



HAL
open science

Innovation in Plant Breeding for a Sustainable Supply of High-Quality Plant Raw Materials for the Food Industry

Michel J.F. Dubois, Vincent Pétiard

► **To cite this version:**

Michel J.F. Dubois, Vincent Pétiard. Innovation in Plant Breeding for a Sustainable Supply of High-Quality Plant Raw Materials for the Food Industry. *Megatrends in Food and Agriculture: Technology, Water Use and Nutrition*, Wiley, 2018, 1119391148. hal-04485311

HAL Id: hal-04485311

<https://hal.science/hal-04485311>

Submitted on 1 Mar 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Innovation in Plant Breeding for a Sustainable Supply of High- Quality Plant Raw Materials for the Food Industry

Michel J. F. Dubois,

Unité de recherche INTERACT 2018.C102

GIS UTSH Unité de la Technologie et des Sciences Humaines

Mail : Michel.dubois@unilasalle.fr

19 rue Pierre Wagué – BP 30313 – F-60026 BEAUVAIS Cedex



Vincent Pétiard, Executive vice-president, Nature Source Genetics,

Mail : Vincent Petiard <vpetiard@gmail.com>

28 allée de la côte Fleurie - 37100 Tours

33 thornwood Drive - Suite 300 - Ithaca, New York 14850 USA

If you think in terms of a year, plant a seed; if in terms of ten years, plant trees; in terms of 100 years, teach the people.

Confucius

Introduction

“Plant breeding is the development of new varieties with new properties, enabling the company who places such varieties on the market to obtain or increase its market share. The development of a new variety or new breeding technique requires much time, effort and money” (Niels et al., 2009). Plant breeders are in process of continuous innovation. They play an important role in a many socioeconomic objectives, such as food needs and security, energy production, environment, quality of soils, health, and quality in food chain in the context of sustainability. Innovation in plant breeding is built on specific know-how, scientific knowledge, new technologies, and systematic transversal management. It also requires the access to genetic resources, which is a prerequisite to any development of new plant varieties.

Competition and profitability of the seed industry is necessary for the sustainable evolution of the whole agri-food chain. Farmers are the first to benefit from the innovation of seed industry, especially when facing new

environmental challenges as a result of pests and diseases. However, the development of new varieties should also better meet the needs of the processing industry and consumers. But these needs between stakeholders are often disconnected.

The aim of this study is to examine the relationship between the seed industry, farmers and players in the food chain, by proposing a few examples of different species that may represent different business models. The first objective is therefore to compare the seed industry's investment in research and development (R&D) with the value and surface area of production. The second objective is to provide a comprehensive overview of the techniques and strategies available in the plant seed sector. The third aim is to understand how the food chain operates from seeds to consumers. The ultimate aim is to propose recommendations to all players in the agri-food chain.

The structure of this chapter is as follows: after a brief introduction, section 3.2 looks at the future challenges facing agriculture; section 3.3 presents plant breeding and its technical limitations and possibilities; section 3.4 presents the analysis of megatrends, after providing the methodology for collecting data on the main crop species, their areas and production, the analysis of investment in seed R&D and the analysis of gaps/distances between R&D investment and production volumes and values. These trends form the basis for our recommendations. Finally, section 3.5 concludes the discussion and suggests avenues for future research.

1. Challenges for Future Agricultures and Food Industries

1.1. Strongly Growing Food Needs

The challenge for agricultural production in the 21st century is to produce sufficient quantities of quality food while limiting the ecological impact. From 7.4 billion in 2016, the population is expected to rise to 8.5 billion in 2030 and exceed 9 billion in 2050, an increase of around 25% on the 2016 population (World Population Prospect, 2012). The urban population, which represented 50% of the world's population in 2011, is expected to reach around 70% of the world's population by 2050, with large cities accounting for more than half of the world's population. This growth of "megacities" generally takes place at the expense of the best arable land.

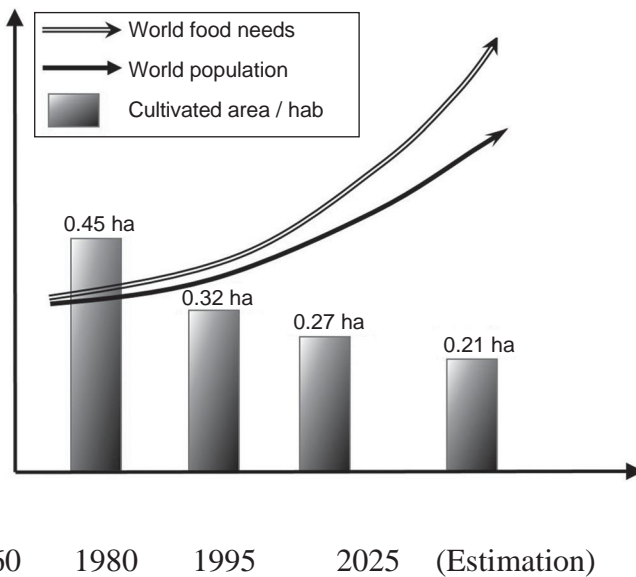
The total cultivated area, which today stands at around 1,600 million hectares, will increase very little. In fact, according to an assessment by the Food and Agriculture Organization of the United Nations (FAO; 2016a, 2016b, 2016d), gains in arable land will be offset by surface losses induced by global economic development, urban growth and desertification. The foreseeable decline in cultivated area per capita will therefore be of the same order of magnitude as population growth. This

means that average yields will have to increase in the same proportions, to achieve the same results in terms of food supply.

Rising demand for meat further increases the need for animal feed and the land to produce it. According to the FAO (2016c), annual meat production will have to increase by over 200 million tons to reach 470 million tons. Indeed, economic development and the growth of cities are accompanied by a growing need for meat supplies. However, the feed-conversion¹ ratio of meat consumption requires a significant increase in plant production. This conversion ratio of 1.7 for fish farming is close to 2 for poultry production, around 3.5 for pork and over 7 for cattle.

Figure
growth
growth

Source:



3.1 How to answer to a of population without a of cultivated lands.

FAO Statistics.

For the production of milk or beef from field crops (corn, soy), this ratio can be as high as 10. For example, it is generally considered that one hectare (ha) of soybeans can feed around 17 to 20 people for 1 year by consuming beans, whereas it does not exceed 2.5 by consuming beef products. Thus, integrating these different parameters, according to the FAO (2016c), agricultural production, quantitatively, will have to increase by almost 70% for the year 2050 compared to 2016. Annual production of cereals for food will have to be around 3 billion tons, which is close to the 2.1 billion of 2016 and is illustrated in figure 1.

¹ Is a measure of an animal efficiency in converting feed mass into increases of the desired output.

Figure 1 shows that rising demand, coupled with stagnant growth in cultivated areas, is leading to a reduction in productive area per inhabitant. Based on arable crops (excluding permanent grassland), in 2050, each hectare will have to feed 5.8 inhabitants, or each inhabitant will have an average of 0.17 ha. If we calculate in "cereal equivalent", on the basis of an average yield of 5 tons/ha (well below the current European average) and annual caloric requirements equivalent to 400 kg of cereals per year, one hectare could feed 12.5 people/year, or 0.08 ha/person required, provided we adopt an entirely vegetarian diet. On average, if the meat supply, made up of a balanced mix of poultry, pigs and ruminants, reaches 50% of the calorie intake, we just barely reach the projected data. In other words, the target of an average overall yield of 5 tons/ha seems right and should, at the very least, be achieved.

The African continent, particularly Sub-Saharan Africa, has the lowest average yields. This is where yield gains are likely to be greatest, as it is also the continent where population growth will be strongest over the next 20 years. A change is needed. The Alliance for a Green Revolution in Africa (AGRA; 2015) showed that 80 small and medium-sized African seed companies from 16 different countries produced more than 80,000 tons of certified seed in 2014. For 2015, 18.2 million small farmers were able to benefit from certified seed on 9.2 million hectares. The aim is to double the income of at least 30 million small farmers in Africa by 2020. Until now, the major seed producers have not been there for these farmers.

Global average cereal yields, calculated by the World Bank, are 3.9 tons/ha for 2013 (World Bank, 2016). FAO data (see Table 3A.1) show that in 2014, maize was the only cereal crop with an average yield of over 5 tons/ha.

The calculation of average yields does not take into account the inputs used to grow the crop, in particular fertilizers and plant protection products. For example, average cereal yields exceed 8 tons/ha in Western Europe, but are around half that for organic cereals (France AgriMer, 2012). In other words, with the same level of technology today, inputs "weigh in" for 50% of production. This issue needs to be analyzed.

1.2. Energy, Environmental and Health Issues

1.2.1. Value of Agriculture Energy Production

It seems that non-food uses of agriculture (mainly fuel, but also green chemistry and pharmaceuticals) are set to expand. This is borne out by trends over the last 20 years, as shown by the increase in non-food crops. In 2011, global ethanol production was 1.439 million barrels of oil per day (boe) or 72 million tons of oil equivalent (toe) per year, and biodiester production 403 thousand boe or 20 million toe, for a total of 92 million toe (Souza et al., 2015).

Agriculture cannot replace the use of fossil fuels, as annual fossil fuel consumption is estimated at 9 billion tons. On the basis of 3,000 billion tons of cereals (which is the target for 2050), this means that total agricultural production cannot reach the equivalent of 1,000 billion tons. The energy value of one ton of cereals is less than that of 0.3 tons of oil. There's a problem of scale. Fossil energy requirements are around 10 times greater than agricultural energy production. We can imagine the development of green chemistry, but certainly not the replacement of fossil fuels. Green energy could play a more important role when technology masters the transformation of agricultural by-products into energy.

No effective plant breeding tool will multiply yields by 10! Agriculture cannot reasonably be expected to solve the problem of fossil fuel consumption, which will eventually run out.

1.2.2. Energy needs of Agriculture

It is necessary to limit the energy consumption of agricultural production and therefore to increase the efficiency of energy use. The cost of fertilizers is first and foremost an energy cost. This efficiency combines new agronomic methods and adapted varieties. It is therefore necessary to adapt current cultivar evaluation procedures, in order to promote the selection of multi-resistant cultivars for low-input systems (Loyce et al., 2012).

Reducing the energy cost of inputs in agriculture is a major objective recognized by the FAO and described in its objectives: "producing more with less". The aim is to achieve this average yield of 5 tons of cereal equivalent per year, but with a concomitant reduction in inputs. The two paths to be followed in parallel are therefore new agronomic practices and the selection of disease- and predator-resistant varieties (Bharadway, 2016; Singh et al., 2016).

1.2.3. Environmental issues

There is now evidence that global warming resulting from climate change has led and will lead to more droughts, floods, tornadoes, typhoons and storms, as well as rising sea levels and increased salinity in deltas. Climate adaptation will require varieties that are resistant to abiotic stresses.

It has also been shown that the yield objective, based on the use of pesticides and fertilizers, has led to a dead end due to its impact on the environment. We now need to focus on the multifunctionality of the ecosystem as a whole (Thompson & Gonzalez, 2016). To increase multifunctionality, we need to increase the number of species grown in longer, more complex rotations, including intercropping and multiple cropping (Byrnes et al., 2014).

This requires a greater number of cultivated species, probably new species adapted to specific agronomic functions, as well as new varieties of currently cultivated species to adapt them to the requirements of new agronomic methods (Singh et al., 2015).

1.2.4. Quality of the soils

To produce better, we know we'll need soil of good physical, chemical and biological quality. Soils must be protected from pollution and erosion, and a high level of physical, chemical and biological quality must be maintained. Conservation agriculture systematically combines direct seeding, intercropping and long rotations, all of which help to capture carbon (against climate change), be more productive, limit inputs and improve soil quality (Johnson et al., 1997; Tóth, Stolbovoy & Montanarella, 2007; Dubois & Sauvé, 2016).

Here again, there is a need for species and cultivars adapted to this new context, and therefore a need to adapt current procedures (agro-practical itineraries) for the evaluation of cultivars and species, which must be adapted to these systems.

1.2.5. Health Issues

Humans are omnivores. We need many vitamins, minerals and even amino acids and essential fatty acids. These complex needs are met by a wide variety of organic products, distributed worldwide but also produced and distributed locally. Logistical and energy costs are kept to a minimum.

In addition to food toxins resulting from plant pathologies (mycotoxins), it may also contain pesticide residues, depending on the sensitivity of cultivars to these pathologies. Obtaining resistant cultivars will help reduce the various risks. On the other hand, previous issues show the interest of crops associated with cereals and nitrogen fixers such as Fabaceae (Corre-Hellou et al., 2009).

These associations of cereals and Fabaceae, already present in antiquity, enable good dietary supplements to reduce the consumption of products of animal origin by increasing the use of plant proteins in food products (e.g. meat analogues, dessert creams, dairy product substitutes, etc.). Health concerns thus integrate environmental issues, opening up opportunities for the development of "flexitarianism" and "vegetarianism".

The aim is to rebalance the ratio of plant proteins to animal proteins. Fabaceae proteins will be supplied by cereal products, legumes and plant proteins derived from the shattering of seeds, leaves and tubers, and will be selected for their techno-functional or nutritional properties. Plant proteins present a wide diversity of

structures and properties, depending on their botanical origin, their location in the plant and the technologies used. Significant progress is possible (Guéguen, Walrand & Bourgeois, 2016). The trend towards the consumption of plant proteins, possibly purified, and used in food compositions can be considered a strong trend as it corresponds as much to health concerns as to the issues mentioned above. This means that a specific plant breeding effort on cultivated fabaceae will have to be put in place. This should include industrial uses and extraction techniques.

1.2.6. Quality Control and Traceability, as Requested by Consumers, Food Chains, and Nonfood Agro- Industries

Traceability and quality control of agri- food products is a strong societal demand. In the context of a growing diversification of agricultural production, it is necessary to anticipate a need for traceability, which will concern the cultivated species, cultivars, the raw material storage, and transformations throughout the industrial food chain.

Some vitamins, such as B₁₂, iron, essential amino acids, essential fatty acids, and vegetable proteins (Gueguen et al., 2016), must be expected from plant products. With the decline in meat consumption, in nearly all advanced industrial countries, of about 2% per year, the selection of new cultivars will have to be considered by integrating the entire processing in the food chain.

The nonfood industries must answer to specifications of any industry according to the process of Total Quality Management.

1.2.7. Synthesis

It will be necessary to produce more and better on smaller areas in relation to the growth of the population. Produce more quantitatively, in better quality and in a wide range of products, on limited areas to be protected. The production will be more diversified to find a global answer, even if, in fact, a good part of the answers will be local. Bharadway (2016) presented that fossil fuels, fertilizers, water, and chemical products are at their peak of use, but this situation will not remain linear in the future. He deduced that the amount of arable land for crop cultivation is decreasing as a result of urbanization, salinization, desertification, and environmental degradation.

This synthesis proposed a change in plant breeding goals that need an improved rationalization between yield, areas, crops and farmers' practices, inputs coupled with high- quality food, and environment protection. It's consistent with a sustainable crop production. However, besides the fact that an increasing number of countries will be largely dependent on food imports, by impossibility of quantitative self- sufficiency (e.g., United Kingdom, Mediterranean Africa, part of the Middle East, Singapore, Japan, South Korea, Philippines), needs for food diversity will contribute to global food trade. An increased demand can be expected in

terms of numbers of species and numbers of cultivars adapted to different agronomic and food demands. This delicate appropriateness will return in large part to the stakeholders in plant breeding.

2. Genetic- Based Techniques for Plant Breeding in the Context of Agricultural Production

2.1. Genetic Innovation and Agronomic Practices

When it comes to the challenges facing agriculture in meeting the needs of the world of 2050, policy-makers can consider different approaches, and will probably need to set priorities.

These approaches are mainly based on genetic knowledge and agronomic practices. Crop genetics is a prerequisite for a significant quantitative or qualitative improvement in crop production, which is the result of interactions between genetics, environment and agronomic practices. Only part of the genetic improvements can be useful if these crops are grown with unsuitable agronomic practices. However, some can be resistant to certain diseases without any change in cultivation practices, and can save the harvest of certain crops. The best agronomic practices may also require adapted varieties. And each specific soil and climate condition requires specific varieties. These two key approaches need to be considered simultaneously and adapted according to the crop and the economic and sociological environment. Figure 2 illustrates the evolution of corn yields in the United States since 1960.

It is generally accepted that genetic innovation counts for about 50% of the improvement in crop yields over the last 50 to 80 years, with the remaining 50% being the result of agricultural practices, including agrochemicals for crop protection, fertilizer, irrigation and mechanization (see Fig. 2). However, it is now accepted that genetics will account for 70-80% of future improvements in agricultural production, due to the limitations of agrochemicals and perhaps mechanization, although precision agriculture will increasingly improve crops and their production systems. personalized. And while some new agronomic practices, such as conservative farming, direct seeding, double cropping or intercropping, could undoubtedly increase yields, varieties improved under these conditions will be even better.

Agricultural performance characteristics are currently referred to as “input characteristics” and quality characteristics as “output characteristics”. The demand for plant raw materials better suited to their end use (“decommodification”) will also require genetic innovation on the pathways that allow the crop to produce (or not) certain specific biochemicals and secondary metabolites. For example, the tomato used for ketchup may be different from the tomato used for dehydrated sauces or soups, and certainly not fresh tomato. Genetic innovation will therefore become increasingly important, either for productivity or for the quality and safety of the raw materials produced. Once again, there's no denying the importance of

agronomic practices, but for the reasons given above, we've decided to focus this chapter on genetics and plant breeding.

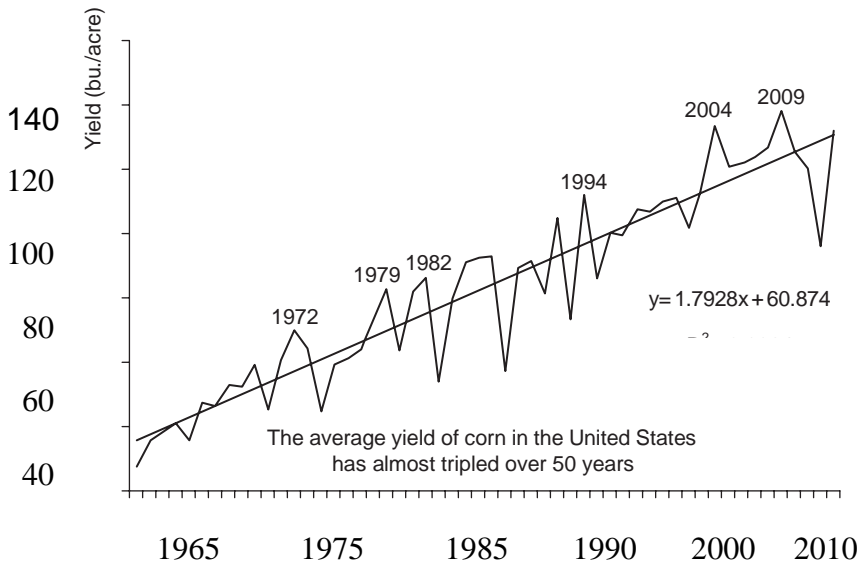


Figure 2 Evolution of corn yield in the United States since 1960. *Source:* farmdocdaily.illinois, July 9, 2014; The 2014 U.S. Average Corn Yield: Big or Really Big? Scott Irwin and Darrel Good, Department of Agricultural and Consumer Economics, <http://farmdocdaily.illinois.edu/2014/07/2014-us-average-corn-yield-big-or-really-big.htm>

From the earliest days of agriculture, man has domesticated and then selected the plants he cultivates. Plant selection by science took off with genetics and, more recently, with cellular and molecular biology. It is interesting to note that until the 1950s or 1960s, plant breeding and the development of new varieties were mainly carried out in universities and public institutes. Today, although it's a real industry, it focuses on crops with the highest seed value.

Plant breeding requires a wide range of skills, including genetics, agronomy, statistics and cellular and molecular biology. It was originally based on phenotypic observations in the field, determined by the combination of genotype and environment (generally referred to as "gxe"). It is now possible to base decisions on both phenotype and genotype, which clearly makes the orientation of the process more reliable. Nevertheless, breeders need to bear in mind that the process must provide a variety that can be grown in a field (or greenhouse), and must be attractive to farmers and users or consumers. It must also be produced in sufficient quantities in as short a time as possible, the so-called "seed increase" phase. An exceptional variety that cannot be produced and distributed quickly to farmers is simply useless. Coffee breeders, for example, were confronted with this situation when the first Arabica hybrids were produced in Kenya or Ethiopia

(Riuri 11). Hybrid seed production by hand pollination was easy for a small number of seeds, but quickly became impossible and unreliable for large-scale production.

2.2. The Process of Plant Breeding and Its Main Limitations

Figure 3 describes the whole process, which is fairly similar whatever the crop considered. There are many differences depending on the breeding system, but at the end of the day, it's all about recombining the best traits according to objectives in a given variety and multiplying it to make it commercially and rapidly available to farmers.

There are many differences depending on the breeding system, but ultimately it's a question of recombining the best traits according to objectives in a given variety and multiplying it to make it commercially and rapidly available to farmers.

Whole Process of Plant Breeding

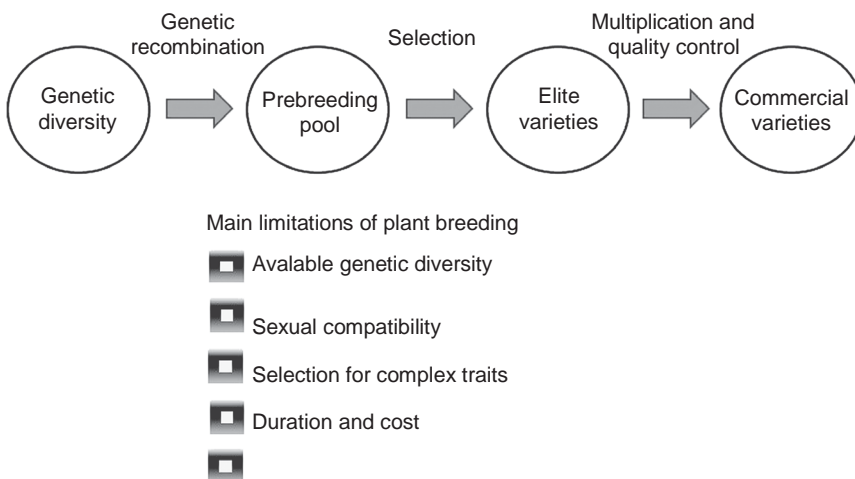


Figure 3 Plant breeding: The process and its limitations.

2.3 Strategic and Technical Use of Available Genetic Diversity

Needless to say, if the genetic information coding for a given trait is not present in genetic diversity, it is impossible to obtain it in a new variety through conventional breeding. Plant breeders have always looked for new characteristics in the natural diversity of the species under consideration, or in related species that can be crossed. In this sense, collecting, identifying and preserving natural genetic diversity has become a priority to ensure the future of the crop when it is sooner or later faced with new environmental or quality challenges. Breeders' first approach is always to

examine their breeding material, the collections available, and check whether the new trait they are looking for might be present, and if so, to use it as a donor for the creation of new varieties. However, it has taken time to master the new technologies that facilitate the use of natural diversity, technologies that are now available at ever-decreasing cost.

The first techniques needed for management are collection and preservation. This is fairly easy for many "orthodox" species, as their seeds can be stored, in some cases, for long periods under controlled conditions. For others, "semi-recalcitrant or recalcitrant", live plants have to be maintained in the field with all the associated risks as their seeds cannot be stored (immediate germination due to lack of survival after dehydration) or even they do not produce seeds. For the latter, scientists have developed methods of cryopreserving different organs in liquid nitrogen to guarantee genetic diversity. This has proved useful in maintaining collections of many tropical species.

Secondly, we still have to optimize the cost for this preservation or conservation. We therefore need to identify the most genetically original material and not maintain everything that might be costly for recalcitrant species. Recent developments of DNA fingerprinting or genotyping by sequencing (GBS) allows identification of core collections that may represent 95% of the total genetic diversity. These so-called *optimized core collections* could then be shared in various breeding centers to be used by different breeders.

Secondly, we still need to optimize the cost of this preservation or conservation. We therefore need to identify the most genetically original material and not conserve everything, which could be costly for recalcitrant species. Recent developments in DNA fingerprinting and genotyping by sequencing (GBS) have made it possible to identify core collections that may represent 95% of total genetic diversity. These so-called optimized core collections could then be shared between different breeding centers for use by different breeders.

When facing this difficulty, scientists are often using a technology called "embryo rescue," which means extracting the young embryo that could not properly develop as a normal seed and developing it in vitro on an artificial medium under aseptic conditions.

Third step: how do you choose which individuals to cross? If there are hundreds of different individuals (or accessions) in the basic collection, the breeder must choose those with the highest probability of displaying the trait he is looking for. If you're looking for resistance to a disease, it's obvious that all you have to do is subject all the accessions to the pressure of this disease and select those that appear tolerant or resistant. When it comes to complex quantitative traits, this is more difficult, and it is only with the help of DNA analysis that the breeder can identify the best donors to cross with a variety to be improved.

Fourth specific limitation: how to obtain interspecific hybrids? The breeder must obtain hybrid seeds from crosses made between the donor and the variety to be improved. This can involve related species that may be quite distant from the cultivated species, which can be more difficult, easy and immediate, but also when it comes to obtaining hybrid seeds. When facing this difficulty, scientists are often using a technology called “embryo rescue,” which means extracting the young embryo that could not properly develop as a normal seed and developing it in vitro on an artificial medium under aseptic conditions.

2.4. New Sources of Genetic Diversity

An interesting trait existing in a given species cannot be transferred by a conventional species to another species if no cross-breeding is possible or if no result of the cross-breeding is obtained, even with embryo rescue. Scientists therefore sought new techniques to create a certain genetic diversity that they could not find in nature or in collections.

The first technique considered by plant breeders was mutagenesis induced either by irradiation or by chemicals such as ethyl methane sulfonate. This technique was not very successful, not so much because of the effectiveness of the treatment as because of the difficulty of identifying positive mutations occurring at random in a large number of treated plants.

The second technique is genetic engineering, used to create genetically modified organisms (GMOs). This technique, which developed rapidly in the early 1980s for the production of pharmaceuticals (e.g. insulin) or enzymes (e.g. chymosin) in micro-organisms, was first successfully applied to a plant (tobacco) in 1983 in the USA and Europe. It developed rapidly and the first commercial GMO variety was a tomato marketed in 1996 by Calgene and modified to deactivate two enzymes involved in fruit softening. Most seed companies then began to apply this technique, mainly to create herbicide-, insect- and virus-resistant crops such as corn, soybean and cotton. Minor commercial success has been achieved for quality traits such as fatty acid composition in rapeseed and starch in potato. However, the seed industry has encountered enormous reluctance on the part of consumers, non-governmental organizations and some authorities towards GM crops, as they are considered "unnatural products" and must be specifically labeled as such in many countries. Nevertheless, in 2015, around 180 million hectares were planted with GMOs. From a more technical point of view, one of the limits to GMO development is that many important characteristics are not determined by a single or even a small number of genes, and in many cases they are not yet known. From a commercial point of view, the costs of deregulation for environmental and food safety have become so great that this technology cannot be considered for minor

crops, although successes have been seen with cabbage and other vegetables that have not yet been brought to market in any significant way.

The third technique, plowing, is a less random mutagenesis that combines mutagenesis with high-throughput screening of mutants based on target gene DNA sequencing. Plants whose target gene sequence has been modified are developed and phenotyped.

Plants in which the target gene sequence has been modified are developed and phenotyped to observe the effect of the mutation, possibly after a sexual generation so that the mutant gene is double recessive. This has led to new products with improved biochemical characteristics, particularly in the field of fatty acid composition. However, it comes up against the same technical limits as GMOs in terms of the number and knowledge of the genes to be targeted. On the other hand, it is not subject to the same regulatory and image constraints, as it is not based on a DNA recombination technique and leads to products that could have been obtained by mutations in nature. It should also be noted that hidden mutations may have been induced in genes other than those targeted, leading to unexpected changes in important traits.

The fourth and most recent technique is called gene editing, or cluster regularly interspaced short palindromic repeats (CRISPR), targets a specific gene to be deactivated. This is certainly the most advanced technique for creating gene-targeted diversity, but the regulatory status is debated in many countries, and it remains unclear whether the products will be considered GM crops. In this case, it is necessary to know the gene coding for the trait to be edited.

It should also be noted that most of these new DNA-based technologies are applied to isolated cells or tissues, and the regeneration of a whole plant from these cells must be properly mastered by cell biology. This may still be a limitation for some species.

Another approach, not based on DNA, was developed in the 1970s to increase diversity. This was called “protoplast fusion.” It involves the fusion of single cells whose cell wall has been enzymatically degraded to allow their fusion either with chemicals or with electrically opposite charges. Originally the idea was to combine nuclear genetic information between different species, but this only worked for crossable species and was not as interesting as breeders hoped. For example, it was possible to produce plants from Tomato + Potato cells, but these plants were chimeric and sterile most certainly due to the incompatibility of the two sets of chromosomes to pair in a balanced manner during the mitosis and the creation of cells lacking certain elements. chromosomes and others with extra chromosomes. However, another application of protoplast fusion has proven important to breeders. It allowed the transfer of genetic information contained in the cytoplasm, in particular that of the mitochondria, likely to code

for “cytoplasmic male sterility”. This transfer has been used to produce hybrids of field crops (e.g. winter rapeseed, etc.) or vegetables (e.g. carrots, cabbages, etc.).

2.5. Selection of Quantitative and Complex Traits

Plant breeding always begins with the observation of agronomic, biochemical, and quality traits that is called phenotyping; it also ends by a selection or screening of specific combination. In theory, the number of plants to select is as high as the probability of detecting the right genetic combination and the ideal plant sought.

Although some traits may be quite easy to screen, other ones can be more difficult or costly to quantify. For example, about sensory quality of strawberries or tomatoes, it has been often claimed by the consumers that today’s varieties do not have the quality of old varieties they used to eat in the garden of their grandparents, and that is true. It is certainly not because the breeders positively selected varieties having a neutral sensory profile. They simply could not select for positive sensory attributes because either they did not know them or they could not screen for them. When not screening for some specific characteristics, the breeders will logically progressively lose, by genetic drift, the genes encoding for them. A good example of this was the progressive loss of bakability of soft wheat varieties in France during 1970s and 1980s when focusing more on yield and animal feed. That imposed the import of hard red spring Canadian wheat to rebalance the quality of flour for production of bread.

Breeders are open to screening for any trait relevant to farmers or consumers, but they need reliable screening tools to do so. Scientists have looked for biochemical markers or DNA markers which not only allow screening but also ensure the presence of the required genes in the genetic background of the plant they select. This is certainly even more important when considering perennial crops where the trait of interest may only be expressed in adult plants after perhaps 5 or 7 years. Any early detectable DNA or biochemical marker that could be applied at the nursery stage of the tree allows a breeder to reject plants that are not promising and should therefore not be pursued further for field evaluation.

Another problem facing plant breeders is the selection of quantitative traits such as yield, which are not determined by a single gene but, in most cases, by many genes. Starting in the 1980s, breeders looked for what are called quantitative trait loci (QTL). They discovered that it is possible to detect areas of the genome (QTL) significantly associated with a quantitative trait. They superimpose and compare phenotyping and genotyping “images” of a population of plants resulting from a cross between two parents differing in

character. These areas can be more or less large, depending on the density and distribution of markers scattered on the genetic map, and it is therefore correct to speak of association of genes or traits and not of correlation because they may not be directly involved in the determination of the quantitative trait. It is possible to detect the QTL gene directly involved in the trait by moving step by step, increasing the density of markers in this area and checking their association with the trait. Definitive proof of the involvement of this QTL gene in the trait could also be established by transferring it to a plant that did not possess it, showing the consequent improvement of the trait. However, most of this QTL work has not been done for the discovery of new genes and "native traits", but rather to guide breeders toward these markets through strategies called marker-assisted selection (MAS), and marker-assisted recurrent selection (MARS). Another great advantage of this QTL-based approach is to differentiate plants that have the same phenotypic value but for different genotypic reasons, from those that have a similar value due to the same genetics. The former should be considered for further selection on this trait, and the latter would not offer great prospects to breeders.

Recently, the development of Genome Wide Selection, initially developed for cattle breeding, allows breeders to predict with good reliability the expected performances (hybrid vigor, etc.) of the plants created before developing and diversifying them into many places. Only promising ones will be scaled up, saving time for crops where it is carried out step by step with an increase in intermediate seeds (e.g. potato, fruit trees, etc.).

2.6. Duration and Cost

As should have been understood in light of the developments mentioned, plant breeding requires successive generations of crossings or multiplications to result in a new variety. The duration of a project is generally more than 5 years, 7 to 10 years is common, and often with perennial crops between 10 and 20 years. This obviously depends on the length of the generation time (from seed to seed) and the number of generations to achieve the objective. Plant breeding is therefore organized as a pipeline to regularly publish new varieties. Breeders and scientists also look for any possible time savings. Different strategies and innovations have emerged over the last 20 years.

For example, they use all possible climatic conditions to speed up the process. Alternative crop cultivation in the Northern and Southern hemispheres makes it possible to produce two generations of corn per year. Using greenhouses for rapid growth and multiplication of certain vegetables saves time throughout the process. Propagation with tissue culture plants that are not in sufficient numbers to proceed to the next stage of the program is also used to save time.

One of the most important technologies developed to save time during

breeding is the production of dihaploid (DH) plant lines. For many crops, whether self-pollinated or crossed, breeders look for pure lines, that is to say, plants with two sets of strictly identical chromosomes (homozygous), also called fixed lines because their descendants come from Self-fertilization is 100% similar to the mother plant. The hybrids resulting from two pure lines are also 100% homogeneous, and therefore, either it is a question of creating new self-pollinated varieties, or new hybrids; breeders often have to go through purely fixed lines. These pure lines are currently obtained by successive generations of self-fertilization which could take years and years. In the mid-1960s, scientists successfully regenerated tobacco plants from pollen grains. Developed from a sex cell, they had only one set of chromosomes which, after doubling it with a natural alkaloid called colchicine, resulted in a 100% pure lineage and perhaps saved five or six generations of self-fertilization. This strategy was then extended to numerous cultures, using either pollen or the ovule, but also interspecific crosses or irradiated pollen which make it possible to induce the development of the ovule without effective fertilization by the pollen cell. DH technologies are now commonly used for many cereals (e.g. corn, wheat, barley) but also other field crops (e.g. rapeseed and sugar beet) and vegetables (e.g. cabbages, pepper, melon, cucumber, etc.).

A large part of the cost of a plant connection project comes from field testing at successive stages of the process. Any reliable prediction tool that can reduce the number of plants to try or the number of locations and plots in which to try them saves money. New algorithms based on genomic selection or previously tested environments are integrated throughout the breeding strategy to optimize the use of the number of plots allowed to a breeder according to budget.

2.7. Seed Increase and Production

For any new variety, seed growth and production is the final challenge the plant breeder faces. Marketing must be as rapid as possible in order to limit the risk that a new variety from the competition will outstrip that which will be launched commercially. Competition in plant breeding is such that some vegetable seed companies could lose up to 30% of their production because the varieties produced have become obsolete on the market by the time they increase their production.

For clonal varieties propagated by horticultural or tuber methods, new in vitro tissue culture techniques have accelerated production and marketing and, for some of them, have eliminated viruses (e.g. potato , raspberry) or other diseases currently spread by suckers (e.g. banana) or other grafting sticks (e.g. cocoa). More recently, tissue culture regeneration through somatic embryogenesis has allowed the propagation of elite individuals of oil palms, date palms, Arabica

hybrids, cocoa trees and forest products that could not be produced in large numbers, thus making their genetic advantages available to planters. They could be essential for rapid renewal of plantations with a new disease-resistant clone (e.g. Bayoud-resistant date palm, Ganoderma-resistant oil palm). Finally, quality and purity control of commercial batches of seeds or clones can be carried out at an affordable cost through the analysis of specific DNA markers that reinforced these controls and traceability down to the shelf.

2.8. Preliminary Conclusions

The preceding description of the main challenges encountered by plant breeders and the different techniques developed to overcome them, or limit their constraints, should lead decision-makers to understand that innovation in plant genetics is not very limited by technology. Numerous tools in conventional breeding, cell biology and molecular biology have been developed and validated on different crops.

All of these tools can be used successfully to meet the challenges of future agriculture. Breeders must now select from a diverse toolbox the most suitable ones based on the crop, objectives and expected timetable for developing a new variety. But, in our opinion, the food industry is facing a new paradigm for sourcing specialty crops that are not considered by the seed industry and are often referred to as "orphan crops." There are various reasons why conventional breeding or new techniques are not developed for all of these species, including certain regulatory issues and the resulting higher costs. For some of these crops which often create more value than raw materials, the agri-food industry will have to invent new economic models, sharing the value down to the seeds or plant material to encourage private entities to invest in these orphan crops in transferring adapted technologies that have already been validated. on the main field crops or vegetables.

It is no longer a question of technology, it is a question of transfer, which may require regulatory decisions but also, for the agri-food industry, strategic decisions. This will be discussed and analyzed in the next section.

3. Trends: change in the allocation of resources to global needs?

3.1. Methodology

All data are extracted from FAO statistics (2016a), for the year 2014 and for 173 products. The 101 main productions were recovered, from which the surface areas and volumes produced by species were extracted. The total area considered represents 1.33 billion hectares, or 83% of the world's cultivated area. The 41

products corresponding to the production of basic foods were extracted (see table 3A.1). They correspond to all agricultural products aimed at satisfying plant-based diets, that is to say calories, proteins and fatty acids. They cover 1.15 billion hectares. From these data, dry matter production is calculated, which is converted into Kcal, taking into account the nature of the products. Yield can be evaluated in Kcal/ha.

The total Kcal produced by these 41 productions is thus estimated at 12.3×10^{15} Kcal. Considering an average requirement of 2800 Kcal per day/person and an average loss of 35%, this should make it possible to feed 7.8 billion people, which seems consistent with the current global situation, knowing that 12% of the production of sugarcane and approximately the same proportion of corn is used in bioethanol. There is no evidence that this is a major trend because the challenge of the future will be to produce enough. The 132 productions excluded from the previous calculations mainly concern fresh fruits and vegetables, aromatic plants and various local productions with a low overall impact on calory consumption. They certainly contribute less than 20% of the world's caloric intake, while being essential (e.g. vitamins, minerals) and nevertheless cover more than 28% of cultivated areas.

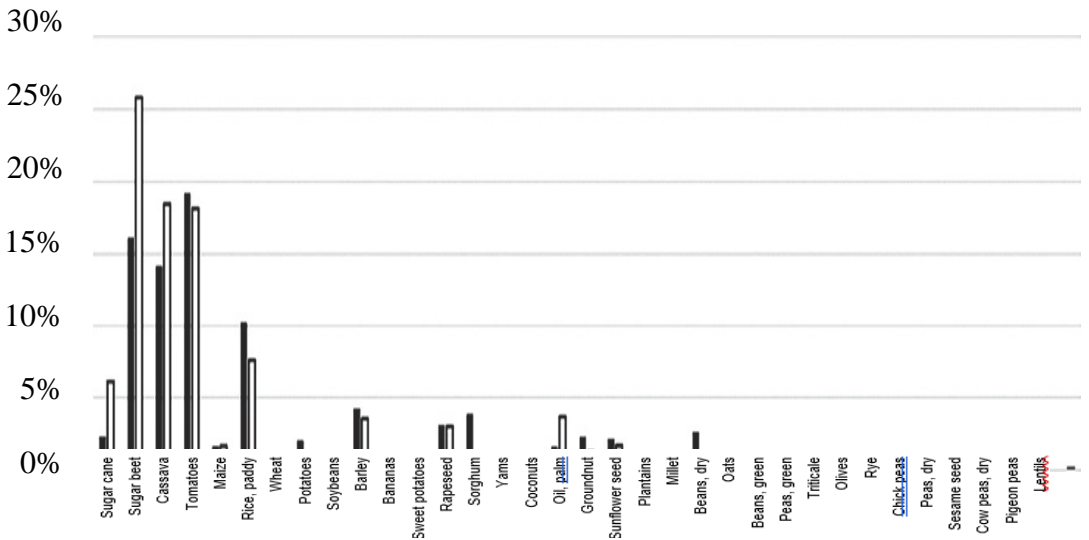


Figure 4 Average caloric production of different crops.

■ %Areas
□ % Kcal

All calculations are made from cultivated areas, which de facto excludes pastures and therefore the resulting share of animal production. In compensation, a large part of agricultural production is intended for livestock. This creates two opposite bias, approximately equivalent in overall quantitative terms because a large part of agricultural production (mainly corn, soybeans and wheat) is

also used for livestock, which was also not counted in the described calculation of caloric production. Nevertheless, it makes it possible to roughly assess the contributions of each type of production to the average caloric intake of consumers. This is illustrated in Figure 4.

This figure is extracted from Table A.1 (appendix below) to show the major importance of the three main cereals. They account for 62.6% of the considered cultivated area. All cereals combined accounted for 68.6% of caloric intakes. Tubers and bananas 4.26% and the fabaceae, which have often been mentioned above, represent only 9.47%, with soybean alone representing 80% of all of them. Alfalfa, not presented here with 33 million hectares, only adds 3%, to be used in animal feed for dairy farms. This weakness of fabaceae has an important disadvantage; it does not promote R & D in plant improvement for protein production. This figure is taken from Table A.1 (annex below) to show the major importance of the three main cereals. They represent 62.6% of the cultivated area considered. All cereals combined represent 68.6% of caloric intake. Tubers and bananas 4.26% and fabaceae, often mentioned above, represent only 9.47%, with soya alone representing 80% of the whole. Alfalfa, not shown here with 33 million hectares, only adds 3%, intended for animal feed on dairy farms. This weakness of Fabaceae presents a significant disadvantage; it does not promote R&D in plant improvement for protein production.

It should be noted that a significant part of cereals and soya, especially in industrialized countries, are transformed into animal products, but on the one hand the overall areas concerned are much lower than the pasture areas, and on the other hand the balances worldwide are mainly affected by the grain trade, knowing that the aim here is to first study the issues specific to plant breeding.

3.2. Analysis of Investment in Seed Research and Development

Using data from the professional world (e.g.: turnover, average R&D rate, market for different crops), it is possible to estimate the distribution of R&D effort by large group of species, although generally confidential. These results make it possible to study the relationship between agricultural production and investment in R&D for genetic innovation and plant breeding as illustrated in Table 1.

Table 1 Investment of seed industry in R&D (US\$).

Turnover of seed industry	\$60 billion
R&D of seed industry	\$7.8 billion
Of which Field crops	\$6.24 billion
Corn	\$2.5 billion

Soybean + Rapeseed	\$2.5 billion	
Other field crops	\$1.24 billion	
Vegetable and ornamentals	\$1.56 billion	
Of which Tomato	\$0.7	billion

The global turnover of the seed industry is not high compared to the value of global commercial agricultural production. It represents a little less than 4% of the total value of commercial plant production intended for human and animal food. But it can exceed 10% of the production value for hybrid plant production. In this case, the gain for the farmer, thanks to a better yield, is generally higher. The higher the gain for the farmer, the more interested he is in buying the seeds. There is balance between the cost of the seeds and the gain they provide in yield and quality.

The investment in R&D as it relates to the seed industry's turnover is remarkable. Only pharmaceuticals and biotechnology have such high R&D spending. These are innovation-driven industries. But this scope must also be nuanced because it focuses on a small number of species. Of the 7.8 billion dollars allocated to private R&D, 6.24 (82%) are intended for field crops, which is more important than their representation in total production calculated by area, volume or even value . In particular, corn experiences an overallocation of R&D compared to its share in overall production, but the gap between allocated R&D and production is even greater for soybeans and rapeseed. Likewise, tomatoes, with 45% of R&D devoted to vegetables and ornamental plants, are disproportionate to their share in total production.

Table 1 shows the concentration of R&D efforts on a limited number of species; this shows that many species can be considered “orphans” and are of little interest to seed companies (e.g. oats, rye, triticale, cassava, coffee, cocoa and many vegetables).

Furthermore, linked to biotechnology and the high cost of developing and disseminating a genetically modified cultivar (due more to regulations than to R&D costs), the globalization of the seed industry has accelerated since more than 20 years (Niels et al., 2009). Today, the top five companies in the sector represent 52% of the seed market, and the next five, only 10%². More recent developments have shown even greater globalization with the creation of only three companies dominating this market: Dupont, Bayer and Chem China (Syngenta).

This analysis of plant breeding objectives involves optimization of yield, surface area, caloric intake, investments in R&D, coupled with high quality food without environmental degradation. There are different approaches to improving the sustainability of farms (Bharadway, 2016). The following analysis will show that, due to the gap between the different determining factors, the actors in the agri-food sectors are very far from sustainability.

² Phil Howard (<https://msu.edu/~howardp/seedindustry.html>)

3.3. Analysis of Deviations and Distortions of R&D Investments and Production Volumes

To understand the evolution of the seed sector, it is necessary to understand how food chains work, from seeds to consumers, as illustrated in Figure 5.

Farmers pay inputs from their suppliers (e.g. seeds, crop protection, fertilizers and other technological components) to sell their output to primary processors, whose products can be used in secondary processing, and to distributors, to whom the consumers buy the products they need. This does not mean that they could sell fresh produce to retailers or more directly to consumers (see Fig. 5).

For the sake of information exchange, the arrows between stakeholders are two-way. Depending on what consumers buy or what they ask for, the information goes back to the distributor and, hopefully, to the producers. If consumer demand were only correlated to the price they are willing to pay, they would be able to dictate what they want. But they are often in contradiction and the consumer population is diverse. Thus, different channels can be set up depending on the demand for the product. But among products of similar perceived quality, consumers, as a population, are generally consistent; they choose the cheapest product. In other words, no food industry or private label retailer can raise product prices for reasons that are not recognized as worthless by consumers.

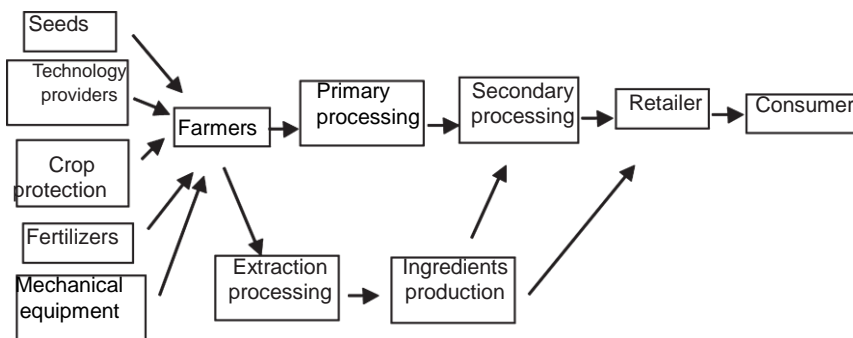


Figure 5 A schematic flow chart of the agro food chain

There are heterogeneous entities along the food chain, with the consequence of loss of contact between the agricultural upstream and the consumers according to Maynard and colleagues (2016). When distributing the same products retailers can only differentiate on price and services. In this way, different

distribution strategies can be developed, all the more based on price because volumes are large and the diversity of products is broad, or all the more based on the quality that the range of products targeted is specific. This can lead to distinct channels (the organic segment). Food manufacturers are looking to build a positive perception of their products to value them independently of the distributor and compete with private labels. The stronger and unique the image the more they can impose their price to the retailers. This image can be supported as much by a stable and appreciated quality than by a communication on the relation with the upstream part of the chain (i.e., traceability, sustainability, etc.). The upstream manufacturers, and in particular all those who produce ingredients, seek to meet business- to- business marketing or technical specifications. Thus, the differentiation in terms of value is built according to the logic of evolution of any industrial product from the raw material to the concept of functional ingredient. Their goal is to provide solutions to their customers.

There are heterogeneous entities throughout the food chain, resulting in a loss of contact between the agricultural upstream and consumer agreement according to Maynard & al (2016). When distributing the same products, retailers can only differentiate themselves on price and service. In this way, different distribution strategies can be developed, generally based on price as the volumes are large and the diversity of products is wide, or all the more based on quality as the targeted product range is specific. This can lead to distinct sectors (e.g. the organic segment). Food manufacturers seek to build a positive perception of their products to promote them independently of the distributor and compete with distributor brands. The stronger and more unique the image, the more they can impose their price on retailers. This image can be supported as much by stable and appreciated quality as by communication on the relationship with the upstream part of the chain (i.e. traceability, sustainability, etc.). Upstream manufacturers, and in particular all those who produce ingredients, seek to meet business-to-business marketing specifications, technical-economic ones. Thus, differentiation in terms of value is built according to the logic of evolution of any industrial product from the raw material to the notion of functional ingredient. Their goal is to provide solutions to their customers.

Farmers, even if wishing to differentiate themselves by changing their products as a response to a specific or local demand cannot all move in that same direction. A production area is made up of many farmers, all competing, and where differentiation will be almost impossible. But the logic of a production area is necessary for logistical reasons. As, in such a specific area, they could not decide the selling price of their products, the only remaining solution for them is to control the production cost. But if farmers cannot control the price of

their products and also the produced volumes that are depending on climatic conditions, at the end they have little potential to influence net income. Hence, they must manage volatility in volumes and in prices. Singh & al (2016) have shown that farmers may be the passive receivers of any technology or information or be the active partners in research action with breeders. They suggested that improved lentil varieties and integrated crop management technologies resulted in higher gain both in yield and net return. Other technology components like fertilizer management, irrigation, and pest and disease control contribute to increase yields and net returns.

There are different innovation levers along the agri- food chains, but there is a lack of coordination between actors that is one reason of the quasi absence of innovative supply chain (Meynard et al., 2016). Niels et al. (2009) presented business models in the breeding sector:

- Local and traditional breeding companies that integrate variety development, production, marketing of seeds, and planting materials.
- Local and traditional breeding companies in home country but licensing their varieties to third parties in other countries.
- Traditional breeding companies that are also integrating biotechnology in their breeding programs.
- Companies that combine biotechnology activities with the production and marketing of seed and also licensing technologies or traits to other seed companies.

We can add another one: biotechnology companies that are focusing on income from services in R&D to seed companies and on licensing income, that are often called *technology providers*.

With all these different models can we imagine the possible strategies conducted by these competitive groups of companies? These strategies are connected to the short- term demands of farmers and not to the needs of the processors or final consumer market.

This strategy analysis does not consider:

- Technical feasibility for improving yields or quality production (i.e., hybrids production and high hybrid vigor effect, efficient solution by biotechnology) and specific needs for agriculture such as disease resistance or abiotic stress resistance for a specific species, such as maize versus wheat;
- Specific difficulties in genetics resources and seed production;
- Needs of food industry and consumers that are not connected to the “seed profitability loop.”

Considering these conditions, the relationship between farmers and seed companies can be described according to Figure 6. We can raise some business models through this figure.

The trend is that the seed industry turnover of a species directly depends on the benefits and final net income of the farmer. The more value the variety generates for the farmer, the more expensive the seeds can be. This positive feedback leads to investment and incessant growth of the species, which gradually takes over "the whole place." We can call it the seed profitability loop; We consider this mode of operation as the first business model which is the traditional and dominant model today.

This is even accentuated by the downstream development opportunities offered by supplying raw materials at reduced prices. Thus, we now find new chips made from corn flour to the detriment of potatoes. This means that the downstream industry unconsciously adapts to this business model and does not require improvement of the species initially used. Simply put, if the industry can make the final product better or cheaper with corn than with another raw material, it will. Two species are "taking all the share" in investment in seeds: corn and tomatoes. Does this mean that these are the most promising species for the future of processors and consumers?

Unfortunately, that is probably not the real situation for most of these crops.

The table of Table 3B.1, comparing the evolution of production and cultivated acreage between 1990 and 2014, is reflecting a global evolution between two given years and may not be directly representative of the trend. In addition it reflects the global increase of productivity that might be as a result as much to crop protection than to genetic innovation. Taking the example of coffee, it considers both Arabica and Robusta species and the positive evolution of average yield/ha is mainly because the increase of importance of Robusta (better yielder than Arabica), during the 1990s in the global production. Vietnam, Robusta producer, became the number- 2 coffee producer in the world, during this period. However, if this situation came to happen, we could consider it as an emergence of a second business model: the downstream, industry provoking an evolution of the seed profitability loop. A better understanding about how this work needs more precise analysis.

There is a specific analysis about the species with very weak R&D investment (cocoa, cassava, oats, olive, millet, barley, peas, coffee). Peas and cocoa, are typical examples, in this selected group of the cultivated species, of growth driven by demand, with low R&D investment for various reasons: surface is still limited and lack of involvement of downstream industries. Coffee is in the same situation with two specificities: on the one hand, particularly low yields, and on the other hand, the high value of its production and its importance in international trade. This might lead to a third business model, by which the consumers demand for traceability and quality would be considered by retailers

and processing industries, but that did not change the seed profitability loop. In this model, the risk is that the cost of raw material increases, because of the decrease of cultivated areas. An integrated third model could be that the processing industries, even in competition, could find a way for specific plant breeding.

One of the problems in this kind of vertical integration of breeding by the downstream industry is the following: what kind of business model could create value for the industry or the retailers without creating strong image risks on the end products? Could the company take some industrial property rights and value on the created varieties without being accused of squeezing poor growers, especially when talking about tropical crops produced by small holders of emerging countries? The only way that has yet been found is to create a consortium of food companies running precompetitive R&D that would benefit the whole community. However, it is quite difficult to organize and manage, and in most cases, it relies on unstable resources.

This analysis revealed also that nearly 60% of the R&D of the seed industry is focused on crops for animal feed, because this is where the seed profitability loop is optimized. It concerns commodities for which only the cost of production comes into account. The processing tomato may know this benefit, thanks to the industry of tomato sauce that is vertically integrated through contract farming because of the need for a regular supply of fresh fruits every day during season. This is probably the reason for its lesser advantage than for maize and soybeans (the latter dominates R&D on fabaceae). It is therefore understandable that the seed industry is ultimately mainly controlled by American and European groups. The construction of significant research potential has taken place through this process, which requires high consumption of meat produced from the cheapest feed.

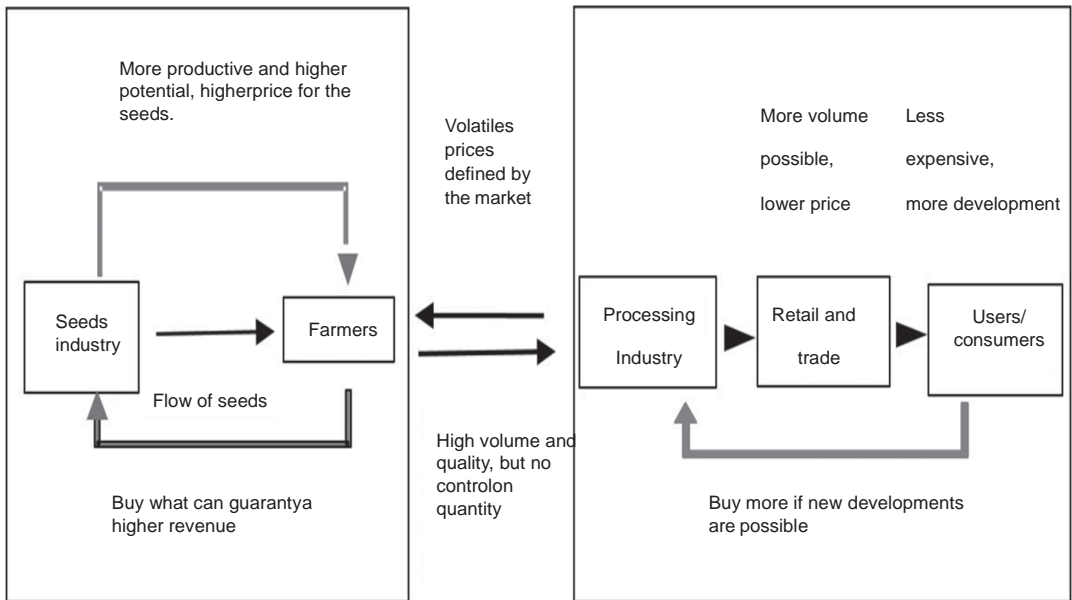
So, one could claim that commodity production for industry is an adaptation of downstream industry according to the first business model. What would be the consequences of such plant- breeding situation in the long run? Analysis of the evolution of maize and soybeans suggests a rather worrying scenario. The increase in synergy between farmers and seed producers, thanks to higher yields and lower production costs, results in a high overall growth of these crops and their gradual domination of a small number of cultivated species. Large- scale crops would move toward monoculture, and other species could simply be abandoned by the farmers.

What is an “orphan species”?

It is a species known and even appreciated, but that has not entered the seed profitability loop described for various but generally well- identified technical and business reasons (e.g., genetics, biology of reproduction, protectability, size and value of seed market). This may be a species identified as important for nutritional, agronomic, ecological or environmental, economical and societal reasons, but it was

not possible to construct, this loop of mutual benefit between seed producers and their customers.

This would require prior support from consumers and the agri- food industry, such as what appears to be taking place for certain vegetables for frozen and canned products where integrated models, are progressively set up with exclusive varieties



customized for the processors.

Table B.1 (appendix below) also makes it possible to conclude that the improved yields and production costs offered by plant breeding tools have also benefited other species not included in the profitability loop. For 7 species, yields have increased by more than 50% and for another 10 by 20% to 35%, but these averages mask considerable variability depending on the region, either for agronomic reasons, or access to certified seed. Technologies developed thanks to R & D investments made on the dozen species that account for 90% of the turnover in the seed industry could be transferred to orphan species, but that would require to create value on seeds or plants of these species and to build favorable conditions at the regulatory and organizational levels in the different local contexts.

The distortion between R&D in plant breeding and global needs, as well quantitative than qualitative, in food production, can be well understood. Whatever are the strategies of seed industries, they are driven by the seed profitability loop and not by a potential interest for the food chains and the consumers. This profitability loop is built on three major characteristics: size and renewal rate of the market, possibility to improve yields by protected varieties (attractivity for the farmers), and technical feasibility for fast improvement.

It has no connection with environmental needs or nutritional needs.

4. A First Set of Conclusions and Recommendations

Agriculture will have to adapt its productions to climate change, but it can also mitigate its effects, and plant breeding must play an important role in association with the new systems of production (i.e., agro-ecology, conservative agri-cultures). This is already largely recognized.

The first immediate conclusion is that increasing the production of biofuels represents a major risk to long- term food security without resolving otherwise the global issue of energy (i.e., production and consumption). The replacement of fossil energy by biomass has a limited impact, as even the net primary production cannot reach 10% of energy value of fossil energy already used. Therefore, policies that encourage the use of biofuels from potential food production should be reconsidered cautiously. Except if new development would allow to use by products of agriculture, it would be much better not to involve too much, on a long- term vision, agriculture production for energy. Policies that favor the breeding in most species, supporting the needs of consumers/ citizens and food industry would be more adapted.

The second conclusion is that cattle and dairy production should not compete too much for croplands because the energy transformation rate is high, and fabaceae products could be much better for nutrition purposes. Apart for soybean breeding that has never been really oriented to make substitutes of animal- based food products, nearly all fabaceae are orphan species for breeding programs.

The third conclusion is that the fast evolutions of technologies useful for plant breeding have broadened the possibilities for crop improvement. Whatever the biology of reproduction of the plant species, a plant- breeding program can be designed for improving yield, disease resistance, adaptation to abiotic or biotic stresses, adaptation to new systems of production, including less inputs, environment protection, and energy consumption. We have now the technical possibilities to find genetic answers to the challenges of the future, in interaction with a lot of innovation in NTIC, robotic, and new agricultural systems. The

large range of technologies offers the breeders a choice of strategies depending on the aims and on the genetic traits to be combined, but also depending on national or international regulations about the different technologies. It is not the purpose of this chapter to argue about transgenic or gene-edited plants, or about the recognition of the different used methodologies for obtaining new combinations of traits. But it must be considered that for any powerful technique, heavy and expensive regulatory controls or studies for authorization already led to an amazing globalization of seed companies. Any low-cost powerful technique will help any small or local company to focus on an orphan species.

With all we know today about genetic recombination, recommendation could be not to unduly increase the cost for launching a new variety onto the market. Any unnecessary added cost for launching a new variety onto a market is an impediment for small breeders to access to the market.

In developing countries, about 80% of the necessary increase in production will come from yield increase, and probably less than 20% could come from an expansion of arable land. The growth rate of yield for the crops on which breeding companies invest massively declines regularly despite increasing biggest R&D investments, and the strategic choices of the seed companies may therefore have negative effects in the medium and long terms. The recommendations in these conditions are to help, by political and regulatory actions, the emergence of small producers of certified seeds for varieties adapted to the local conditions. Once these productions are set up, there are possibilities for the breeders to increase the value of production of farmers and to create some new seed profitability loops. Investment in agricultural R&D has been neglected in most GDP countries. Because R&D in developing countries are dominated by the public sector, additional investment will have to come from public money, unless breeding companies will change their strategy and offer new opportunities for local breeders with possibly new local regulations.

The fourth conclusion is that, although billions of dollars are invested into R&D by seed companies, there is an excessive concentration of investment on a few numbers of species that are now close from their maximum potential of production. The low R&D investment on some important species for food, as, for instance, cassava, sorghum or any other orphan species, although important in international trade, nutritional, social and environmental values, creates a real disadvantage for producing them and therefore for some countries to import other crops while the local ones might be used for the same food purpose. It is really possible that each dollar invested in orphan crops could offer better benefits for food security, nutritional, and environmental impacts. It depends on new business models to be invented for providing a fair return on investment to

the breeding companies that would decide to consider them.

The question becomes: how to build new business models according to the real needs of the society in the next 30 to 50 years? Business model 1, which is built only on that we named the seed profitability loop, is not sustainable, if being the only one driving plant- breeding activity. The business model 2 looks to have a much better effect, although it is not sufficient to save the orphan species, the production of which could decrease inexorably if a third new model does not emerge. The business model 2 was developed according to different criteria depending on the species concerned (e.g.: public R&D, foundations, downstream industries or seeds), only in developed or moderately developed countries. The potential involvement of downstream actors in the sector and the agri-food industry also depends on culture. As has been the case for many years for dairy products, the food industry can be vertically integrated (contract farming) for crops that must be managed within a few hours after harvest, as is the case for frozen vegetables. and canned, tomato paste or for specific products (baby food). In this business model, plant breeding can be governed by processor specifications under a model of equitable sharing of added value with the seed industry partner. However, as for a given crop, adaptation to the needs of a single food processor may not justify launching the selection of a new species, limited to crops for which the seed industry already has activity driven by the seed profitability loop.

The commitment of downstream industries in plant breeding is limited to the crops where the industry has clearly identified risks on the supply chain or traits and specifications of interest for them, but also a dynamic and responsible marketing strategy of the derived products. However, there are examples where it is not sufficient. For instance, tequila production, oatmeal, and quinoa- based dishes, until now, have not yet lead to significant plant- breeding programs, although it would be possible. The major issue is to become fully conscious about risks and benefits for a product based on a given crop that could not be easily substituted by another plant raw material and that is not in a dynamic process of improvement. In a competitive market, the upstream involvement of food industry should not create a competitive disadvantage on costs. For increasing interaction between plant breeding and downstream industries, one prerequisite would be to permit, through regulation, agreements between competitors for joint involvement in upstream R&D (i.e., plant breeding).

This is particularly important when the final consumer is active nearly everywhere in the world and the agriculture (e.g., coffee, tea, cocoa, vanilla) is only in countries with low labor cost. Low labor cost of agriculture and high value of the final product, associated with competing multinational food companies, is a system that prevents genetic improvement because it supports short- term vision and only technical innovation in processing and final

products according to short- term consumer insights. The impediment could come from a necessary agreement between competitors that might have an impact, on short term, in the final price of their products.

Many possibilities do exist. One would be a real and fair sharing of the downstream added value with the upstream by subsidizing the purchase of improved plants or seeds by the producer. This can also come from a gain in productivity and profitability for producers that will allow them to self- finance more expensive plants or seeds. This may first require a loan on future crop to initiate a virtuous circle. For some species, this may justify direct verticalization or crop contracting. In this case, end producers engage themselves directly, in- house or out-sourced, in the supply of its plant raw material.

The last recommendation would be to have a general pragmatic position on a case- by- case basis, in the food chains, as well as for plant species or accessible technologies and when needed to involve regulation authorities.

3.5 Summary and Major Learning

- For quite diverse demographic, environmental, societal reasons food production might be facing shortage of plant raw materials in the next 20 to 30 years
- The productivity of agriculture will therefore have to meet these challenges, especially if nonfood demands of agriculture products continue to increase.
- It is generally admitted that most of these gains of productivity will come from genetic improvement of the cultivated varieties.
- The development of new agronomic practices such as precision agriculture, inter- cropping, and others will also require the development of adapted varieties.
- Plant breeders have developed and validated numerous conventional and biotechnological (molecular and cell biology) techniques on main field crops and vegetables. They now have a quite diversified toolbox to tap in according to the crop, the objectives, and the breeding.
- The economics of seed industry has led it to focus on a small number of crops where seed sales is highly competitive and profitable: 33% of private R&D expenses in field crops are dedicated to maize alone and 50% of private R&D expenses in vegetables are dedicated to tomato alone.
- This situation has led to the creation of numerous orphan crops, not receiving significant genetic innovation that are quantitatively and qualitatively strategic for many food products.
- This situation is increasing the production and income gaps for the farmers between modern and orphan crops, leading to a reduction of the diversity of cultivated species but also to big risks of shortage.

- Food industry should take or reinforce consortium initiatives as the Sustainable Agriculture Initiative (SAIN) or World Coffee Research and will also have to be investing in new business models where part of the added value will be effectively shared upstream, not only with the farmers, but also to their seed or plant suppliers.

Bibliography

- AGRA. (2015). Programs Performance Progress Reports 2007–2015. Available from: <https://agra.org/wp-content/uploads/2016/04/2015-Progress-Report.pdf> [Accessed June 3, 2017].
- Bharadway, D. N. (2016). Sustainable agriculture and plant breeding. *Advances in Plant Breeding Strategies: Agronomic, Abiotic and Biotic Stress Traits*. 2, 3–34.
- Byrnes, J. E. K., Gamfeldt, L., Isbelle, F., Lefcheck, J. S., Griffin J. N., Hector, A., Cardinale, B. J., Hooper, D. U., Dee, L. E., & Duffy, J. E. (2014). Investigating the relationship between biodiversity and ecosystem multifunctionality: Challenges and solutions. *Methods in Ecology and Evolution*. 5 (2), 111–24
- Corre- Hellou, G., Faure, M., Launay, M., Brisson, N., & Crozat, Y. (2009). Adaptation of the STICS intercrop model to simulate crop growth and N accumulation in pea–barley intercrops. *Field Crops Research*. 113, 72–81.
- Dubois. M., J., F., & Sauvé, L. (Eds.). (2016). *Évolution agrotechnique contemporaine—Les transformations de la culture technique agricole*. UTBM.
- FAO. (2016a). Available from: <http://www.fao.org/faostat/en/#data/QC> [Accessed June 3, 2017].
- FAO. (2016b). Produce more with Less. Available from: <http://www.fao.org/ag/save-and-grow/fr/accueil/index.html> [Accessed June 3, 2017].
- FAO. (2016c). Available from: http://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/Issues_papers_FR/Comment_nourrir_le_monde_en_2050.pdf [Accessed June 3, 2017].
- FAO. (2016d). Available from: <http://www.fao.org/world-food-day/2016/theme/en/> [Accessed June 3, 2017].
- France AgriMer. (2012). Variétés et rendement des céréales biologiques 2011. Available from: <http://www.franceagrimer.fr/content/download/18021/142430/file/11%20-%20Etude%20FAM%20-%20Vari%25C3%25A9t%25C3%25A9s%20et%20rendements%20c%25C3%25A9r%25C3%25A9ales%20bio%20r%25C3%25A9c%202011.pdf> [Accessed June 3, 2017].

- Guéguen, J., Walrand, S., & Bourgeois, O. (2016). Plant proteins: Context and potentialities for human food. *Cahiers de Nutrition et de diététique*. 51 (4), 177–85.
- Johnson, D. L., Ambrose, S. H., Bassett, T. J., Bowen, M. L., Crummey, D. E., Isaacson, J.S., Johnson, D. N., Lamb, P., Saul, M., & Winter- Nelson, A. E. (1997). Meanings of environmental terms. *Journal of Environmental Quality*. 26, 581–89.
- Loyce, C., Meynards, J. M., Bouchard, C., Rolland, B., Lonnet, P., Bataillon, P., Bonnefoy, M., Charrier, X., Debote, B., Demarquet, T., Duperrier, B., Félix, I., Heddadj, D., Leblanc, O., Leleu, M., Mangin, P., Méausoone, M., & Doussinault, G. (2012). Growing winter wheat cultivars under different management intensities in France: A multicriteria assessment based on economic, energetic and environmental indicators. *Field Crops Research*. 125, 167–78
- Meynard, J.- M., Jeuffroy, M.- L., Le Bail, M., Lefèvre, A., Magrini, M.- B., & Michon C. (2016). Designing coupled innovations for the sustainability transition of agrifood systems. *Agricultural Systems*.
- Niels, L., Hans, D., Geertrui Van, O., Hans, R., Anthony, A., Derek, E., Annemiek, N. (2009). *Breeding business. The future of plant breeding in the light of developments in patent rights and plant breeder's rights*. Centre for Genetic Resources, the Netherland (CGN), Wageningen University and Research Centre.
- Singh, A. K., Singh, A. K., Misha, A., Singh, L., & Dubey, S. K. (2016). Improving lentil (*Lens culinaris*) productivity and profitability through farmer participatory action research in India. *Indian Journal of Agricultural Sciences*. 86 (10), 1286–92.
- Singh, R. P. Prasad, P. V. V., & Reddy, K. R. (2015). Climate change: Implications for stakeholders in genetic resources and seed sector. *Advances in Agronomy*. 129, 117–80.
- In Souza, G. M., Victoria R., Joly, C., & Verdade L. (Eds.). (2015). *Bioenergy & Sustainability: Bridging the Gaps*. Paris: SCOPE (Scientific Committee on Problems of the Environment).
- Thompson, P. L., & Gonzalez, A. (2016). Ecosystem multifunctionality in metacommunities. *Ecology*. 97 (10), 2867–79.
- Tóth, G., Stolbovoy, V., & Montanarella, L. (2007). Soil quality and sustainability evaluation—An integrated approach to support soil- related policies of the European Union. EUR 22721 EN. Luxembourg: Office for Official Publications of the European Communities.

World Bank. (2016). Cereal yield (kg per hectare). Available from: <http://data.worldbank.org/indicator/AG.YLD.CREL.KG> [Accessed June 5, 2017].

World Population Prospect. (2012). Available from: https://esa.un.org/unpd/wpp/publications/files/key_findings_wpp_2015.pdf [Accessed June 3, 2017].

3.6 Appendix Tables

Table 3A.1 Areas, production, and calorie intake.

Product	Quantity	Acreage (ha)	Yield (t/ha)	Areas (%)	Dry matter	Millions Kcal	Kcal (%)
Sugar cane	1 884 246 253 27 124 723		69,47	2.36	188 424 625	753 698 501	6.13
Maize	1 037 791 518 184 800 969		5,62	16.08	882 122 790	3 175 642 045	25.82
Rice, paddy	741 477 711	162 716 862	4,56	14.16	630 256 054	2 268 921 796	18.44
Wheat	729 012 175	220 417 745	3,31	19.18	619 660 349	2 230 777 256	18.13
Potatoes	381 682 144	19 098 328	19,99	1.66	57 252 322	206 108 358	1.68
Soybeans	306 519 256	117 549 053	2,61	10.23	260 541 368	937 948 923	7.62
Sugar beet	269 714 066	4 471 580	60,32	0.39	40 457 110	16 182 844	0.13
Cassava	268 277 743	23 867 002	11,24	2.08	40 241 661	144 869 981	1.18
Tomatoes	170 750 767	5 023 810	33,99	0.44	25 612 615	92 205 414	0.75
Barley	144 489 996	49 426 652	2,92	4.30	122 816 497	442 139 388	3.59
Bananas	114 130 151	5 393 811	21,16	0.47	17 119 523	61 630 282	0.50
Sweet potato	106 601 602	8 352 323	12,76	0.73	15 990 240	57 564 865	0.47
Rape Seed	73 800 809	36 117 722	2,04	3.14	62 730 688	376 384 126	3.06
Sorghum	68 938 587	44 958 726	1,53	3.91	10 340 788	37 226 837	0.30
Yam	68 132 129	7 755 803	8,78	0.67	10 219 819	36 791 350	0.30
Coconut	60 511 756	11 939 801	5,07	1.04	9 076 763	32 676 348	0.27
Oil, palm	57 328 872	18 697 276	3,07	1.63	57 328 872	458 630 976	3.73
Groundnut	43 915 365	26 541 660	1,65	2.31	26 349 219	158 095 314	1.29
Sunflower seed	41 422 310	25 203 554	1,64	2.19	35 208 964	211 253 781	1.72
Plantains	30 667 662	4 495 057	6,82	0.39	4 600 149	16 560 537	0.13
Millet	28 384 668	9 591 795	2,96	0.83	24 126 968	86 857 084	0.71

(Continued)

Table 3A.1 (Continued)

Product	Quantity	Acreage (ha)	Yield (t/ha)	Areas (%)	Dry matter	Millions Kcal	Kcal (%)
Beans, dry	26 529 580	30 612 842	0,87	2.66	22 550 143	81 180 515	0.66
Oats	22 721 702	5 298 873	4,29	0.46	19 313 447	69 528 408	0.57
Beans, green	21 720 588	1 527 613	14,22	0.13	3 258 088	11 729 118	0.10
Peas, green	17 426 421	2 356 340	7,40	0.20	2 613 963	9 410 267	0.08
Triticale	16 953 565	4 135 952	4,10	0.36	14 410 530	51 877 909	0.42
Olives	15 401 707	11 000 000	1,40	0.96	2 772 307	22 178 458	0.18
Rye	15 242 551	5 306 288	2,87	0.46	12 956 168	46 642 206	0.38
Chick peas	13 730 998	13 981 218	0,98	1.22	11 671 348	42 016 854	0.34
Peas, dry	11 186 123	6 931 941	1,61	0.60	9 508 205	34 229 536	0.28
Dates	7 600 315	3 500 000	2,17	0.30	6 080 252	21 888 907	0.18
Sesame seed	6 235 530	10 819 558	0,58	0.94	5 300 201	31 801 203	0.26
Cow peas, dry	5 589 216	2 178 613	2,57	0.19	4 750 834	17 103 001	0.14
Pigeon peas	4 890 099	826 523	5,92	0.07	4 156 584	14 963 703	0.12
Lentils	4 827 122	622 427	7,76	0.05	4 103 054	14 770 993	0.12
Beans, dry	4 139 972	2 150 905	1,92	0.19	3 518 976	12 668 314	0.10
Chestnut	2 051 564	530 809	3,86	0.05	1 641 251	5 908 504	0.05
Buckwheat	1 924 082	2 011 289	0,96	0.17	1 635 470	5 887 691	0.05
Lupins	1 014 022	31 432 088	0,03	2.73	861 919	3 102 907	0.03
Hazelnuts	713 451	462 489	1,54	0.04	428 071	1 541 054	0.01
Quinoa	192 818	195 342	0,99	0.02	163 895	590 023	0.00
Brazil nuts	109 300	11 300	9,67	0.00	65 580	236 088	0.00
Total		1 149 436 662				12 301 421 666	100

Source: ©FAO, FAOSTAT 2014

Table B1. Area, yield and production from 1990 to 2014 for 24 cultivated species.

Area harvested (ha)		Yield (t/ha)		Production (t)		Area increasing	Yield increasing
		Production increasing					
Apple	1990	5 146 764	7,98	41 047 874			
	2014	5 051 851	16,75	84 630 275	-1.8%	110.0%	106.2%
Asparagus	1990	580 105	3,47	2 012 830			
	2014	1 451 123	5,40	7 830 219	150.1%	55.5%	289.0%
Bananas	1990	3 774 758	13,23	49 932 878			
	2014	5 393 811	21,16	114 130 151	42.9%	60.0%	128.6%
Barley	1990	74 186 774	2,41	178 937 965			
	2014	49 426 652	2,92	144 489 996	-33.4%	21.2%	-19.3%
Beans, green	1990	938 951	6,30	5 912 848			
	2014	1 527 613	14,22	21 720 588	62.7%	125.8%	267.3%
Cassava	1990	15 185 262	10,03	152 243 051			
	2014	23 867 002	11,24	268 277 743	57.2%	12.1%	76.2%
Cocoa	1990	5 712 868	0,44	2 531 907			
	2014	10 434 201	0,43	4 450 263	82.6%	-3.8%	75.8%
Coffee	1990	11 250 724	0,54	6 062 766			
	2014	10 485 408	0,84	8 790 005	-6.8%	55.6%	45.0%
Eggplants	1990	836 066	13,59	11 359 951			
	2014	1 870 728	26,83	50 193 117	123.8%	97.5%	341.8%
Kiwi fruit	1990	66 715	12,64	843 102			
	2014	219 134	15,73	3 447 604	228.5%	24.5%	308.9%
Lentils	1990	3 219 508	0,80	2 563 048			
	2014	4 524 043	1,07	4 827 122	40.5%	34.0%	88.3%
Maize	1990	131 038 436	3,69	483 623 773			
	2014	184 800 969	5,62	1 037 791 518	41.0%	52.2%	114.6%

(Continued)

Table B.1 (Continued)

		Area harvested (ha)	Yield (t/ha)	Production (t)	Area increasing	Yield increasing	Production increasing
Millet	1990	37 496 606	0,80	30 004 192			
	2014	31 432 088	0,90	28 384 668	-16.2%	12.9%	-5.4%
Oats	1990	20 691 016	1,93	39 938 278			
	2014	9 591 795	2,37	22 721 702	-53.6%	22.7%	-43.1%
Olives	1990	7 402 116	1,22	9 023 959			
	2014	10 272 547	1,50	15 401 707	38.8%	23.0%	70.7%
Oranges	1990	3 175 061	15,66	49 707 067			
	2014	3 885 966	18,23	70 856 360	22.4%	16.5%	42.5%
Papayas	1990	232 096	14,18	3 290 566			
	2014	411 355	30,80	12 671 038	77.2%	117.3%	285.1%
Peas, dry	1990	8 677 343	1,92	16 638 494			
	2014	6 931 941	1,61	11 186 123	-20.1%	-15.8%	-32.8%
Peas, green	1990	973 182	7,70	7 491 306			
	2014	2 356 340	7,40	17 426 421	142.1%	-3.9%	132.6%
Potatoes	1990	17 659 630	15,11	266 827 112			
	2014	19 098 328	19,99	381 682 144	8.1%	32.3%	43.0%
Rice, paddy	1990	146 987 918	3,53	518 579 272			
	2014	162 716 862	4,56	741 477 711	10.7%	29.2%	43.0%
Soybean	1990	57 207 200	1,90	108 455 175			
	2014	117 549 053	2,61	306 519 256	105.5%	37.5%	182.6%
Tomato	1990	2 901 330	26,31	76 328 887			
	2014	5 023 810	33,99	170 750 767	73.2%	29.2%	123.7%
Wheat	1990	230 750 672	2,56	591 324 680			
	2014	220 417 745	3,31	729 012 175	4.5%	29.1%	23.3%

Source:

©FAO,

FAOSTAT

1990–201

