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Biodiversity and Plant Breeding as Tools for Harmony Between Modern Agriculture Production and the Environment

João Carlos da Silva Dias

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1. Introduction

There are now almost 7.25 billion human beings inhabiting this planet, and it has been projected that world population growth may exceed 70 million annually over the next 40 years. The world population will be approximately 9.2 billion in 2050, when the concentration of carbon dioxide and ozone will be 550 ppm and 60 ppm, respectively and the climate will be warmer by 2°C [1]. At that time it is expected that approximately 90% of this global population will reside in Asia, Africa, and Latin American countries [2,3]. Currently, about 1 billion human beings suffer from hunger; 3 billion malnourished people suffer one or more micronutrient deficiencies (especially vitamin A, iodine and iron) and live with less than 2 US dollars per day; and anthropogenic climate change continues to affect food output and quality [4,5]. By 2050, to sufficiently feed all these people, the total food production will have to increase 60 to 70% to meet a net demand of 1 billion tonnes of cereal for food and to feed, and 200 million tonnes of meat [6-8], depending on assumptions of population growth, income growth and dietary changes. This projected increase of global crop demand is partly due to a growing global population, but a larger driver is increasing global affluence and associated changes in diet due to higher incomes [4,8]. As global incomes increase, diets typically shift from those comprised of mostly grains, to diets that contain greater proportion of meat, dairy products, and eggs and more vegetables and fruits [4,8-10].

In order to meet these demands, global livestock production systems are shifting from using mostly marginal lands and crop residues to more industrial systems which require less land and use of higher value feed crops [11,12]. Increasing demand for meat and dairy products is also of importance to the global environment because their production requires more land,

water and other resources [13-15]. Livestock production is also responsible for other environmental impacts. Besides livestock production is estimated to be responsible for 18% of total greenhouse gas emissions [16], and animal products generally have a much higher water footprint than vegetal products [17].

In 2008, the world's arable land amounted to 1,386 M ha, out of a total 4,883 M ha land used for agriculture [18]. Each year, arable and agricultural land is lost due to deforestation, overgrazing, agricultural activities, gathering and overexploitation for fuel-wood, urbanization and industrialization. The most direct negative impact of agriculture on biodiversity is due to the considerable loss of natural habitats, which is caused by the conversion of natural ecosystems into agricultural land. The arable land is limited. Increases in arable land can only be done by deforestation. Agricultural production should be increased without further deforestation. This requires innovation and better technologies, as well as substantial investment, to increase yields on existing agricultural land.

Climate models predict that warmer temperatures and increases in the frequency and duration of drought during the twenty-first century will have negative impact on agricultural productivity [19-24]. For example, maize production in Africa could be at risk of significant yield losses as researchers predict that each degree-day that the crop spends above 30°C reduces yields by 1% if the plants receive sufficient water [23]. These predictions are similar to those reported for maize yield in the United States [25]. Lobell et al. [23] further showed that maize yields in Africa decreased by 1.7% for each degree-day the crop spent at temperatures of over 30°C under drought. Wheat production in Russia decreased by almost one-third in 2010, largely due to the summer heat wave. Similarly, wheat production declined significantly in China and India in 2010, largely due to drought and sudden rise in temperature respectively, thereby causing forced maturity [26]. Warming at +2°C is predicted to reduce yield losses by 50% in Australia and India [27,28]. Likewise, the global maize and wheat production, as a result of warming temperatures during the period of 1980 to 2008, declined by 3.8% and 5.5%, respectively [24]. So climate change poses a serious threat to species fitness [29,30], and to agroecosystems essential to food production [31].

Climatic variation and change are already influencing the distribution and virulence of crop pest and diseases, but the interactions between the crops, pests and pathogens are complex and poorly understood in the context of climate change [32]. We will need to integrate plant biology into the current paradigm with respect to climate change to succeed in defeating emerging pests and pathogens posing a new threat to agriculture due to climate change [33-35].

In this context we can ask: can we feed and clothe the growing world population while simultaneously preserving or improving ecosystems and the natural environment?

History shows that modern agriculture has the potential to feed the world population but also to be worst and even catastrophically with the natural environment. Some examples are deforestation, overgrazing and erosion, in many parts of the world, which contributed to the outright collapse of ecosystems. One classical example is Madagascar's central highland plateau that has become virtually totally barren (about ten percent of the country), as a result of slash-and-burn deforestation, an element of shifting cultivation practiced by many natives.

Intensification of production systems have also led to reduction in crop and livestock biodiversity, and increased genetic vulnerability and erosion. In contrast, the "Green Revolution", which began providing high-yielding crop cultivars and high-input management techniques to developing countries in the 1960s, has prevented mass starvation and improved living standards throughout the world [36]. Dwarfing, photoperiod insensitive genes and host plant resistance genes to pathogens and pests were bred for various crops during the "Green Revolution" [37]. Crop yields were increased in many nations of Asia and Latin America by innovations of the "Green Revolution". Calorie consumption would have dropped by about 5% and the number of malnourished children would have increasing by at least 2%; i.e., the "Green Revolution" helped to improve the health status of 32 to 42 million pre-school children. Since the beginning of the "Green Revolution" in 1960, land devoted to crops increased some 10%, land under irrigation has doubled, pesticide use by agriculture has tripled, fertilizer use is up 23-fold, pesticide use is up by a factor of 53. Nowadays, forty per cent of crop production comes from the 16% of agricultural land that is irrigated. Irrigated lands account for a substantial portion of increased yields obtained during the "Green Revolution". The enhancement of yield achieved in the "Green Revolution" (29% in food supplies per capita since 1960) may have been associated with an increased level of greenhouse gas emissions associated with higher fertilizer production and application, but, overall, its net effect has been calculated to have reduced CO₂ emission by some 161 gigatons of carbon (GtC) over the period 1961-2005 [38], implying that gains in crop productivity can make a positive contribution to reducing greenhouse gas emissions.

Developing sustainable agriculture in environmentally sensitive systems is the great challenge of the coming decades. More food, animal feed, fiber, fuel, and forest products must be produced with less available land, water, and nutrients, to meet basic human needs and improve the sustainability of production [39]. In addition, pressure from an increasing global human population will necessitate more efficient and diversified land use.

Identifying the most appropriate technologies and practices to achieve these objectives are critical. This requires the building of a knowledge base to support such tasks. Agro-ecological approaches are known to increase farming system productivity, to reduce pollution, and to maintain biodiversity through careful management of soil, water, and natural vegetation. The agenda for a new "Green Revolution" needs to consider new approaches to promote innovations in plant science, agricultural and management practices and benefits to farmers and consumers.

Modern production agriculture in the developed world is highly industrialized. There is considerable discussion about the inadequacy of the dominant model of agricultural intensification and growth, which relies on increased use of capital inputs, such as fertilizer and pesticides [40]. Technology and purchased inputs, e.g. fertilizer, pesticides and water are required to maintain high levels of production, and use of these inputs continues to increase in the developing world. Despite the critical need for agricultural production and continued improvements in management practices, current systems are still not in "harmony" with the environment because they can create many problems for ecosystems and human communities. The generation of unacceptable levels of environmental damage and problems of economic

feasibility are cited as key problems with this model of industrial agriculture [39,41]. Specific external costs of industrial agriculture which should be improved include soil deterioration, erosion, declining surface water and groundwater quality, limited recycling of nutrients, excessive use of off-farm fertilizers and pesticides, diminished biodiversity within the agricultural system (both in terms of the variety of crops sown and coexisting species), lapses in food safety, and the loss of rural employment. By developing new field crops, and trees that meet societal needs, plant breeding plays a distinctive and crucial role in addressing these challenges, which must be dealt with immediately to develop sustainable agronomic systems for the future.

In this article two general ways are described in which plant breeders can engage in environmental issues: i) by breeding plants that are better adapted to environment and environmental stresses, producing more with less and where productivity can be maintained in the face of increasingly variable weather patterns and sub-optimal conditions, as well as pest and disease pressures; and ii) by breeding plants that can alter and “improve” environments, as breeding alternative crops and crops for new uses or breeding for local adaptation and sustainable solutions. Previously, the concepts of crop biodiversity, soil biodiversity and agro-biodiversity were briefly presented.

2. Crop biodiversity, soil biodiversity and agro-biodiversity

2.1. Crop biodiversity

Today, 150 plant species (out of 250,000 known plant species) dominate the world’s agricultural landscapes, but only 12 crop species provide 80% of the world’s food chain [42]. Three main cereals: wheat, rice and maize, provide about 50% of the energy we obtain from plants.

The wise use of crop genetic diversity in plant breeding can contribute significantly to protect the environment. A major role of genetic resources will be to provide germplasm resistant to pests and diseases, more efficient in their use of water and nutrients and less dependent on external inputs to maintain current levels of productivity. Natural genetic diversity is becoming increasingly important to understanding the ways in which we can improve plant breeding. There is a continuing need to assemble and screen germplasm strategically and discover new sources of variation that will enable developing new crop cultivars. Complex traits can be improved dramatically by bringing novel alleles from diverse ecotypes into breeding material.

Crop genetic biodiversity is considered a source of continuing advances in yield, disease and pest resistance, and quality improvement. It is widely accepted that greater varietal and species diversity would enable agricultural systems to maintain productivity over a wide range of conditions. The loss of biodiversity is considered one of today’s most serious environmental concerns. In the last 50 years vegetable genetic resources have been lost, on a global scale at the rate of 1-2% per year [43] and it has been estimated by FAO that 6% of wild relatives of cereal crops (wheat, maize, rice, etc.) are under threat as well as 18% of legume species, and 13% of solanaceous [44].

There is a growing world-wide awareness about the need to conserve plant germplasm for the use of future generations. Consequently, considerable media attention has been given to the creation of the Svalbard Global Seed Vault (see <http://www.croptrust.org/main>) and relates to storage of seeds of many economically important crops [3,45]. Gene banks are crop genetic diversity reservoirs and sources of alleles for sustainable genetic enhancement of crops [46]. Indeed breeding gains depend on capitalizing on the useful genetic variation present in the crop gene pools, which for many crops is being conserved in gene banks. There are about 1,700 gene banks and germplasm collections around the world (the number in FAO's database). They maintain about 7.4 million accessions of plant genetic resources, with cereals and legumes constituting 52% of the accessions [47]. The CGIAR consortium holds about 0.7 million accessions of 3,446 species from 612 genera. The International Crops Research Institute for the Semi-arid Tropics (ICRISAT) possesses one of the largest gene banks in the world with approximately 115,000 accessions of cereals (sorghum, millets) and legumes (chick-pea, groundnut, pigeon-pea) [48]. In spite of these large collections maintained *ex situ*, there are still important collection gaps that must be addressed before these priceless genetic resources are lost as a result of climate change or other driving forces leading to the genetic erosion and loss of biodiversity [47,49]. These *ex situ* collections are to a large extent safe from the adverse impact of climate change.

Ex situ collections should be subjected to phenotypic, disease resistance and molecular characterization to facilitate the potential use of this genetic endowment for the amelioration of crops. Plant breeders seldom access accessions from some gene banks with large collections. A systematic assessment of the genetic diversity in such collections has helped to establish core collections, which should be subsets of large collections [50-52], containing chosen accessions that capture most of the genetic variability in the entire collection. A core collection therefore improves the management and utilization of a germplasm collection. Genetic studies in selected crops have shown that both common widespread and localized alleles occurring in the entire collection are contained in the core collection subset. Only rare localized alleles may be excluded during the aforementioned sampling process. The core collection subset often provides an entry point to the entire collection for further investigation of the genetic diversity or for the utilization of these resources. Core collections which are *a priori* selected by the curator are often of limited use to those users of the gene bank germplasm collection who are interested in specific trait or domain. The current revolution in information technology makes it possible for users to make such selections themselves directly on the Worldwide Web using a stratified sampling in the domain(s) of interest. This approach allows a more focused selection of the germplasm accessions which shows variation for the trait of interest to the user compared with the use of core collections. These smaller core collections are sometimes enough to capture most of the useful variations.

Research undertaken on the large global collection of sorghum landraces and genetic stocks held at ICRISAT (in excess of 35,000) demonstrates how the challenge of maintaining a large number of accessions and the related information documented for this collection can be addressed by gene bank curators. Different sampling strategies were proposed to obtain core collection subsets of reduced size [53]. Three core collections subsets were established follow-

ing: i) a random sampling within a stratified collection (logarithmic strategy); ii) non-random sampling based upon morpho-agronomic diversity (principal component score strategy); and non-random sampling based upon an empirical knowledge of sorghum (taxonomic strategy). These core collections subsets did not differ significantly in their overall phenotypic diversity according to principal component representation of the morpho-agronomic diversity using the Shannon-Weaver diversity indice. But when comparisons for morpho-agronomic diversity and passport data were considered, the principal component strategy subset looked similar to the entire landrace collection. The logarithmic strategy subset showed differences for characters associated with the photoperiod reaction that was considered in the random sampling stratification of the collection. The taxonomic strategy subset was the most distinct subset from the entire landrace collection. It represented the landraces selected by farmers for specific uses and covered the widest range of geographical adaptation and morpho-agronomic traits.

In the same sorghum landraces collection of ICRISAT, partial assessment of host response to five sorghum diseases provided another means to quantify the importance of agro-biodiversity in resistance [54]. Frequency distributions of host response to major sorghum pathogens were the same between the entire collection and core collection subsets for all diseases, except between the entire collection and the logarithmic core subset for grain mold. This was not surprising because the sampling strategy for this core subset and the material included in the screening for this disease did not match. The logarithmic core subset had the widest range of adaptation to photoperiod whereas only photoperiod insensitive germplasm had been screened for grain mold. The lack of accessions that fall in the highest resistance class for some diseases in the core subsets is the result of sampling statistics, but the χ^2 tests for homogeneity clearly confirmed that the entire collection and the core subsets included the same distribution of variation with only the above stated exception for grain mold in the logarithmic strategy core subset. New accessions with high resistance to specific diseases are likely to be identified by completing the screening of the core subsets. This rational, targeted approach may also be cost-effective and more precise than long term screening of the entire collection. Furthermore this analysis also shows that large sample sizes do not appear to always be associated with capturing useful variation for disease resistance (i.e., entire *vs.* core collections), neither when the sampling was defined by breeding objectives (like the logarithmic strategy subset), a mirror of the entire collection (principal component score strategy subset) or by maximizing farmer's landraces (taxonomic strategy subset).

The latest database on world plant genetic resources highlighted that there are still large gaps, more specifically in crop wild relatives and landraces, in *ex situ* gene bank collections preserved across the globe [55]. Unlike cultivated germplasm, there are difficulties associated with *ex situ* conservation of crop wild relatives due to their specific crop husbandry, tendency for natural pod dehiscence, seed shattering and seed dormancy, high variability in flowering and seed production, and rhizomatous nature of some of the species. Crop wild relatives have contributed many agronomically beneficial traits in shaping the modern cultivars [56], and they will continue to provide useful genetic variations for climate-change adaptation, and also enable crop genetic enhancers to select plants which will be well-suited for the future's environmental conditions [57]. There is a growing interest that crop wild relatives should be

preserved *in situ* in protected areas to ensure the evolutionary process of wild species contributing new variants, which as and when captured by plant explorers, should be able to contribute to addressing new challenges to agricultural production [58]. Worldwide, there are 76,000 protected areas, spread in ~17 million km², and several countries have taken initiatives to establish crop wild relative's *in situ* conservation [59-61]. Promoting *in situ* conservation may allow genes to evolve and respond to new environments that would be of great help to capture new genetic variants helping to mitigate climate-change impacts [62].

2.2. Soil biodiversity

Biodiversity and soil are strongly linked, because soil is the medium for a large variety of organisms, and interacts closely with the wider biosphere. Soil biodiversity exceeds the aboveground systems biodiversity, and is crucial for the sustainability of agro-ecosystems [63]. It consists of macrofauna or soil engineers (earthworms and termites), mesofauna (microarthropods such as mites and springtails), microfauna (nematodes and protozoans), and microflora (bacteria and fungi). The soil organisms perform a number of vital functions such as: i) decomposition and degradation of plant litter and cycling of nutrients; ii) converting atmospheric nitrogen into organic forms (immobilization) and remineralization of mineral nitrogen, leading to the formation of gaseous nitrogen; iii) suppression of soil pathogens through antagonism; iv) regulating microclimate and local hydrological processes; v) synthesizing enzymes, vitamins, hormones, vital chelators and allelochemicals that regulate population and processes; vi) altering soil structure and other soil physical, chemical and biological characteristics; and vii) microbial exudates have a dominant role in the aggregation of soil particles and the protection of carbon from further degradation [64,65]. Biological activity helps in the maintenance of relatively open soil structure; it facilitates decomposition and its transportation as well as transformation of soil nutrients. It is not surprising that soil management has a direct impact on biodiversity. This includes practices that influence global changes, soil structure, biological and chemical characteristics, and whether soil exhibits adverse effects such as soil acidification.

Soil acidification has an impact on soil biodiversity. Roem and Berendse [66] in the Netherlands, examined the correlation between soil pH and soil biodiversity in soils with pH below 5 in grassland and heath land communities. A strong correlation was discovered, wherein the lower the pH the lower the biodiversity. Soil acidification reduced the numbers of most macrofauna and affected rhizobium survival and persistence. So extremely low pH soils may suffer from structural decline as a result of reduced microorganisms. This brings a susceptibility to erosion under high rainfall events, drought, and agricultural disturbance.

Land use pattern, plant diversity, soil desertification and pollution, including those resulting from N enrichment, alter soil biodiversity [67-69]. The changes in soil biodiversity are also observed through effects on soil organisms as a result of the changes in temperature and precipitation and through climate-driven changes [like rising atmospheric/ambient CO₂ (hereafter aCO₂) and warming] in plant productivity and species composition.

Accumulated evidence so far reveals that soil biota is vulnerable to global changes and soil disturbance. Castro et al. [70], in a multifactor climate change experiment, reported increased

fungus abundance in warmed treatments, increased bacterial abundance in warmed plots with elevated atmospheric CO₂ (hereafter eCO₂) but decreased in warmed plots under aCO₂, changes in precipitation altered the relative abundance of proteobacteria and acidobacteria where acidobacteria decreased with a concomitant increase in the proteobacteria in wet relative to dry treatments, altered fungal community composition due to the changes in precipitation, and differences in relative abundance of bacterial and fungal clones varied among treatments. All these observations led the researchers to conclude that climate change drivers and their interactions among them may cause changes in the bacterial and fungal abundance, with precipitation having greater effect on the community composition.

Dominique et al. [71] in their research, where the influence of plant diversity and eCO₂ levels on belowground bacterial diversity were analyzed observed that the variability in plant diversity level had significant effects on bacterial composition but no influence on bacterial richness. This research therefore suggests that the soil microbial composition is mainly related to plant diversity, assuming that different plant species might harbor specific rhizospheric microbial populations, rather than altered soil carbon fluxes induced by eCO₂ which can lead to increased photosynthesis. Bardgett [72] points out there is sufficient evidence to show that the transfer of carbon through plant roots to the soil plays a primary role in regulating ecosystem responses to climate change and its mitigation.

Very little is known about the influence of eCO₂ on the structure and functioning of below ground microbial community. In a 10-year field exposure of a grassland ecosystem to eCO₂, Zhili et al. [73] detected a dramatic alteration in the structure and functional properties of soil microbial communities. They found the total microbial and bacterial biomass significantly increased under eCO₂, while the fungal biomass remained unaffected. Furthermore, the structure of microbial communities was markedly different between aCO₂ and eCO₂. More recently, using tag-encoded pyrosequencing of 16S rRNA genes, Deng et al. [74] also found that the soil microbial community composition and its structure were significantly altered under eCO₂. In both studies, the changes in microbial structure were significantly correlated to soil moisture, soil status relative to C and N contents, and plant productivity.

2.3. Agro-biodiversity

Agro-biodiversity is the result of the interaction between the environment, the variety and variability of animals, plants and microorganisms that are necessary for sustaining key functions of the agro-ecosystem, and the management systems and practices. It is the human activity of agriculture which shapes and conserves this biodiversity.

Agro-biodiversity consists of the genetic diversity within the species, the species diversity, and the ecosystem diversity, which comprises the variation between agro-ecosystems within a region.

There are several distinctive features of agro-biodiversity, compared to other components of biodiversity: i) agro-biodiversity is actively managed by farmers and would not survive without this human interference; ii) due to the degree of the human management and interference, conservation of agro-biodiversity in production systems is inherently linked to

sustainable use; iii) many economically important agricultural systems are based on 'alien' livestock and crop species introduced from elsewhere; iv) in regards to crop diversity, diversity within species is at least as important as diversity between species; and v) as stated before in industrial-type agricultural systems, much crop diversity is now held *ex situ* in gene banks or breeders' materials rather than on-farm.

Agro-biodiversity provides the main raw material for intensifying sustainable crop yields and for adapting crops to climate change, because it can provide traits for plant breeders and farmers to select input-efficient, resilient, climate-ready crop germplasm and further release of new cultivars. Agro-biodiversity is crucial to cope with climate changes as the entire diversity of genes, species and ecosystems in agriculture represents the resource base for food [58]. Many farmers, especially those in environments where high-yield crop cultivars and livestock races do not prosper, rely on a wide range of crop and livestock types. This is the best method for increasing the reliability of food production in the face of seasonal variation. Diversified agricultural systems not only render smallholder farming more sustainable, but also reduce the vulnerability of poor farmers since they can minimize the risk of harvest failures caused by the outbreak of diseases and pests, by droughts or floods, or by extremely high temperatures, all of which will be exacerbated by climate change [75].

Monoculture means growing a single plant species in one area. Monoculture however should not be regarded as synonymous to a single crop cultivar in a farmers' field since monoculture can present intra-specific genetic diversity. For instance, a crop under monoculture can be a mixture of distinct cultivars or landraces having genetic variation within each population. Intra-specific crop diversification can provide a means of effectively controlling diseases and pests over large areas and therefore contribute to sustainable intensification of crop production. Nonetheless, an agro-ecosystem with many species of different taxa will be richer in species diversity than another agro-ecosystem where many species of the same taxon occur. Genetically diverse populations and species-rich agro-ecosystems may show greater buffer potential to adapt to climate change. Agro-biodiversity at the gene, species and agro-ecosystem levels increase resilience to the changing climate. Promoting agro-biodiversity remains therefore crucial for resilience of agro-ecosystems.

There is much evidence that global agriculture would benefit from an intensified utilization of existing biodiversity. We need to shift the focus of agricultural research from genes alone to management and their interactions. There is much to be gained with mixed cropping, as shown in a study performed by Tilman et al. [76], where plots with 16 species produced 2.7 times more biomass than monocultures. Bullock et al. [77] in comparing meadows with different number of species, found, after 8 years experiment, that the richer meadows yielded 43 % more hay than species-poor fields. Increased grassland diversity promotes temporal stability at many levels of ecosystem organization [78]. Mixtures of barley cultivars in Poland generally out-yielded the means of cultivars as pure stands [79]. The highly intensive agricultural system of home gardens are some of the most diverse production systems in the world and also some of the most productive [80,81]. Agro-biodiversity in home gardens reduces year-to-year variation, thus contributing to stability in yield. Although they are usually highly labor intensive and small, they provide income and nutrition for millions of small farmers throughout the world.

3. Plant breeding, agriculture and environment

3.1. Introduction

Farming and plant breeding have been closely associated since the early days when crops were first domesticated. The domestication of staple crops, for example, rice and soybean in eastern Asia; wheat in the Middle East; sorghum in Africa; and maize, beans, and potatoes in the Americas [82], began independently, in multiple locales, 5000-12 000 years ago [82]. For thousands of years, these crops were grown and morphologically altered by farmers, who selected the most desirable and adaptable cultivars to plant in the next growing season. Without understanding the science behind it, early farmers saved the seed from the best portion of their crop each season. Over the years, they selected the traits which they liked best, transforming and domesticating the crops they grew.

After the discoveries of Darwin and Mendel, scientific knowledge was applied to plant breeding in the late 1800s [36]. Commercial hybridization of crop species began in the United States in the middle of the 1920s with sweet corn and followed by onions in the 1940s [4]. With the implementation of hybrid crop breeding, yield per unit land area rapidly increased in the United States [83] and since that time, public and private breeding companies have been placing more and more emphasis on the development of hybrids, and many species have been bred as hybrid cultivars for the marketplace. Besides heterosis, hybrids also allow breeders to combine the best traits and multiple disease and stress resistances. Furthermore, if the parents are homozygous, the hybrids will be uniform, an increasingly important trait in commercial market production. The creation of hybrid cultivars requires homozygous inbred parental lines, which provide a natural protection of plant breeders' rights without legal recourse and ensure a market for seed companies.

In the 1970's breeders' rights protection has been provided through International Union for the Protection of New Varieties of Plants (UPOV), which coordinates an international common legal regime for plant variety protection. Protection was granted for those who develop or discover cultivars that are new, distinct, uniform, and stable [84]. Cultivars may be either sexually or asexually propagated. Coverage for herbaceous species is 20 years. Protective ownership was extended by UPOV in 1991 to include essentially derived cultivars [84]. At the same time, the farmer's exemption (which permitted farmers to save seed for their own use) was restricted; giving member states the option to allow farmers to save seed. Additionally, in Europe after 1998 and the United States after 2001, plant breeding companies can take advantages of patent laws to protect not only the cultivar itself but all of the plant's parts (pollen, seeds), the progeny of the cultivar, the genes or genetic sequences involved, and the method by which the cultivar was developed [85]. The seed can only be used for research that does not include development of a commercial product i.e., another cultivar, unless licensed by the older patent. The patents are considered the ultimate protective device allowing neither a farmer's exemption nor a breeder's exemption (that permitted the protected cultivar to be used by others in further breeding to create new cultivars) [86]. The use of patents for transgenic crops introduces additional problems according to the IAASTD report [41] developed with the contribution from 400 scientists around the world, and adopted by 58 governments. In

developing countries, especially instruments such as patents may boost up costs and restrict experimentation by individual farmers whereas potentially undermining local practices for securing food and economic sustainability. Thus, there is particular concern regarding present intellectual property rights instruments, which may inhibit seed-saving, exchange, sale, and access to proprietary materials of vital importance to the independent research community, specifically in view of the need for analyses and long term experimentation on climate change impacts [84,85].

Research and development (hereafter R&D) for improved seed development is expensive. Such product protection has presented a business incentive to corporations to invest in the seed industry, which supported an enormous increase in private R&D leading to strong competition in the marketplace between the major seed companies. The majority of current crop cultivars sold nowadays are proprietary products developed by private R&D. A significant consequence of this increase in R&D has been a reduction in public breeding programs. As a result, the cost for R&D to develop new crop cultivars is shifting from the publicly supported research programs to the customers of the major seed companies [4,87].

One of the main factors to determine success in plant breeding is crop biodiversity and genetic capacity. Access to genetic variation, biodiversity, is required to achieve crop cultivar improvement. No practical breeding program can succeed without large numbers of lines (genotypes) to evaluate, select, recombine and inbreed (fix genetically). This effort must be organized in order for valid conclusions to be reached and decisions to be made. Scientists, breeders, support people and facilities, budgets, and good management are requirements to assure success in the seed business. Science must be state-of-the-art to maximize success in a competitive business environment. The continued need for fundamental breeding research is critical to support development of new technology and expansion of the knowledge base which supports cultivar development, competition among proprietary cultivar results in owner-companies striving to do the best possible research to develop their own products and to compete on genetic and physiological quality of crop seed in the marketplace. Reasonable profit margins are essential to pay back the R&D costs to the owner and to fund future research on developing even better crop cultivars to stay competitive. There is considerable genetic variation within the numerous crop species, which can be exploited in the development of superior proprietary cultivars. The consequences of this dynamic situation will mean relatively short-lived cultivars replaced by either the owner of the cultivar or a competitor seed company. This intense competition means constantly improved and more sophisticated cultivars. Seed companies are in the business of manipulating genes to improve plant cultivar performance for a profit. The success of the research is judged by the success of the product in making a reasonable profit. The research must improve economic performance starting with the seed production costs and including the farmer-shipper/processor and the end user. If any link in this sequence of events is weak or broken, the new cultivar will likely fail [4,88].

Modern plant breeding is the science of improving plants to achieve farmer needs and better fit production environments, but it is a long-term proposition. Each released cultivar represents a culmination of a decade or more of work, from initial crosses through final testing. The rate of improvement is a function of the amount of heritable genetic variation present in a population, the time it takes to complete a breeding cycle (from seed production through

selection to seed production again), which can range from multiple generations per year (e.g. maize on field sites in both hemispheres) to decades (some trees require 8 years of growth before flowering). In hybrid crops, several years (multiple breeding cycles) are necessary to develop inbred lines that must then be tested in hybrid combinations. Many years of testing under various environmental conditions must be conducted to ensure that the new cultivar (inbred, hybrid, or population) will perform well for the farmer, consumer, or end-user before any substantial additional investment is made to increase production and distribution of the cultivar.

Biotechnology is a new and potentially powerful tool that has been added by all the major seed corporations to their crop breeding research programs, and is part of an ongoing public research for developing genetic engineered crop projects. It can augment and/or accelerate conventional cultivar development programs through time saved, better products, and more genetic uniformity, or achieve results not possible by conventional breeding [89]. Genetic engineering provides innovative methods for modern plant breeding to adapt crops to agricultural systems facing new challenges brought by the changing climate. New breeding methods, relying on genetic engineering, can accelerate the pace to improve crops, or be more precise in transferring desired genes into plant germplasm. Some limited target traits already available in transgenic cultivars include those adapting agriculture to climate change and reducing their emissions of greenhouse gases.

Plant breeding may benefit from recent advances in genotyping and precise phenotyping, and by increasing the available agro-biodiversity through the use of genomics-led approaches. Today marker-assisted breeding is applied to a broad range of crops and could facilitate domesticating entirely new crops. Marker-assisted selection is particularly important for improving complex, quantitatively inherited traits that alter yield, and for speeding up the breeding process [90]. Crop genomics has also been improving in the last decade and today there are faster and cheaper systems being increasingly used in gene banks, genetic research and plant breeding, e.g. for studying interactions between loci and alleles such as heterosis, epistasis and pleiotropy, or analyzing genetic pathways. Advances in crop genomics are providing useful data and information for identifying DNA markers, which can be further used for both germplasm characterization and marker-assisted breeding. Genomics- assisted breeding approaches along with bioinformatics capacity and metabolomics resources are becoming essential components of crop improvement programs worldwide [84,91].

Progress in crop genome sequencing, high resolution genetic mapping and precise phenotyping will accelerate the discovery of functional alleles and allelic variation associated with traits of interest for plant breeding. Genome sequencing and annotation include an increasing range of species such as wheat, rice, maize, sugarcane, potato, sorghum, soybean, banana, cassava, citrus, grape, among other species. Perhaps, one day further research on the genome of a plant species from a drought-prone environment may assist in breeding more hardy and water efficient related crops due to gene synteny.

Transgenic breeding involves the introduction of foreign DNA. While conventional plant breeding utilizing non-transgenic approaches will remain the backbone of crop improvement strategies, transgenic crop cultivars should not be excluded as products capable of contributing

to development goals. Available commercial transgenic crops and products are at least as safe in terms of food safety as those ensuing from conventional plant breeding [89,92-94].

The use of transgenic crops remains controversial worldwide after almost two decades of introducing them into the agro-ecosystems. Using plant-derived genes to introduce useful traits and plant-derived promoters, may overcome some concerns about the development of genetically engineered crops. In this regard, cisgenesis addresses some negative views regarding the use of genes from non-crossable species for breeding crops. Cisgenesis involves only genes from the plant itself or from a crossable close relative, and these genes could also be transferred by conventional breeding methods. Crop wild relatives are therefore a valuable source of traits for cisgenesis.

Plant breeders need to understand the various valuation strategies very early in the breeding process if they are to direct long-term selection toward reducing agriculture's negative environmental impacts and achieving greater sustainability while maintaining productivity. Regardless of method, breeding objectives can be broadened to include traits which reduce the environmental footprint of traditional production systems (e.g. nutrient and water use efficiencies that reduce off-farm inputs), to adapt crops to new climates, to host plant resistance to tackle old and emerging pathogen epidemics, or new cultivars for new production systems (e.g. perennial polycultures that mimic the biodiversity of natural systems), albeit with some reduction in rate of gain for the traditional agronomic traits of interest. Interdisciplinary crop improvement strategies accounting for ecological, socio-economic and stakeholder considerations will help identify traits leading to plant cultivars using fewer inputs, less land, and less energy, thereby resulting in a more sustainable agricultural ecosystem.

The impact of breeding on crop production is dependent upon the complex relationships involving the farmers, the cultivars available to them, and the developers of those cultivars. Farmers consist of commercial producers with varying size land holdings ranging from moderately small farms to very large ones, and subsistence farmers with small farms often on marginal lands. The subsistence farmers are usually poor. Several types of cultivars are available. The least sophisticated in terms of methods of development are landraces, also known as local cultivars. Modern cultivars consist of development by crossing and selection alone, those developed by crossing and selection with specific important improvements are often obtained from crosses with wild species or by transgenic methods, and F_1 hybrids between desirable inbred lines. The developers of landraces are usually farmers themselves, and are obtained by repeated simple selection procedures of generation after generation. Improved cultivars and hybrids are created either by public sector breeders or seed companies.

Nearly 70% of the world's farmers, from 570 million world exploitations, are small/subsistence and poor farmers. They feed 1,5 billion of the world's population. So they are also a key for biodiversity and for improving the sustainability. For these farmers improved cultivars, hybrids or transgenic seeds tend to be riskier than landraces, since the higher costs associated with seeds and production impose a greater income risk. The lack of capital available denies them the opportunity to invest in production inputs. Small farmers may have lower production costs with landraces because they achieve adequate yields with fewer inputs. In addition, profits from improved hybrid or transgenic cultivars tend to be more variable. Yields are often

higher but market prices tend to be inconsistent. For example in India states of Andhra Pradesh and Maharashtra, farmers have been promised higher yields and lower pesticide costs when using *Bt* cotton, thus they acquired loans to afford the costly seeds (Monsanto has control over 95 % of the Indian *Bt* cotton seed market and this near monopoly has resulted in great increased prices). When, in many cases, the farmers found the yields failed to meet their expected result, the consequences were usually very serious and many farmers died by committing suicide over the past 15 years, perhaps due to this reason. This situation of using *Bt* cotton seeds was explained by the absence of irrigation systems combined with specialization in high-cost crops, and played low market prices. Without collateral help these farmers are usually unable to secure a loan from a bank or money lender [43,88]. Rates are often unmanageably high for those able to get a loan, with strict penalties for late payments. Similarly, a lack of education, resources, skill training and support prevent these farmers from using improved cultivars and then to generate a stable income from their production. In addition, governments do not usually regulate the price of crops or even provide market information. Improving market information systems for crops and facilitating farmers' access to credit are then essential components for a strategy to enable poor farmers to grow improved cultivars. A major obstacle to success in crop production using improved cultivars is the shortage of affordable credit. Desperate for cash, subsistence farmers are forced to sell their crops immediately after the harvest to middlemen or their creditors at unfavorable prices. Low cost quality seeds are essential for these poor farmers to improve their life [43].

3.2. Breeding to adapt plants to the environment

3.2.1. *Producing more with less*

In the coming decades we will need to produce more with less. Fresh water suitable for irrigation is expected to become increasingly scarce and the costs of fertilizer and other agricultural inputs will increase as fossil-fuel costs rise. Nevertheless, continuing gains in production per hectare must be realized to offset the loss of premium agricultural lands (e.g. from urbanization and industrialization), while supplying a growing population. By developing resource efficient plants, plant breeders can continue to improve the sustainability of agricultural ecosystems. Plants requiring fewer off-farm input applications (specifically water, pesticides, nitrogen, phosphorus, and other nutrients) decrease the cost of production, lower fossil energy use, and reduce contamination of water systems, which help to improve public health and stabilize rural economies [95,96].

Although modern plant breeding efforts initially focused on improving uptake of inputs, recent efficiency gains have been made in physiologically increasing yield and biomass production without further increasing inputs. Many crops already have genetic variation in nutrient use efficiency, utilization, and uptake [97-99] and plant breeding will further improve these traits. Intensive agro-ecosystems should emphasize improvements in system productivity, host plant resistance and enhance use-efficiency of inputs such as water and fertilizers.

Water use-efficiency and water productivity are being sought by agricultural researchers worldwide to address water scarcity. Under water scarcity, yields of crops, are a function of

how efficiently the crop uses this water for biomass-growth, and the harvest index. Water use efficiency is the ratio of total dry matter accumulation to evapotranspiration and other water losses. An increase in transpiration efficiency or reduction in soil evaporation will increase water use efficiency. Water productivity is the ratio of biomass with economic value produced compared to the amount of water transpired. Both water use efficiency and water productivity may be improved through plant breeding. Farooq et al. [100] discuss the advances in transgenic breeding for drought-prone environments. In their review, they noted the testing of 10 transgenic rice events [unique DNA recombination taking place in one plant cell and thereafter to be used for generating entire transgenic plant(s)] under water scarcity. It seems the transgenic expression of some stress-regulated genes leads to increased water use efficiency.

Agriculture contributes significantly to greenhouse gas emissions. Nitrous oxide and dioxide are potent greenhouse gases released by manure or nitrogen fertilizer, particularly in intensive cropping systems. Nitrous oxide (N_2O), which is a potent greenhouse gas, is generated through the use of manure or nitrogen fertilizer. In many intensive cropping systems nitrogen fertilizer practices lead to high fluxes of N_2O and nitric oxide (NO). Several groups of heterotrophic bacteria use NO_3 as a source of energy by converting it to the gaseous forms N_2 , NO, and NO_2 (nitrous dioxide). N_2O is therefore often unavailable for crop uptake or utilization.

Genetic enhancement of crops shows great potential for reducing N_2O emissions from soils into the atmosphere. Some plants possess the capacity to modify nitrification *in situ* because they produce chemicals which inhibit nitrification in soil. This release of chemical compounds from plant roots suppressing soil nitrification has been called biological nitrification inhibition, which seems to vary widely among and within species, and appears to be a widespread phenomenon in some tropical pasture grasses, e.g. *Brachiaria humidicola*. Biological nitrification inhibition may be an interesting target trait of crop genetic engineering for mitigating climate change.

Almost one-fifth of global methane emissions are from enteric fermentation in ruminant animals. Apart from various rumen manipulation and emission control strategies, genetic engineering is a promising tool to reduce these emissions. The amount of methane produced varies substantially across individual animals of the same ruminant species. Efforts are ongoing to develop low methane-emitting ruminants without impacting reproductive capacity and wool and meat quality. A recent study by Shi et al. [101], to understand why some sheep produce less methane than others, deployed high-throughput DNA sequencing and specialized analysis techniques to explore the contents of the rumens of sheep. The study showed that the microbiota present in sheep rumen was solely responsible for the differences among high and low methane emitting sheep. It was further observed that the expression levels of genes involved in methane production varied more substantially across sheep, suggesting differential gene regulation. There is an exciting prospect that low-methane traits can be slowly introduced into sheep.

Crops are bred for nitrogen use efficiency because this trait is a key factor for reducing nitrogen fertilizer pollution, improving yields in nitrogen limited environments, and reducing fertilizer costs. The use of genotypes of same species efficient in absorption and utilization of nitrogen is an important strategy in improving nitrogen use efficiency in sustainable agricultural systems. Crops are being bred for nitrogen use efficiency because this trait will be a key factor

for reducing run-off of nitrogen fertilizer into surface waters, as well as, for improving yields in nitrogen limiting environments. There are various genetic engineering activities for improving nitrogen use efficiency in crops [98,102]. The gene Alanine aminotransferase from barley, which catalyzes a reversible transamination reaction in the nitrogen assimilation pathway, seems to be a promising candidate for accomplishing this plant breeding target. Transgenic plants over-expressing this enzyme can increase nitrogen uptake especially at early stages of growth. This gene technology was licensed to a private biotechnology company, and is slated to be commercialized within the next six years [103]. A patent gave this biotechnology company the rights to use the nitrogen use efficiency gene technology in major cereals, as well as, in sugarcane.

Keeping nitrogen in ammonium form will affect how nitrogen remains available for crop uptake and will improve nitrogen recovery, thus reducing losses of nitrogen to streams, groundwater and the atmosphere. There are genes in tropical grasses such as *B. humidicola* and in the wheat wild relative *Leymus racemosus* that inhibit or reduce soil nitrification by releasing inhibitory compounds from roots and suppressing *Nitrosomonas* bacteria [104]. Their value for genetic engineering crops for reducing nitrification needs to be further investigated.

3.2.2. Adapting to global climate change and for abiotic and biotic stress tolerance

Extreme weather events are expected to increase in both number and severity in coming years [105]. Climate change impacts agro-ecosystems through changes over the long-term in key variables affecting plant growth (e.g. rising temperatures) and through increasing the variability (frequency and intensity) of weather conditions (rainfall, drought, waterlogging and elevated temperatures). These changes affect both crop productivity and quality. In addition to physically destroying crops, climate change has altered host-pathogen relationships and resulted in increased disease incidence, in insect-pest borne stress in crop plants, and in invasive pests which feed and damage them.

There are two ways to adapt crops to new environments: developing new crops (long-term endeavor starting with domestication) and introducing target traits into existing crops through plant breeding, which includes genetic engineering. However, the job of crop improvement is becoming increasingly difficult. Cultivars which are not only high yielding but are also efficient in use of inputs are needed, tailored to ever more stringent market demands, able to maintain stability under increasing climate variability, and potentially contribute to climate mitigation. These multi-trait demands for new cultivars provide significant challenges for crop breeders, and standard selection approaches struggle under such complexity. To maintain productivity in the face of increased climatic variability, both the population and the plant cultivars will need to be continually developed to withstand “new” climate extremes and the stresses which these will entail [106].

Many breeding programs are already developing plants which tolerate extreme weather conditions, including drought, heat, and frost [107,108]. Plant breeders are also beginning to address expected changes due to increased climate variability, by increasing genetic diversity sources and by adjusting selection and testing procedures [109].

More frequent weather extremes will likely affect the existing ranges of not only agronomic cultivars but also local native plant species [110]. Because some genetic variation useful for climate change adaptation will be found only in wild plant relatives of cultivated crops, preserving genetic biodiversity is essential in order for breeders to select plants that will be well-suited for future environmental conditions [111].

Global climate change notwithstanding, additional stress tolerances in crop species are needed to maintain productivity and survival. In the near future, tolerance to various soil conditions including acidic, aluminum-rich soils (particularly in the tropics) and saline soils (especially those resulting from irrigation), will be increasingly important for production on marginal agricultural lands or as the salt content of irrigated lands increases [112]. Bhatnagar-Mathur et al. [113] suggested that genetic engineering could accelerate plant breeding to adapt crops to stressful environments. They further underline that engineering the regulatory machinery involving transcription factors (TF; a protein binding specific DNA sequences and thereby governing the flow of genetic information from DNA to messenger RNA) provides the means to control the expression of many stress-responsive genes. There are various target traits for adapting crops, through genetic engineering, to high CO₂ and high O₃ environments of the changing climate [114]. Ortiz [115], Jewell et al. [116], and Dwivedi et al. [117,118] provide the most recent overviews on research advances in genetic engineering for improved adaptation to drought, salinity or extreme temperatures in crops. The most cited include TF, and genes involved in: i) signal sensing, perception, and transduction; ii) stress-responsive mechanisms for adaptation; and iii) abscisic acid biosynthesis for enhanced adaptation to drought. Transporter, detoxifying and signal transduction genes as well as TF are cited for tolerance to salinity. Genes related to reactive oxygen species, membrane and chaperoning modifications, late abundance embryogenesis proteins, osmoprotectants/compatible solutes and TF are pursued in crop genetic engineering for temperature extremes.

Transgenic crops provide the means to adapt crops to climate change, particularly in terms of drought and salinity. Duration and intensity of drought has increased in recent years, consistent with expected changes of the hydrologic cycle under global warming. Drought dramatically reduces crop yields. Genetic engineering may be one of the biotechnology tools for developing crop cultivars with enhanced adaptation to drought [119]. It should be seen as complementary to conventional plant breeding rather than as an alternative to it. The function of a TF such as the *Dehydration-Responsive Element Binding (DREB)* gene in water stress-responsive gene expression has been extensively investigated [120]. The main research goal was to gain a deep understanding of TF in developing transgenic crops targeting drought-prone environments [121]. For example, the *DREB1A* gene was placed under the control of a stress-inducible promoter from the *rd29A* gene and inserted via biolistic transformation into wheat bread [122]. Plants expressing this transgene demonstrated significant adaptation to water stress when compared to controls under experimental greenhouse conditions as manifested by a 10-day delay in wilting when water was held. Saint Pierre et al. [123] indicated, however, that these transgenic lines did not generally out-yield the controls under water deficit in confined field trials. Nonetheless, they were able to identify wheat lines combining acceptable or high yield under enough irrigation which also showed stable performance across the

water deficit treatments used in their experiments; i.e., severe stress, stress starting at anthesis, and terminal stress.

Soils affected by salinity are found in more than 100 countries, and about 1/5 of irrigated agriculture is adversely affected by soil salinity. Therefore, breeding salt-tolerant crops should be a priority because salinity will most likely increase under climate change. Mumms [124] lists some candidate genes for salinity tolerance, indicating the putative functions of these genes in the specific tissues in which they may operate. Genes involved in tolerance to salinity in plants, limit the rate of salt uptake from the soil and the transport of salt throughout the plant, adjust the ionic and osmotic balance of cells in roots and shoots, and regulate leaf development and the onset of plant senescence. The most promising genes for the genetic engineering of salinity tolerance in crops, as noted by Chinnusamy et al. [125], are those related to ion transporters and their regulators, as well as the C-repeat-binding factor. The recent genome sequencing of *Thellungiella salsuginea*, a close relative of *Arabidopsis* thriving in salty soils, will provide more resources and evidence about the nature of defense mechanisms constituting the genetic basis underlying salt tolerance in plants [126].

In the quest for breeding transgenic rice and tomato, advances showing salt tolerance have occurred. Plett et al. [127] were able to show an improved salinity tolerance in rice by targeting changes in mineral transport. They initially observed that cell type-specific expression of *AtHKT1* (a sodium transporter) improved sodium (Na^+) exclusion and salinity tolerance in *Arabidopsis*. Further research explored the GAL4-GFP enhancer trap (transgenic construction inserted in a chromosome and used for identifying tissue-specific enhancers in the genome) to drive expression of *AtHKT1* in the root cortex in transgenic rice plants. The transgenic rice plants had a higher fresh weight under salinity stress due to a lower concentration of Na^+ in the shoots. They also noted that root-to-shoot transport of $^{22}\text{Na}^+$ decreased and was correlated with an up-regulation of *OsHKT1*, the native transporter responsible for Na^+ retrieval from the transpiration stream. Moghaieb et al. [128] bred transgenic tomato plants producing ectoine (a common compatible solute in bacteria living in high salt concentrations). Ectoine synthesis was promoted in the roots of transgenic tomato plants under saline conditions, which led to increased concentration of photosynthesis in improving water uptake. Likewise, the photosynthetic rate of ectoine-transgenic tomato plants increased through enhancing cell membrane stability in oxidative conditions under salt stress.

Transgenic crops can also contribute to climate change mitigation efforts by reducing input use intensity [129]. The integration of genetic engineering with conventional plant breeding, within an interdisciplinary approach, will likely accelerate the development and adoption of crop cultivars with enhanced adaptation to climate change related stresses [130]. Global warming will reduce yields in many crops about 6% and 5% average yield loss per 1°C in C_3 and C_4 crops, respectively, whose optimum temperature ranges are $15\text{--}20^\circ\text{C}$ and $25\text{--}30^\circ\text{C}$ [131]. The extent of yield loss depends on crop, cultivar, planting date, agronomy and growing area. For instance, an increase of 1°C in the night time maximum temperature translates into a 10% decrease in grain yield of rice, whereas a rise of 1°C above 25°C shortens the reproductive phase and the grain-filling duration in wheat by at least 5%, thereby reducing grain yield proportionally. Heat stress will exacerbate climate change impacts in the tropics, while it may

put agriculture at risk in high latitudes where heat-sensitive cultivars are grown today. Hence, new cultivars must be bred to address heat stress. Ainsworth and Ort [132] suggested giving priority to traits improving photosynthesis for adapting to heat stress. However, plants have various mechanisms to cope with high temperatures, e.g. by maintaining membrane stability, or by ion transporters, proteins, osmoprotectants, antioxidants, and other factors involved in signaling cascades and transcriptional control [133,134]. Furthermore, Gao et al. [135] noted that *bZIP28* gene (a gene encoding a membrane-tethered TF) up-regulated in response to heat in *Arabidopsis*. Some of these genes can be used in crop genetic engineering to enhance plant adaptation to heat stress. For example, some stress-associated genes such as *ROB5*, a stress inducible gene isolated from bromegrass, enhanced performance of transgenic canola and potato at high temperatures [136]. Likewise, Katiyar-Agarwal et al. [137] introduced *hsp101* gene (a heat shock protein gene from *Arabidopsis*) in basmati rice. This transgenic rice had a better growth in the recovery phase after suffering heat stress.

Globalization has, among other consequences, led to the rapid spread of plant disease and invasive pests. Being immobile, plants are unable to escape pathogens causing plant disease and pests which feed and damage them. Plant disease is mainly caused by fungi, bacteria, viruses, and nematodes. Approximately 70,000 species of pests exist in the world, but of these, only 10% are considered serious [138]. Synthetic pesticides have been applied to crops since 1945 and have been highly successful in reducing crop losses to some pest insects, plant pathogens, weeds and in increasing crop yields [138]. One estimate suggests that without pesticides, crop losses to pests might increase by 30%. Despite pesticide use, insects, pathogens and weeds continue to exact a heavy toll on world crop production, approaching 40% [138,139]. Pre-harvest losses are globally estimated at 15% for insect pests, 13% for damage by pathogens, and about 12% for weeds [138]. Developing resistant cultivars reduces the need for expensive and environmentally damaging pesticides to be applied. For example, a recent outbreak of *Xanthomonas campestris* pv. *musacearum* led to the devastating *Xanthomonas* wilt of banana in the Great Lakes Region of Africa, thereby threatening the food security and income of millions of East and Central African people who depend on this crop. Transgenic banana plants with the hypersensitivity response-assisting protein (*Hrap*) gene from sweet pepper did not show any infection symptoms after artificial inoculation of potted plants with *Xanthomonas* wilt in the screen house [140]. Selected transgenic banana plants with putative host plant resistance to *Xanthomonas* wilt are ongoing confined field-testing in East Africa, where elevated temperatures, due to the changing climate, will likely favor banana production.

Weather influences how pathogens and pests affect and interact with crops and their host plant resistance, and thus climate change can also have wide-ranging impacts on pests and diseases [118]. Late blight, which is caused by *Phytophthora infestans*, ranks as the most damaging potato pest. Late blight accounts for 20% of potato harvest failures worldwide, translating into 14 million tonnes valued at 7.6 billion US dollars. Global warming will increase late blight spread, e.g. expanding its range above 3,000 meters in the Andes [141]. Chemical control may lead to more aggressive strains of the pathogen and chemical control is often regarded as being environmentally damaging. Cisgenic potato cultivars with late blight resistance are becoming available and will impact growers, consumers and the environment favorably [142]. Related

wild *Solanum* species can be a source of alleles to enhance host plant late blight resistance in potato. For example, *S. bulbocastum* (a wild relative with high resistance to late blight from Mexico) was used to breed the cultivar “Fortuna” using genetic engineering. Cisgenesis allows inserting several host plant resistance genes from wild crop species in one step without linkage drag (reduction in cultivar fitness).

3.3. Breeding plants to improve the environment

In general, plants are bred for their most obvious end products, including grain, fiber, sugar, biomass yield, fruit quality, or ornamental qualities. However, plants deployed across the landscape in agricultural or forestry settings affect the environment in measurable ways. Perennial crops have environmentally beneficial properties not present in annual crops, such as helping to prevent erosion in agricultural systems, providing wildlife habitat, and acting as sinks for carbon and nutrients. Traditionally, perennial crops have not been a major focus of breeding programs because they generally take more time and scientific knowledge to improve, and therefore, products such as new cultivars are often not produced within the timeframe of funding cycles. Current tree breeding programs are developing elms (*Ulmus* spp), chestnuts (*Castanea dentata*), hemlocks (*Tsuga* spp), and other species which are resistant to introduced diseases and insects [143,144]. As compared with natural selection, artificial selection via plant breeding has overcome these stresses more effectively by rapidly incorporating diverse exotic genetic sources of resistance, hybridizing to include multiple, different genetic resistances into the same plant, and making use of off-season locations or artificial conditions to shorten generation cycles. A more complex example which may be feasible in the future is tree breeding for larger and improved root systems to decrease soil erosion, sequester carbon, and improve soil quality by increasing soil organic matter.

New crop cultivars developed by plant breeders must help improve soil health, reduce soil erosion, prevent nutrient and chemical runoff, and maintain biodiversity. The goal to breed projects for forages, which include several species, is to produce a high yield of leaf and stem biomass, as opposed to grain, for ruminant animals. In the tropics many forages are perennial, providing year-round erosion control, improving water infiltration as compared with that, from annual cropping systems, and in some cases, sequestering carbon. The forage breeding program at the University of Georgia (UG) has developed cultivars in several species and has been proactive in developing agreements with private-sector commercial partners to oversee seed production and marketing of new cultivars. Among the cultivars developed at UG is “Jesup MaxQ” tall fescue, a cultivar carrying a non-toxic endophytic fungus that was both highly persistent under grazing and greatly improved animal weight gain and feed efficiency over standard cultivars. In addition, this program developed the first true dual purpose, grazing and hay, alfalfa cultivar “Alfagraze”, followed by several further improved alfalfa cultivars like “Bulldog 805” which persist through summer under cattle grazing [145].

Cover crops are annual species planted in rotation with crops to specifically improve soil conditions and to control weeds, soil-borne diseases, and pests [146-148]. Continuous cover crops can reduce on-farm erosion, nutrient leaching, and grain losses due to pest attacks and build soil organic matter as well as improve the water balance, leading to higher yields

[149,150]. For instance, in Kenya, Kaumbutho and Kienzle [151] showed in two case studies that maize yield increased from 1.2 to 1.8–2.0 t/ha with the use of mucuna legume as cover crop, and without application of nitrogen fertilizer. Besides farmers who adopted mucuna legume as cover crop benefited from higher yields of maize with less labor input for weeding.

Many current perennial and cover crop cultivars are essentially wild species bred from germplasm collections and developed to increase success in managed agro-ecosystems. As compared with non-native vegetation, plant species native to a particular region are generally thought to survive on less water, use fewer nutrients, require minimal pesticide applications, and be non-invasive; however, counter examples for both native and non-native species are plentiful [152]. As potentially valuable species are identified, breeding to improve them for traits of consumer importance will be needed to broaden available biodiversity in cultivated landscapes. With a changing climate, species considered critical to the landscape may require human-assisted hybridization with distant relatives to better ensure survival from threats posed by novel pests or diseases.

Alternative crops are also being bred for new uses, such as removing toxic chemicals and excess nutrients and improving degraded soils, including mine spoils [153]. Phytoremediation is a biotechnology to clean the contaminated sites of toxic elements (e.g. Cd, Cu, Zn, As, Se, Fe) via plant breeding, plant extracting, and plant volatilizing [154]. The last few years have seen a steady expansion in the list of hyper-accumulator species, which could be valuable plant resources for phytoremediation. For example an ecotype of the Zn/Cd hyper-accumulator *Thlaspi caerulescens* from southern France was able to phytoextract Cd efficiently in field trials through the different seasons with good growth of biomass [155,156]. The Chinese brake fern *Pteris vittata* has a strong ability to hyper-accumulate arsenic (As) and shows promising potential for phytoextraction of and from contaminated soils under field conditions [157,158].

A major goal of harmonizing agriculture with the environment is to “tailor” crops to individual landscapes. Plant breeding has always maximized production by selecting for adaptation in the target environments of interest, using local environmental forces for plant selection [131]. By selecting breeding germplasm growing under local environmental conditions, individual cultivars can be optimized for small regional areas of production that fit prevailing environmental and weather patterns. Likewise, plants could be tailored to provide specific ecosystem services to local environments, to address local needs. One cost-effective way to achieve this is through participatory plant breeding, which involves local farmers in the breeding process.

Alternative crop rotations, planting densities, and tillage systems may make production more environmentally benign but will require altering breeding targets and an understanding that systems biology is complex and rarely has simple solutions. For example, no-tillage systems used for soil conservation can lead to colder soils in spring and change the prevalence and onset of various soilborne diseases, thus requiring the addition of specific disease resistances in the breeding objectives [159]. Breeders must select from conditions prevailing under new management practices to ensure cultivars will be optimally productive.

4. Conservation and use of biodiversity – opportunities for cooperation and new partnerships

Plant genetic resources for food and agriculture are the quintessential global public good. No nation is self-reliant. A viable market for their conservation and trade does not exist. The conservation of plant genetic resources is a prerequisite for addressing climate change, as well as water and energy constraints, which will grow in importance in the next decades. The Svalbard Global Seed Vault is an International Treaty which establishes a multilateral System to facilitate access and benefit sharing of plant genetic resources. The Treaty has an insurance policy and provides legal framework for a cooperative and global approach to manage this essential resource. The Svalbard Global Seed Vault has a mechanism for ensuring the permanent conservation of unique crop biodiversity, the Global Crop Diversity Trust, which is structured as an endowment fund [45].

Plant breeding is vital to increase the genetic yield potential of all crops. As mentioned a result of the Green Revolution was the increase of global productivity of the main food staples. Such achievements ensued from crop genetic enhancement partnerships. These partnerships include national agricultural research institutes and international agricultural research centers. For many decades the global wheat yield increased due to an effective International Wheat Improvement Network (IWIN) officially founded as an international organization in 1966 [160]. This wheat network deployed cutting-edge science alongside practical multi-disciplinary applications, resulting in the development of genetically enhanced wheat germplasm, which has improved food security and the livelihoods of farmers in the developing world [161]. The spring wheat germplasm bred in Mexico under the leadership of Nobel Peace Laureate Norman Borlaug was further used for launching the Green Revolution in India, Pakistan and Turkey [162]. The network was broadened during the 1970s to include Brazil, China and other major developing country wheat producers. It resulted in wheat cultivars with broader host plant resistance (especially to rusts), better adaptation to marginal environments, and tolerance to acid soils. Nowadays IWIN, an international "alliance", operates field evaluation trials in more than 250 locations, in roughly 100 countries it tests improved breeding lines of wheat in different environments. The number of wheat cultivars released annually in the developing world doubled to more than 100 cultivars by early 1990s due to this networking and the strengthening of national capacity [163]. The widespread adoption of newly bred wheat cultivars, especially in South Asia and Latin America, due to yield increases, led to 50% average annual rates of investment returns [164]. The urban poor also benefited significantly because grain harvest increases drove wheat prices down. Every year, nursery sets and trials are sent to various researchers worldwide, who share their data from these trials to catalogue and analyze. The returned data are used to identify parents for subsequent crosses and to incorporate new genetic variability into advanced wheat lines that are consequently able to cope with the dynamics of abiotic and biotic stresses affecting wheat farming systems. The full pedigree and selection histories are known and phenotypic data cover yield, agronomic, pathological and quality data [161].

The International Network for Genetic Evaluation of Rice (INGER) is one more example of world cooperation. It was established in 1975 as a consortium of national agricultural research systems of rice-growing countries and Centers of today's CGIAR Consortium. INGER was initially founded as an International Rice Testing Program, but soon became an integral component of world national rice breeding program. INGER partners can share rice breeding lines. Every year partners provide about 1000 genetically diverse breeding lines, which have been grown in about 600 experiment stations from 80 countries. This network facilitated the release of 667 cultivars worldwide, which translated into 1.5 billion US dollars of economic benefits. It was estimated that ending INGER could lead to a reduction of 20 rice cultivars per year and to an economic loss of 1.9 billion US dollars [165]. Further analysis by Jackson and Huggan [166] has shown how genetic conservation of landraces can lead to significant gains in rice breeding.

Two other examples of cooperation and partnership are the Latin American Maize Project (LAMP) and the Germplasm Enhancement of Maize (GEM). The LAMP was established as a partnership between Latin America and the United States to assess national germplasm and facilitate the exchange of maize genetic resources across the American continent [167]. The United States Department of Agriculture, the participating national agricultural research systems and a multinational seed corporation provided the funding. The aim of LAMP was to obtain information about the performance of maize germplasm and to share it with plant breeders for developing genetically enhanced open pollinated and hybrid cultivars. The maize germplasm was tested for agronomic characteristics from sea level to 3300 m, and from 41°N to 34°S across 32 locations in the first stage and in 64 locations (two per region) in the second stage. These locations were clustered according to five homologous areas: lowland tropics, temperate and three altitudes.

There were a total five LAMP breeding stages [167]. In the first stage, 14,847 maize accessions belonging to a region were planted for evaluation in trials using a randomized complete block design with two replications of 10m² plots at a single location, which was environmentally similar to that from where these landraces were originally collected. The next step included the assessment of the upper quintile (20%) of those accessions evaluated for agronomic performance in the previous stage. These accessions were planted in two locations with two replications, and the upper 5% were further selected according to their performance. These best selected accessions of each country were interchanged among regions belonging to the same homologous area in the third stage. They were tested in two locations with two replications in each region. The selected maize accessions from the same homologous area were mated with the best tested accession of the region in an isolated field within each region. In the fourth stage, combining ability tests of 268 selected maize accessions were carried out with a local tester using two replications at two locations within each region. The elite maize germplasm was integrated into breeding programs in the fifth stage, which was the last. The best cross combinations and heterotic pools were also determined by LAMP. Maize breeders obtained access to the most promising accessions identified by LAMP to widen the crop genetic base. A LAMP core subset has been made available for encouraging further use in broadening of maize genetic diversity [168].

The GEM was set up to introgress useful genetic diversity from Latin American maize landraces and other tropical maize donor sources (lines and hybrids) into United States' maize germplasm, to broaden the genetic base of the "corn-belt" hybrids [169,170]. GEM owes its existence to LAMP because it has used the Latin American landrace maize accessions selected by LAMP in crosses with elite temperate maize lines from the private seed companies in North America [167]. GEM used a pedigree breeding system to develop S_3 lines. The GEM breeders arranged their crosses into non-Stiff Stalk and Stiff Stalk heterotic groups [171].

LAMP provided the first step through the sharing of information needed to select gene bank maize accessions for further germplasm enhancement. GEM completed the process by returning to genetically enhanced breeding materials derived from gene bank accessions. This improved germplasm can be further used in maize breeding in the United States and elsewhere. LAMP and GEM are very nice examples of international and national public-private partnerships in crop germplasm enhancement.

Agricultural plant breeding is a typical commodity- or species-oriented and solves problems within a species, rather than making breeding choices based on system wide needs. For example, maize breeders currently maximize the area in which maize can be grown, and maximize the amount of maize produced throughout that area. If environmental harmony is to be a key breeding objective, then a change in agricultural thinking to appropriately value whole cropping systems will be required. Achieving these goals will require collaboration among the private, public, and non-profit sectors, and with society as a whole. Programs within the private sector excel at breeding major, profitable crops, and have economies of scale to increase the efficiency of production and ultimately provide farmers with seed. As a valuable complement to commercial breeding programs, public and non-profit breeding programs may focus on developing alternative crops, breeding for small target regions, tackling long-term and high-risk problems, evaluating diverse genetic resources, and, importantly, conducting basic research on breeding methodology to enhance efficiency. Only publicly funded breeding programs, and in particular those based at universities, can provide the necessary education and training in plant breeding and in specialized fields such as ecology. Without trained students from public programs, private commercial breeding programs suffer from an erosion of intellectual capital. Conversely, without the private sector to commercialize public-sector-derived products, beneficial traits and new cultivars cannot easily and quickly be put in the hands of farmers, as has been seen in developing countries without a developed seed industry [172]. As stated, seed production is high technology and a cost intensive venture and only well organized seed companies with good scientific manpower and well equipped research facilities can afford seed production.

Although due to globalization, most breeding research and cultivar development in the world is presently conducted and funded in the private sector, mainly by huge multinational seed companies. Public breeders, cultivar development activities and research are disappearing worldwide. In general, this means there are fewer decision-making centers for breeding and cultivar development. This has also resulted in the focus on relatively few major crops produced worldwide, to the detriment of all the other cultivated crops. It is imperative that national governments and policymakers, as part of a social duty, invest in breeding research

and cultivar development of traditional open-pollinated cultivars and in the minor crops. More investments in this area will mean less expensive seed for growers to choose from, and an increased preservation of crop biodiversity. To accomplish these goals new approaches may be required to crop breeding research and development by both the public and private sector. Until recently, breeding research and development which targets small-scale and poor farmers has largely been undertaken by public sector institutions and national agricultural research institutes. However, the capacity to undertake the work was mainly dependent on national or international funding and expertise. The work has been limited by the capacity of these institutions to pay for it. As a result, crop breeding advancement has varied enormously among countries and even within regions in developed and still developing countries. In the area of plant breeding, the process to produce improved cultivars is slow, and it requires long-term sustained commitment that may not fit the continuing changes in the national and international politics to fund research. The application of biotechnology promises acceleration in some aspects of plant breeding, but the adoption of more advanced technology raises the cost of research significantly at a time when investment funding has diminished. Public plant breeding remains a key component of crop breeding research systems worldwide, especially in developing countries. However, the increasing presence of private sector breeding and a decrease in national and international support makes it difficult for the public sector to continue operating in the traditional manner. Declining funding for public crop breeding coupled with the rapid increase of crop production and an urbanizing population has created a difficult situation. Public sector breeding must be strengthened. More public sector crop breeders are needed worldwide to select and to produce non-hybrid cultivars of the minor crops. Breeding of major crops and other minor crops must continue as a viable endeavor. This will benefit small farmers, and will safeguard biodiversity and food security in developing countries.

While the maintenance of vigorous public sector breeding programs in areas where private companies are not interested in providing low cost cultivars is highly desirable, an additional approach to maximize crop and agricultural research input would be the development of global programs with public-private partnerships. The public sector may support portions of crop and agricultural R&D, unattractive to the private sector, and feed improved breeding lines and systems to the private sector for exploitation in regions where the private sector is active, and nurture private sector development in regions where it is lacking. In recent years, private plant breeding programs have increased in number and size. Financial investment also increased, as well as interest in intellectual property protection. The spirit of original attempts to protect plant breeders' rights was that granting a certificate of protection should not inhibit the flow of information and products through continued research by the entire plant breeding community [106,107]. In a classic sense, the patent is a defensive tool to prevent competitors from reaping benefits which rightfully belong to the inventor. In the modern context, it is an offensive weapon, to stifle competition, prevent further innovation by others and maximize income [106,108]. The United States utility patent, it is a way to slow down the flow of progress in plant breeding research, unless the research is within the company holding the patent. While obviously benefiting that company, it is a big step backwards for the plant breeding community and by far, for agriculture itself. The intellectual property protection must encourage research

and free flow of materials and information [106,108]. Protection should be for the cultivar only. There should be no constraint against other breeders using that cultivar in further research, including further breeding. Another breeder should be free to use the protected cultivar in a cross, followed by further development through pedigree breeding. Another breeder should also be free to transfer genes controlling economic traits into the protected cultivar by the backcross method or by genetic transformation procedures [106,107].

5. Conclusions

The growing demand for food in the next decades poses major challenges to humanity. We have to safeguard both arable land for future agricultural food production, and protect genetic biodiversity to safeguard ecosystem resilience. Besides we need to produce more food with less inputs.

Plant breeding is the science of improving plants to further improve the human condition. Plant breeding has played a vital role in the successful development of modern agriculture via "new" cultivars. Plant breeders are continually improving the ability of cultivars to withstand various environmental conditions. By reducing the impact of agriculture on the environment while maintaining sufficient production will require the development of new cultivars.

Climate change is altering the availability of resources and the conditions crucial to plant performance. Plants respond to these changes through environmentally induced shift in phenotype. Understanding these responses is essential to predict and manage the effects of climate change on crop plants.

In the foreseeable future and an increase in population will need significant production. Breeding and modern agricultural technologies can increase yield on existing agricultural land. As a result, they can make a significant contribution to biodiversity conservation by limiting the need to expand agricultural land and by allowing nature to be maintained for conservation purposes and harmony between agriculture and the environment.

There is still a debate among researchers on the best strategy to keep pace with global population growth and increasing food demand. One strategy focuses on agricultural biodiversity, while another strategy favors the use of transgenic crops. There are short research funds for agro-biodiversity solutions in comparison with funding for research in genetic modification of crops. Favoring biodiversity does not exclude any future biotechnological contributions, but favoring biotechnology threatens future biodiversity resources. The future breeding programs should encompass not only knowledge of techniques but also conservation of genetic resources of existing crops, breeds, and wild relatives, to provide the genes necessary to cope with changes in agricultural production. Therefore, agro-biodiversity should be a central element of future sustainable agricultural development [173,174]. The concept of sustainability rests on the principle that the present needs must be addressed without compromising the ability of future generations to meet their own needs [175]. Sustainable agriculture is an alternative to solve future fundamental and applied issues related to food production in an ecological way [176].

Farmers in developing countries, especially small farmers, have problems specific to their cultural, economic and environmental conditions, such as limited purchasing power to access improved cultivars and proprietary technologies [43]. These farmers have an important role in conserving and using crop biodiversity. The future of the world food security depends on stored crop genes as well as on farmers who use and maintain crop genetic diversity on a daily basis. In the long run, the conservation of plant genetic diversity depends not only on a small number of institutional plant breeders and seed banks, but also on the vast number of farmers who select, improve, and use crop diversity, especially in marginal farming environments. Their extensive farming systems using landraces or open-pollinated cultivars increase sustainability and less impact from stresses caused by drought, insect and diseases, due to long-term *in situ* selection of these crops cultivated as opposed to the fertilizer, herbicide, and pesticide demands in an intensive crop based system with improved, hybrid, or transgenic cultivars. That is why we should also be alerted and particularly alarmed by the current trend to exclusively use improved, hybrid, and transgenic crop cultivars. Farmers do not just save seeds; they are plant breeders who constantly adapt their crops to specific farming conditions and needs. This genetic biodiversity is the key to maintain and improve the world's food security, and agriculture sustainability [51].

The introduction of genetically modified technology has been hailed as a gene revolution similar to the "Green Revolution" of the 1960s [41,177]. The "Green Revolution" had an explicit strategy for technology development and diffusion, targeting farmers in developing countries, in which improved germplasm was made freely available as a public good, a particular success in Asia. In contrast to the "Green Revolution", the push for genetically modified crops is based largely on private agricultural research, with cultivars provided to farmers on market terms [177]. To date efforts on genetically modified crops have been focused on crops considered to be profitable enough by large plant breeding companies, not on solutions to problems confronted by the world's small farmers. Existing biodiversity in combination with plant breeding has much more to offer the many world's farmers, while genetically modified crops have more to offer the large-scale farms and agro-industry, and this explains why they have received so much research funding. Genetically modified crops and their creation may attract investment in agriculture, but it can also concentrate ownership of agricultural resources. There is particular concern that present intellectual property rights instruments, including genetically modified organisms, will inhibit sowing of own seeds, seed exchange, and sale [178]. And in developing countries, patents may drive up costs and restrict experimentation by the public researcher or individual farmer.

Transgenic crops can continue to decrease pressure on biodiversity as global agricultural systems expand to feed a growing world population. Continued yield improvements in crops such as rice and wheat are expected with insect resistant and herbicide tolerant traits that are already commercialized in other transgenic crops. Although the potential of currently commercialized genetically modified crops to increase yields, decrease pesticide use, and facilitate the adoption of conservation tillage has yet to be realized in some many countries that have not yet approved these technologies for commercialization. Technologies such as drought tolerance and salinity tolerance would alleviate the pressure in arable land by enabling

crop production on sub-optimal soils. Drought tolerance technology is supposed to be commercialized within less than three years. Nitrogen use efficient technology is also under development, which can reduce run-off of nitrogen fertilizer into surface waters. This technology is supposed to be commercialized within the next six years.

One of the major arguments for genetic modified technology is that new cultivars can be developed more quickly than in traditional plant breeding [111,116,179]. But like new cultivars derived from conventional breeding methods, transgenic cultivars developed under laboratory conditions have to be tested under field conditions and this means several years of field trials to ensure that the inserted traits will actually become expressed and have the desired effects in local environments. So currently there is little difference in the speed with which either method (transgenic or conventional) will result in the release of new cultivars.

The knowledge gained from basic plant research will underpin future crop improvements, but effective mechanisms for the rapid and effective translation of research discoveries into public good agriculture remain to be developed. Maximum benefit will be derived if robust plant breeding and crop management programs have ready access to all the modern crop biotechnological techniques, both transgenic and non-transgenic, to address food security issues. This will require additional investments in capacity building for research and development, in developing countries. Technology implementation alone is not sufficient to address such complex questions as food security. Biotechnologies will make new options available but are not a global solution. We must ensure that society will continue to benefit from the vital contribution that plant breeding offers, using both conventional and biotechnological tools. Genetic engineering has the potential to address some of the most challenging biotic constraints faced by farmers, which are not easily addressed through conventional plant breeding alone. Besides other promising traits seems to be host plant resistance to insects and pathogens. However, transgenic cultivars will have one or a few exogenous genes whereas the background genotype will still be the product of non-transgenic (or conventional) crop breeding. One should follow a pragmatic approach when deciding whether to engage in transgenic plant breeding. Biotechnology products will be successful if clear advantages and safety are demonstrated to both farmers and consumers.

There is a need of investment in research breeding and cultivar development in traditionally open-pollinated cultivars and in the minor crops. More investments in this area will mean cheaper cultivars for growers to choose from and more preservation of crop biodiversity. In recent years, private plant breeding programs have increased in number and size. Financial investment also increased, as well as interest in intellectual property protection. Protective measures, especially patenting, must be moderated to eliminate coverage so broad that it stifles innovation. The intellectual property protection laws for plants must be made less restrictive to encourage research and free flow of materials and information. Public sector breeding must remain vigorous, especially in areas where the private sector does not function. This will often require benevolent public/private partnerships as well as government support. Intellectual property rights laws for plants must be made less restrictive to encourage freer flow of materials. Active and positive connections between the private and public breeding sectors and large-scale gene banks are required to avoid a possible conflict involving breeders' rights,

gene preservation and erosion. Partnerships between policy makers with public and private plant breeders will be essential to address future challenges. Many current breeding efforts remain under-funded and disorganized. There is a great need for a more focused, coordinated approach to efficiently utilize funding, share expertise, and continue progress in technologies and programs.

Author details

João Carlos da Silva Dias

Address all correspondence to: mirjsd@gmail.com

University of Lisbon, Instituto Superior de Agronomia, Tapada da Ajuda, Lisbon, Portugal

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