agriculture on the agroecosystem (cultivated areas, field edges, woods, ditches, etc.); and cohabitation between agroecosystems and natural ecosystems across the landscape or even region. As far as the effects are concerned, they distinguish three categories of biodiversity: alpha diversity, i.e., richness of species of the plot; beta diversity, which reflects changes in alpha diversity between habitats across the agroecosystem; and gamma biodiversity, considered at the landscape, region or country scale.

Studies at the *plot level* highlight a number of general factors that have an impact on biodiversity.

In *annual crops*, material flows (inputs, harvests) are very large and the disturbances are severe: destruction by pesticides, massive export of biomass, modification of the soil by tillage, and of the biocenosis by pesticides or indirect trophic effects. The result is a decline in the richness and abundance of many species: microorganisms, soil flora and fauna, insects, amphibians, birds, etc. Deep ploughing, for example, affects macrofauna, especially earthworms. Depending on their modalities and application frequency, synthetic pesticides used to combat insect pests can have dramatic effects on arthropod life cycles. Fungicides are even more toxic to soil organisms. Herbicides have an effect on a number of plant species, but also on species that are functionally associated with the latter. Finally, the development of species resistant to the molecules used causes significant imbalance in the ecosystem. The use of transgenic plants carrying the Bt toxin carries the same type of risk, to which can be added, over the long term, the transfer of genes into other species. Synthetic fertilizers, which have strong positive effects on the growth of plants and soil organisms, significantly modify the physical chemistry of the soil environment and affect trophic chains. They are also responsible for the disappearance of species better adapted to poor or fragile environments and significantly alters aquatic and terrestrial ecosystems (eutrophication, etc.).

Most of these impacts can be estimated by observing the effects of stopping treatment, but in the process, there will be irreversible loss of biodiversity.

Some loss of diversity can also be reversed by changing the production mode to organic farming, eco-agriculture, conservation agriculture, etc. Properly planned and executed rotations can lead to a reduction in pesticide use by disrupting the pathogen cycles.

Permanent grasslands are usually not subjected to pesticide applications. Even though they can be highly fertilized and intensively exploited, they have a much higher biodiversity than do cultivated monoculture plots. However, heavy grazing has, in general, a negative effect on the wealth of flora, arthropods and soil fauna. Moderate grazing, on the other hand, has a beneficial effect on the richness of many species groups. Finally, hayfields are generally richer in plant species than are grazed grasslands. But other factors come into play and have to be considered, such as the impact of different herbivore species, of the products they excrete, etc.

Pesticides are repeatedly applied to *perennial crops* to fight the always present pests and diseases. This is the primary factor to impact biodiversity. Pesticide use has a significant negative impact, for example, on the functional entomological diversity. It is clear that the presence of several exploitable vegetation strata and use of cover crops are conducive to maintaining trophic networks of species. Agroforestry is thus a possible route to diversification.

The results of *abandoning agricultural practices* on plots previously farmed depends on their initial state: the cultivated plots evolve positively for all groups of organisms in the early years. However, in the case of permanent grasslands, abandonment leads to a systematic decrease in the plant species richness. In all cases, when the abandonment time increases, species richness tends to decrease, especially when woody species start growing there. In functional terms, the short-lived plant species, dispersed by the wind and able to acquire resources, are replaced by long-lived woody species which are dispersed by birds. Soil fauna, mainly earthworms, evolves with these woody species.

Organic farming has a positive effect on biodiversity. The richness of plant species, soil microorganisms, vertebrates and arthropods all increase as does the abundance of invertebrate predators. But the structuring of the landscape also affects species richness and should be tuned to the agricultural practices if rare species have to be restored.

The *use of transgenic plants* is part of the technological intensification of agriculture. In 2011, according to estimates by the International Service for the Acquisition of Agri-Biotech Applications (ISAAA) (James 2011), which promotes GMOs, in particular in developing countries, 160 million hectares of transgenic varieties were cultivated in 60 countries. This represented an increase of 8 % over the previous year, proving the continuing strong growth of these varieties. The most common transgenic varieties are maize, cotton, soybean and potato, and the main feature that is disseminated is herbicide tolerance (59 % of surface area). ISAAA figures are disputed by the NGO Friends of the Earth, which also believes that in 2007 'nearly 90 % of all GM varieties marketed worldwide contained Monsanto traits'[2] (most generic GMO patents are American).

The impact of these transgenic crops on biodiversity is primarily due to their wide dissemination. Today, in the United States, 85 % of all maize grown, 91 % of soybeans, 88 % of cotton and nearly 95 % of the beet is genetically modified. Like all elite commercial varieties, they have a narrow genetic base, and their expansion, based on aggressive marketing, is mainly at the expense of crop diversity.

The impact of the transferred genes on the diversity of insects and plants in and around cultivated fields has been extensively studied for both herbicide-resistant and Bt GMOs. Their transfer to plots cultivated without GMO is sufficiently proven, at least for cross-pollinated crops such as maize and rapeseed, for the Scientific Committee of the High Council on Biotechnology in France to issue a notice[3] regarding the coexistence of genetically modified (GM) crops and non-GM crops. In spite of the arguments for and against, controversies and intellectual property litigation, there is no clear unequivocal link between the use of transgenic plants and biodiversity since the results depend so much on the climatic contexts, cultivated species, changes in practices of pesticide use, target species analyzed, etc. The risks associated with the spread of transgenes into wild plants—and thus the modification of wild biodiversity—are not negligible, but the potential damage of these transfers remains controversial.

3.4.2 Effects of the Pressure on Land and the Degradation of Natural Resources

The expansion of cultivated land in tropical and sub-tropical regions during the past five decades has been at the expense of areas of high biodiversity. Population pressures, depletion of cultivated soils and the need to increase industrial production are its main causes. Intensifying agricultural production in these countries without compromising soil fertility or tropical forests remains a major challenge.

Environmental damage and soil degradation turn 5–10 million hectares of land each year unsuitable for crops. Industrialization and urbanization result in a further 19.5 million hectares becoming unavailable[4] (De Schutter 2010). Restoring these

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[2] Friends of the Earth, 2007. Qui tire profit des cultures GM? Monsanto et la « révolution biotechnologique » de l'agriculture menée par les multinationales, 20 p., http://www.foei.org/fr/publications/pdfs/gmocrops2006execsummaryfr.pdf (retrieved: 6 April 2013).

[3] Haut Conseil des biotechnologies, comité scientifique, 2011. Avis en réponse à la saisine 100506-coexistence sur la définition des conditions techniques relatives à la mise en culture, la récolte, le stockage et le transport des végétaux génétiquement modifiés, 46 p., http://www.hautconseildesbiotechnologies.fr/IMG/pdf/120117_Coexistence_Avis_CS_HCB.pdf (retrieved: 6 April 2013).

[4] FAO, *Land Policy and Planning,* http://www.fao.org/nr/land/land-policy-and-planning/en/ (retrieved: 6 April 2013).

areas is a major issue in some regions where it is not possible to expand the area available for cultivation.

Some areas suffer from acute water scarcity. The withdrawal of water from lakes and rivers, of which 70 % is used in agriculture, has doubled since 1960. Deforestation itself leads to a decrease in regional precipitation. Yet, irrigated crops have yields that are, on average, double those of the rainfed ones. We must find ways to improve the capacity of existing systems, especially of crop cultivation, to use water while limiting irrigation's negative aspects, in particular the impacts on natural ecosystems and their diversity.

3.4.3 Effects of Changes in Landscapes

Agricultural intensification very often homogenizes the structuring of the landscape. There is, however, little information on biodiversity in the literature: heterogeneity is measured as a percentage of semi-natural elements though sometimes the level of fragmentation and connectivity between habitats is measured instead or also. But the average size of the different surface areas and the diversity of productions are rarely taken into account. Nevertheless, it is clear that increasing areas of cultivated open spaces—at the expense of semi-natural ones—have led to a decline in inter- and intra-specific biodiversity. The MEA thus recognizes landscape diversity and 'ruggedness' as one of the services provided by ecosystems.

Finally, we can report that the effects of farming practices and landscape structuring on species depends on the latters' mobility. Mobile species are the ones most sensitive to landscape fragmentation, whereas sessile or sedentary species are particularly sensitive to farming practices on the plot and their migrations will occur over much longer timeframes.

Various in-depth studies have compared different options for structuring the landscape for an ecological intensification of agriculture. Should areas designated for intensive and highly productive agriculture but low in biodiversity be separated in space from protected natural areas interconnected between themselves (land sparing)? Or, on the other hand, should biodiversity in crops be maintained (land sharing)? The first solution is recommended in intensive agricultural systems (Franklin and Mortensen 2011) for the maintenance of plant biodiversity and of species with low populations (Phalan et al. 2011). This requires that incentivizing public policy be implemented to preserve spaces for biodiversity and its connectivity.

In countries of the South, this type of choice is closely linked to development policies. How to compensate the shortfall in income of people faced with pressure from and proposals of powerful economic groups (examples of rubber and oil palm)? Any workable solution will have to perforce include payments for environmental services (PES) as one of its components, but these are not problem-free themselves: how to calculate payments, how to assess changes, etc.

The second solution, land sharing, is the basis of many development programmes for sustainable development of agriculture, especially in areas where maintenance of agricultural biodiversity requires a real know-how and where the maintenance of populations in rural areas is a priority for food security (De Schutter 2010).

3.4.4 Effects of Climate Change

In the long term, climate change—in particular global warming—could affect agriculture and biodiversity in many different ways. Climate change will notably lead to an increased frequency of extreme weather events (floods and droughts, for example). Rainfall variability already makes it difficult to plan agricultural operations, and reduced rainfall threatens regions that rely on rainfed agriculture. Parts of the world are more susceptible to this variability than others, for example, the Sahel, north-eastern Brazil, Central Asia and Mexico. Global warming has already resulted in changes in agricultural calendars, such as earlier harvest dates. It also results in an increase in net primary production in temperate zones and in a decrease in hot and mountainous regions (Feldmann 2008b).

Furthermore, it is possible that the climatic and ecological zones will shift geographically, disbalancing natural vegetation and wildlife and forcing farmers to scramble to adapt. Some species have already started moving, for example, pests and vector-borne diseases spreading into areas where they were previously unknown.

Rising sea levels lead to water salinity, rendering some coastal land unsuitable for farming, particularly in small low-lying islands. Biodiversity of some very fragile environments—mangroves are the prime example—finds itself under threat.

If agriculture is reeling under the impacts of climate change, one must not forget that it itself is also responsible for 14 % of global greenhouse gas emissions. But it also has the potential of becoming an important part of the solution by reducing and/or eliminating a significant amount of global emissions (see below 'Coping with new hazards caused by global changes, especially climatic ones'). Traditional farming is inherently resilient, a quality it retains due to its agrobiodiversity. By using practices such as conservation agriculture, integrated management and agroforestry, this resilience can be used to improve the management of natural resources such as water, soil and genetic resources.

4 Why 'Cultivate' Biodiversity?

Biodiversity is the undeniable basis of food security for mankind. We have tried to show how far it has been part of mankind's history and how it has provided all that is necessary for feeding man and for his sustenance (clothing, medicines, habitat, energy, etc.).

4.1 Building Up Ecosystem Services and Food Security

Our planet will have to accommodate and feed an additional three billion people over the next 50 years. More than 85 % of them will be added to the populations of developing countries, in an unpredictable context of poverty and access to resources. With such an increase in population, human societies will be and are being forced to draw increasingly on natural resources. Thus, the Global Footprint Network announced on 27 September 2012 that the quota of resources produced by the planet in 2012 had already been consumed by the world population on that date. According to scientists, mankind's global ecological footprint has exceeded the Earth's biological capacity to produce resources and absorb our waste ever since the mid-1980s. The countries that consume the most are, of course, the United States and those in Europe, but emerging ones like China, India and Brazil, are fast catching up, at least in total consumption.

An increase in global agricultural production remains, despite everything, an imperative necessity. This goal has to be pursued agressively but only through an optimum use of current resources. Mankind will also need to limit waste and adopt lifestyles that consume less material and less energy. How can humanity preserve, adapt and mobilize all the know-how, technologies, cultures and lifestyles to *transform agriculture* in order to make this increase possible, while still limiting the impacts on ecosystems to acceptable levels? What useful knowledge will be required on the functional interactions between species regarding efficiency of water use, control of pests and diseases, soil conservation, fertilization, etc.? How to structure agricultural landscapes to promote interaction between species?

Thanks to photosynthesis, agriculture is one of the few human activities that produces renewable biomass. However, its intensification generates externalities that can be very burdensome. The choice of the path to intensification of agricultural production, the burden of fossil fuel dependency and the use of synthetic inputs determine these externalities to a large extent. An improved understanding of the functioning of ecosystems and interactions that will allow us to make the best use of biodiversity is necessary in order to increase production and, at the same time, preserve our planet for future generations.

Ecological intensification of agriculture can provide sustainable solutions to the issues of environmental impact and the finiteness of resources. But the path to follow becomes increasingly complex as our planet deteriorates. The erosion of natural biodiversity is accelerating day after inexorable day. The species extinction rate is 100–1,000 times greater than its average for the past hundreds of millions of years (MEA 2005). Between now and 2025, 10 % of flowering plants will be gone, and with them, a whole population of associated species and their services: pharmacopoeia (40–70 % of medicines are derived from natural substances, especially plants), fibres, genetic resources of cultivated species, auxiliary fauna and flora, fresh water, large biogeochemical cycles, crop values, etc.

Furthermore, we know that man needs a balanced food intake to maintain good health. Food should not only be sufficient in quantity, but must also be diversified.

The extraordinary variety of edible species, culinary know-how and nutrients in all their forms are the basis of diets around in the world. This variety is, in some ways, under threat by the homogenization and industrialization of production and with consumer preferences and diets undergoing profound changes. Nevertheless, at the level of a low-income family or a village, the diversity of agricultural production and food preparation know-how is also a treasure to be preserved.

We must act quickly and avoid mistakes; nature itself can serve as a guide. Ecology and agronomy researchers must build innovative methods and approaches in collaboration with farmers and local communities. This issue is inextricably linked to agricultural development in the countries of the South.

4.2 Overcoming the Finiteness of Resources

4.2.1 The Finiteness of Land

According to work carried out by IIASA (International Institute for Applied Systems Analysis) and the FAO, there are 2.9 billion hectares of arable land in the world, of which 90 % is located in sub-Saharan Africa and Latin America.

The *Agrimonde 1* scenario in the Agrimonde foresight (Paillard et al. 2010) attempts to minimize agriculture's externalities. This scenario suggests that is should be possible to increase the acreage of cultivated land by 25–40 % by 2050 with minimal impact on forests to meet these production requirements. The expansion of arable lands into new areas of high potential is possible mainly in sub-Saharan Africa and South America. Other parts of the world, such as regions of the former USSR, Asia, North Africa and the Middle East will be forced to cultivate land with a much lower potential, some of it even marginal. In some cases, recourse will have to be taken to remediation. But how to control the land rush, especially when it comes to industrial crops requiring large swathes of natural forests to be cleared and which are presented to local populations as important sources of income? (Box 6).

Box 6. Rubber in Laos, Thailand and Côte d'Ivoire

The rubber tree is a veritable natural factory. The latex that it produces has technological qualities not found in any chemical equivalent. At present, China's growing demand has led to an expansion of rubber plantations at the expense of natural forests and their biodiversity (Abel 2007). Thus, in Laos, where plantations today cover 14,000 ha, the authorities are planning for an additional 200,000 ha in 3 years, to be managed mainly by private Chinese firms. Twenty-seven Chinese companies own rubber plantations in Laos. They provide seedlings, technology and chemical fertilizers, train farmers, build refining factories and roads to China for transporting the production. In exchange, they have rights over 40–80 % of the crop for 30 years. Thus, in Bokeo province in northern Laos, not far from the Chinese border, a primary rainforest of great ecological wealth and one of the best preserved in the world was completely destroyed to make way for these plantations. Local farmers agree to manage these plantations because they are allowed to plant rice between the trees for 2 years.

Other approaches are nevertheless possible. In Thailand[*], rubber plantations were set up in the north–east of the country as part of the reforestation movement launched in 1990. This is an impoverished region, where decades of sugar cane and cassava cultivation have led to land degradation. The introduction of rubber is seen as an economic opportunity for farmers[**] as well as an ecological opportunity to maintain or even restore the soil's physical and chemical properties. Unfortunately, rainfall has proven insufficient for the requirements of growing rubber. Extensive studies on the effects of this reforestation on soil fertility, productivity and hydrogeology are underway, as are agroforestry trials.

The approach towards these large monoculture plantations needs to be further improved to orient them towards more diverse systems, such as agroforestry. In Côte d'Ivoire, a 17-year study compared the monoculture production of rubber with when it is associated with other tree crops (Snoeck et al. 2013). It shows that the combination of rubber with coffee or cocoa is quite comparable to that of monocultures, even more profitable in the medium term (10 years). And this without even counting the benefits of an improved use of cultivated land and a better distribution of labour seasons and incomes throughout the year. Furthermore, since the producer grows a wider range of products, he has a greater resilience against market fluctuations.

[*]See http://www.thailand.ird.fr/research-and-missions/research-projects/ecosystems-and-natural-resources/evaluation-of-agro-environmental-impacts-of-rubber-plantations (retrieved: 7 April 2013).

[**]Programme undertaken by IRD (France), Khon Kaen University (KKU), Mahidol University (MU), Land Development Department (LDD), Rubber Research Institute of Thailand (RRIT) (Thailand).

4.2.2 The Finiteness of Mineral Natural Resources

The complete depletion of phosphorus deposits, a large part of which is biogenic—i.e., resulting from a detrital accumulation of living organisms over geological eras—is estimated to take place between 2110 and 2350. This mineral fertilizer, essential for high crop yields, has no substitute. Similarly, the nitrogen supply to crops comes from the conversion of fossil fuels, primarily natural gas, which is, of course, not going to last forever. And yet, feeding the world's growing population will require large amounts of these inputs. What, if any, will be the alternatives found?

4.2.3 The Finiteness of the Water Resource

Even though called renewable, the planet's water resource is becoming increasingly less so. Water withdrawal from lakes and rivers, of which 70 % is used in agriculture worldwide, has doubled since 1960. Some areas are worse off than others, such as the Mahgreb and the Middle East, where non-renewable aquifers are today being exploited. In addition, there is the issue of the quality of water discharged from agriculture.

Fighting against desertification and implementing systems adapted to prolonged droughts is a major challenge in the Maghreb. We now begin to see systems being set up there for the collection and efficient use of water. The imperative challenge is to avoid the depletion of non-renewable fossil water. Another concern remains water potability. It will be necessary to develop ecosystems that can play a purifying or depolluting role or that are resistant to salinity.

4.2.4 The Finiteness of Energy Resources

Biomass is an important source of energy in developing countries in the form of firewood or charcoal. It is naturally abundant in the humid tropics, but its supply is now insufficient around major urban areas. Grown or recycled, it can contribute to population needs and even be a source of income under certain conditions through the emergence of new sectors.

4.3 Coping with New Hazards Caused by Global Changes, Especially Climatic Ones

In 2007, the Intergovernmental Panel on Climate Change (IPCC) estimated that, under certain conditions, agriculture could contribute significantly to sequester greenhouse gases, mainly through biological soil activity. The total stock of organic carbon in the soil is, in fact, at least double that in the atmosphere. There are large variations between ecological zones—the amount of carbon stock varies from about 4 kg/m^3 in arid areas to 8 kg/m^3 in the tropics to as high as 24 kg/m^3 in some polar regions (Batjes 1999)—but we know of agricultural practices that can increase these stocks. The amounts involved can be phenomenally large: a very tiny change in the stock contained in the first 30 cm of soil could either cancel the terrestrial carbon sink or allow it to absorb the annual increases (Bernoux 2011). However, this contribution towards mitigating climate change can be fully effective only when practices that respect soil life are adopted.

Moreover, only chlorophyll production is capable of capturing atmospheric carbon and transforming the inexhaustible energy of the sun into usable biomass.

Biomass production in large quantities for various uses (food, energy, materials, soil fertility, environmental services) should therefore be explored from all angles.

The biodiversity of agroecosystems has a proven impact on their resilience to hazards related to climate change: fight against soil erosion and loss of soil fertility, balance of auxiliary flora and fauna, large biogeochemical cycles, resources for responsiveness to shocks, etc.

Biodiversity should also be explored to develop innovative techniques to counter environmental hazards that remain a constant threat to it: biological invasions, pollution, etc.

Some cultivated *varieties or species* from one climatic region can meet the future needs of another region (drought, rainfall, seasons, etc.). Some wild species can be domesticated. Here, too, the adaptability of producers and populations remains the driver for innovation.

5 What is the Best Way of Understanding the Extraordinary Complexity of Living Organisms and Agroecosystems?

Different paths can be taken to design and evaluate the effects of various approaches to ecological intensification. They must be compared at different spatial scales (in particular the plot, the farm and the landscape) and over various temporal scales.

The *study offunctional relationships* within a particular compartment of diversity is very important. It allows the analyses of nutrient cycling, nitrogen conversion, trophic antagonism between species, the chemistry and biochemistry regulating populations and processes, soil structure, and interactions between auxiliaries and pathogens or pests. Some aspects of these relationships have been studied since decades, but others are only now beginning to be documented. Thus, for example:

- *Evolutionary genetics* has been studying, since the early twentieth century, *gene flows between populations of the same species* in time and space in relation to history human (history of cultivated species, origins, domestication, diversification). It accompanies the genetic improvement of cultivated species and their pathogens, with the help of disciplines such as ethnobotany as well as anthropology and, nowadays, linguistics.
- *Functional ecology* has been dealing, since the 1960s, with the functions of organisms and ecosystems in interaction with their environment. It studies, for example, *relationships that connect individuals from a mixture of different species* in a given environment (functional groups of species), with respect to different modes of farming. This branch of ecology has proven especially useful for studying the dynamics of natural forests and grasslands. However, the *functions of soil organisms* are still poorly understood, and the domain of crop mixtures is rarely addressed: nutrient cycling, nitrogen conversion, chemistry

and biochemistry regulating populations and processes, interactions (mutualism, commensalism, competition, pathogenesis).

- *Ecophysiology* addresses the behavioural and physiological responses of organisms to their environment (temperature, altitude, oxygen, food availability, etc.). This discipline also covers *matter and energy flows* between the different compartments of a plot, ranging from the bedrock to the atmosphere and to the climate through plant and animal populations (plantation, grassland, annual crop, agroforestry, natural cover).

Even more integrative scientific approaches have been developed:

- *Agroecology* was born in the 1990s from the convergence of agronomy and scientific ecology. It is considered an approach that combines agricultural development, participatory methods and protection or regeneration of the natural environment. Agroecology is the basis of a multifunctional and sustainable agriculture, which valorises agroecosystems, optimizes production and minimizes input use.
- Various alternative forms of agriculture have been explored, whose impact on the increase of biodiversity and of production can be evaluated only retrospectively: organic farming, high environmental value (HEV) agriculture, conservation agriculture (François et al 2011), eco-agriculture, etc.
- The *study of landscapes*, especially of their structuring between cultivated areas and 'semi-natural' protected areas, is a new area of research. Its goal is to understand what forms of landscape structuring are the most suitable for agrobiodiversity.
- *Associations with civil society and its informed amateurs* (Demeulenaere and Goulet 2012) help human communities share their observations on biodiversity and their know-how for evaluating it, understanding its functions, and managing and restoring it. An example of one such such association is participatory botany,[5] which mobilizes citizens in making observations in time and space. These collected data are then integrated into searchable Internet databases. Other examples include seed exchange networks, such as the Farmers' Seed Network in France[6] (Box 7).

Strategies for agronomy, integrated pest management, improvement of varieties or varietal mixtures, and agroecosystem management can all benefit from the knowledge acquired and methods developed in all these disciplines. But these strategies can be deployed only in processes of innovation that, above all, involve rural communities.

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[5] Tela Botanica network, http://www.tela-botanica.org/site:accueil?langue=en/, Pl@ntnet initiative, http://www.plantnet-project.org/papyrus.php?langue=en/ (retrieved: 7 April 2013).

[6] Réseau des semences paysannes (Farmers' Seed Network), http://www.semencespaysannes.org/ (retrieved: 7 April 2013).

Box 7. Pl@ntNet and Tela Botanica: tools for collaborative research

Bringing together botanical specialists and amateur enthusiasts is one of the objectives of Pl@ntNet*, a collaborative network of more than 300 people organized around a software platform. The idea behind Pl@ntNet is simple: to assist observers in identifying plants they find in the field, to share these observations using simple tools and to allow managers and scientists to valorise these observations through their studies. For example, identifying tree species in the flora of metropolitan France; estimating the distribution of tropical plants from heterogeneous occurrence data; gaining a better understanding of the different grape varieties of French vines; identifying and monitoring plants that have invaded natural habitats or weeds in crops; and a better understanding of the endemic flora of Reunion.

These studies have benefitted from 12 years of experience in managing citizen science projects of the Tela Botanica collaborative network. Tela Botanica now has more than 18,000 members worldwide, including 15,500 in France and 1,150 in the Maghreb. This network provides access to more than 200,000 field observations concerning around 6,700 plant species!

A section of the Pl@ntNet platform relies on user-contributors to develop collaborative software for data management and sharing, and to evaluate its features. Thus:

- Pl@ntNet-Identify is a visual search engine which compares photos submitted as a query to a set of stored and identified images.
- Pl@ntNet-Datamanager can manage a wide variety of botanical data, on a fully configurable system, in an individual or collective basis, online or offline.
- IDAO allows users to make a 'composite picture' of a plant by using a fully graphical interface, thus overcoming the constraints of language and specialized vocabulary. Applications exist for different flora from around the world (West Africa, Reunion, India, Southeast Asia, etc.).
- the online Carnet (notebook) allows everyone to enter and manage his or her field observations on an online system, to illustrate them with images and share them with the community.

Communities can be created around common projects through Pl@ntnet. It is thus a powerful tool for promoting citizen science, and a useful vector for accumulating new data on plant biodiversity.

*The Pl@ntNet project (2009–2013) is an initiative that brings together the JRU AMAP, Botany and bioinformatics of the architecture of plants (Cirad-Cnrs-Inra-IRD-UM2), Inria (Imedia team) and the Tela Botanica network. It is funded by the Agropolis Foundation.

6 Agrobiodiversity: A Development Issue?

With these few points of reference, we have tried to show the importance that agrobiodiversity had in the history of agriculture and on economic development. The history of tropical plants reflects the issues, power relationships, colonization and violent conflicts that have concerned the great powers. International trade in major crop species is still a very important economic issue for countries that produce them. This is often the reason why swathes of rainforest are still being cleared for plantations and highly profitable crops, such as rubber and oil palm. Aware of these problems, companies that manage large plantations are today conceiving and implementing best practices, certifications, and sometimes investing in the conservation of ecosystems. Nevertheless, the expansion of cultivated areas, depleted in biodiversity, seems unavoidable.

Since the Rio Summit, the right of access to genetic resources, formerly considered by Westerners as a public good, has changed. The role of small farmers in the South in the maintenance and diversification of traditional varieties has been recognized. At the same time, advances in biotechnology and massive private investments have led to the recognition by the CBD of the patentability of living organisms. These two views embody the current confrontation between private and public interests (Bonneuil and Fenzi 2011).

Family farming is considered an 'antithesis' to agricultural industrialization by the many ongoing experiments and by the constant cross-pollination between science and traditional knowledge in ever-evolving contexts. Thus, agroecological practices, supported by research, use beneficial biological synergies between the various components of a given agroecosystem: on-site recycling of nutrients and energy, integration of crops and livestock farming, and diversification and association of species and genetic resources in space and time. Emphasis is placed on interactions and productivity at the scale of the entire agricultural system. Biodiversity provides an opportunity to small producers to adjust and optimize their material and resources and even to take advantage of marginal and difficult lands (Altieri et al. 2011).

There are many different routes to sustainable agricultural intensification. Not only do they depend on farmer expertise and capacity for innovation but also on the institutional and policy environment. Based on assessments of past activities, agronomic and economic studies have shown that production yields of diversified systems can exceed those of conventional intensive monocultures, especially in regions where malnutrition is rampant. Some studies have shown that peasant systems are the most effective in terms of workdays or of energy balance (energy supplied/energy extracted) (Altieri et al. 2011). Thus, a study of the results of 286 sustainable agriculture projects in 57 poor countries reveals an increase in production of 80 %, with African projects having an even higher average of 116 % (Pretty et al. 2006). Recent projects have led to the doubling of harvests over a period of three to 10 years in over twenty African countries. But this intensification must also be evaluated through criteria other than solely of production.

Producer incomes, dependence on technology or synthetic inputs, risk management and resilience are all essential criteria in a context of increasing uncertainty.

Research sometimes lags these innovations. Producer organizations, NGOs, governments and production and consumption networks are playing an increasingly important role in the creation and dissemination of knowledge, know-how and innovations. In West Africa, producer organizations do not hesitate to query experts in this field and information flows freely through meetings, radio, telephone, and farmer field schools (FFS). In Burkina Faso, youth groups specialized in the traditional methods of land reclamation move from village to village to help farmers, some of whom go so far as to buy up degraded land to be able to farm it again (Pretty et al. 2011).

7 Conclusion

These examples show the extraordinary diversity of agroecosystems. Even if we can discern some major trends, we cannot predict their effects on specific local contexts or how these systems will adapt. They also show to what extent diversity is an unavoidable issue for food security at the global level.

As an engine of all the mechanisms at work in cultivated ecosystems, biodiversity is a key resource available to farmers in developing countries to improve their production and increase their incomes. There are choices to be made, ones that depend on the diversity of agriculture and societies. They are implemented at the level of the plot, but act at the scale of landscapes, markets and policy incentives.

Current global changes also show societies in developed companies that they are dependent on the future of countries in the South and on these countries' ability to manage their natural wealth. The expansion of mankind into the landscape is accelerating as is the erosion of our collective resources. Biodiversity will have to be cultivated in an ever increasing measure in order to intensify and transform agriculture systems and enable them to meet the challenge of feeding humanity and fulfilling its needs.

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