

Future challenges of plant biotechnology and genomics

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NABIL MOSA ABUMHADI, ATANAS IVAN ATANASSOV⁽¹⁾

Bulgaria, Sofia 11648 Dragan Tzankov Blvd. fl.4

⁽¹⁾corresponding author address: 8 Dragan Tsankov Blvd, fl.4; Sofia 1164, Bulgaria

e-mails: atanas_atanassov@abi.bg; atanas_atanassov@jgc-bg.org

tel. (ABI): +359 2 9635411; fax (ABI): +359 2 9635408

tel. (JGC): +359 2 8193980; fax (JGC): +359 2 8193988

Abstract

The evolution of plant breeding is a classic example of how improved biological understanding has been adapted to provide more effective methods of meeting the demands of a changing world. Plant biotechnology offers significant improvements in virtually every area of crop production and utilisation, with potential benefits to farmers, the food industry, consumers and the environment. Recent progress in plant genomics has allowed us to discover and isolate important genes and to analyze functions that regulate yields and tolerance to environmental stress.

Based on the traditional plant breeding achievements, this review was focused on the recent trends and potential plant of biotechnology and genomics. We summarized some global strategies for radically rethinking agriculture for the 21st century. Briefly, we exposed the main lines and ideas for modern agricultural improvement based on the reports of the European Plant Science Organization, Food and Agriculture Organization and The Royal Society. Unfortunately, in this review we couldn't cover all aspects of the future challenges of plant biotechnology and genomics. But, we underlined some hot points, trying to direct the attention to new approaches, new methods, new technology indeed, perhaps even new crops and new agricultural systems.

Keywords: Agriculture, Genomics, Plant biotechnology, Plant system biology, Novel crops.

Introduction

Agriculture is primary means of meeting the nutritional needs of the world's population. The past half-century has seen marked growth in food production, allowing for a dramatic decrease in the proportion of the world's people that are hungry, despite a doubling of the total population (Fig. 1). Nevertheless, more than one in seven people today still do not have access to sufficient protein and energy from their diet, and even more suffer from some form of micronutrient malnourishment (GODFRAY & al. [1]). The world is now facing a new set of intersecting challenges. The most important humanity's top ten problems for next 50 years are energy, water, food, environment, poverty, terrorism & war, disease, education, democracy and population [Source: Richard Smalley Energy & Nanotechnology Conference Rice University, Houston May 3, 2003]. The global population will continue to grow, yet it is likely to plateau at some 9 billion people by roughly the middle of this century (GODFRAY & al. [1]).

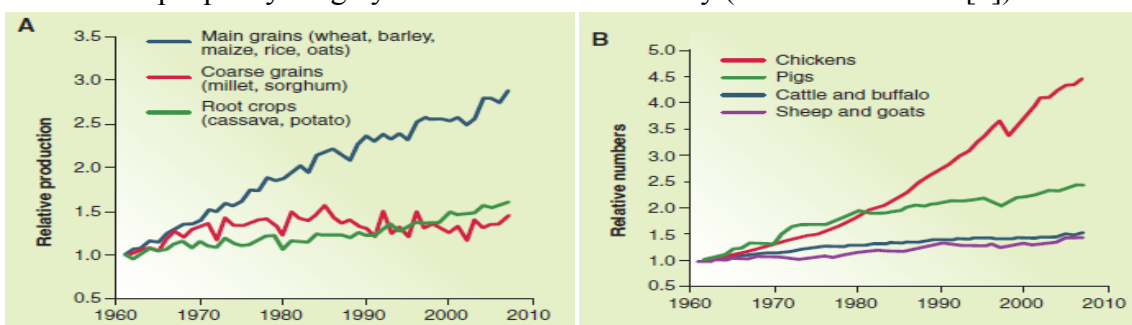


Fig. 1. Changes in the relative global production of crops and animals since 1961 (when relative production scaled to 1 in 1961). (A) Major crop plants and (B) major types of livestock (FAOSTAT [2]).

The 2008 global food price crisis, which sparked riots in more than two dozen countries, rekindled political and scientific interest in food security. In their July 2009 joint statement, the G8 heads of state agreed “to act with the scale and urgency needed to achieve sustainable global food security” (BARRETT & al. [3]). To direct scarce resources to where they can do the greatest good, actions must be guided by reliable information as to who is food insecure, where, when, and why. This requires improved measurement of food insecurity and its causes and greater attention to key institutional and policy lessons learned (BARRETT & al. [3]).

According to the opinions of the authors of “Plants for the Future”, biotechnology and genomics are the most promising tools for addressing new agricultural challenges. The ultimate vision of the plan is a sustainable, resource-conserving, and highly innovative “bio-based economy” (METZLAFF [4]). “Plants for the future” centers around four essential principles:

- The production of safe, high-quality food and feed in sufficient quantities
- Sustainable agriculture
- The development of plants for the production of renewable resources and energy
- Increasing competitiveness while maintaining the freedom of choice for consumers (http://www.gmo-compass.org/eng/news/stories/177.plants_future_research_agenda_2025.html)

The contribution that plant science can make has already been outlined in studies prepared by scientists in the USA (e.g. Plant/crop-based renewable resources 2020, <http://www.oit.doe.gov/agriculture/pdfs/vision2020.pdf>; The Multinational Coordinated Arabidopsis 2010 Project, <http://www.arabidopsis.org/workshop1.jsp>), Japan (The Rice Research Program in Japan, <http://rgp.dna.affrc.go.jp/index.html>), Australia (The Plant Functional Genomics Centre in Australia, www.arc.gov.au), and Canada (The Canadian Crop Genomics Initiative, www.agr.gc.ca/science) (EUROPEAN PLANT SCIENCE ORGANIZATION (EPSO) [5]).

A recent BBSRC report (www.bbsrc.ac.uk/media/pressreleases/04_05_12_csr.html) analyses the problems in the United Kingdom and calls for a national strategy for crop science research. A set of plant scientists at a workshop initiated by the European Plant Science Organization (EPSO) 2005, based on previous analyses and considers examples that illustrate, from a European perspective, why strong strategic investment in plant science will be essential to meet the major societal and environmental issues that we will be facing in the next 25 years. It does this by developing the following theses; (EUROPEAN PLANT SCIENCE ORGANIZATION (EPSO) [5]):

- Advances from basic science can now be used to support plant breeding
- New technology developments and discoveries in basic research will lay the grounds for further major undertakings
- Profiling of composition will integrate plant breeding and agronomic practice with emerging knowledge about nutrition and health
- Improved and novel crops will contribute to the creation of new economies based on plant products
- Advances in knowledge will provide strategies to stabilize agricultural yield in a fluctuating environment
- Changes in crops and management systems will help us to carry out agriculture in concert with the environment
- Knowledge about plants is needed to monitor, understand, and cope with climate change and its impact on agriculture and ecosystems
- A global perspective dictates strong and open support for the developing world

However, Farmers and pastoralists have manipulated the genetic make-up of plants and animals since agriculture began more than 10 000 years ago. Farmers managed the process of domestication over millennia, through many cycles of selection of the best adapted individuals.

This exploitation of the natural variation in biological organisms has given us the crops, plantation trees, farm animals and farmed fish of today, which often differ radically from their early ancestors (see Table 1).

Table 1. An agricultural technology timeline (Source: FAO [6])

Technology	Era	Genetic interventions
Traditional	About 10 000 years BC	Civilizations harvested from natural biological diversity, domesticated crops and animals, began to select plant materials for propagation and animals for breeding
	About 3 000 years BC	Beer brewing, cheese making and wine fermentation
Conventional	Late nineteenth century	Identification of principles of inheritance by Gregor Mendel in 1865, laying the foundation for classical breeding methods
	1930s	Development of commercial hybrid crops
	1940s to 1960s	Use of mutagenesis, tissue culture, plant regeneration. Discovery of transformation and transduction. Discovery by Watson and Crick of the structure of DNA in 1953. Identification of genes that detach and move (transposons)
Modern	1970s	Advent of gene transfer through recombinant DNA techniques. Use of embryo rescue and protoplast fusion in plant breeding and artificial insemination in animal reproduction
	1980s	Insulin as first commercial product from gene transfer. Tissue culture for mass propagation in plants and embryo transfer in animal production
	1990s	Extensive genetic fingerprinting of a wide range of organisms. First field trials of genetically engineered plant varieties in 1990 followed by the first commercial release in 1992. Genetically engineered vaccines and hormones and cloning of animals
	2000s	Bioinformatics, genomics, proteomics, metabolomics

Traditional plant breeding

The art of plant breeding was developed long before the laws of genetics became known. The advent of the principles of genetics at the turn of the last century catalyzed the growth of breeding, making it a science-based technology that has been instrumental in substantial improvements in crop plants. Largely through exploitation of hybrid vigor, grain yields of several cereal crops were substantially increased. Intervarietal and interspecific hybridizations, coupled with appropriate cytogenetic manipulations, proved useful in moving genes for resistance to diseases and insect pests from suitable alien donors into crop cultivars (JAUHAR [7]).

In the past, improvements in agriculture through the use of traditional breeding approaches managed to keep pace with increased demand. In 1960s and 1970s, breeders produced new strains of rice and other crops that significantly increased yields, resulting in what was called the “green revolution”. During the Green revolution, staple-crop yields were rising by 3-6% a year. Now they are rising by only 1-2% a year; in poor countries, yields are flat. The problem facing agriculture today is that traditional breeding requires many years to bring together desirable traits and eliminate undesirable traits. The time required for traditional breeding is one of the major reasons that agricultural researchers both in academia and in biotech industry have turned to genomics as a source of the next green revolution (ATANASSOV [8])

Plant breeding describes methods for the creation, selection, and fixation of superior plant phenotypes in the development of improved cultivars suited to needs of farmers and consumers (MOOSE & al. [9]). Plant breeding has led to large improvements in yield and yield stability, especially by improving plant architecture and by providing resistance to plant pathogens. For a long time, plant breeding was an empirical art that involved carrying out crosses to generate large segregating populations, which were grown in the field and screened for individuals with favorable traits. Here it is usual to distinguish between 'qualitative' and 'quantitative' traits: these are traits that show either a simple segregation of distinct phenotypes or a wide spread of phenotypic variation, respectively. 'Quantitative' traits are often polygenic (i.e. determined by a large number of genes) and influenced by environment (EUROPEAN PLANT SCIENCE ORGANIZATION (EPSO) [5]).

The plant breeding paradigm has been enormously successful on a global scale, with the application of the principles of genetics to crop improvement (JAUHAR [7]), the period from 1930 to 1970 witnessed a phenomenal increase in crop yields, particularly of cereal grains (Khush [10]). Largely through exploitation of hybrid vigor, maize, pearl millet [*Pennisetum glaucum* (L.) R. Br.], and sorghum [*Sorghum bicolor* (L.) Moench] registered a considerable increase in grain yields during 1965 to 1990 (KHUSH [11], JAUHAR & al. [12,13]). Improved wheat and rice varieties with reduced height developed by incorporating dwarfing genes in the 1960s and 1970s launched the famous Green Revolution in Asia (KHUSH [10] see also JAUHAR [13]). Around the same period, the advent of the tools of cytogenetics greatly facilitated wide hybridization and chromosome-mediated gene transfers from wild species into crop plants (JIANG & al.[14], JAUHAR [15,16], FRIEBE & al.[17], FEDAK [18]). Chromosome engineering methodologies, based on the manipulation of pairing control mechanisms and induced translocations, were, for example, applied to transfer into wheat cultivars specific disease and pest resistance genes of alien origin (CEOLONI & al.[19]; JAUHAR [20], MUJEEB-KAZI [21]). Thus, cytogenetic tools were instrumental in the genetic improvement of several crop plants, particularly cereals (JAUHAR [7]).

These and many other products of plant breeding have contributed to the numerous benefits global society has received from greater sustainable supplies of carbon that may be harvested as food, feed, forests, fiber, and fuel (ATANASSOV [8]). However, these procedures are time consuming. Conventional breeding may take 10 or more years to transfer a trait from a donor species into crop cultivar. Wide hybridization is undoubtedly an effective means of incorporating desirable alien genes into crop cultivars, but it has several limitations. It results in transmission of unwanted alien chromosomes and adverse genetic interactions can lead to sterility. Other efficient means of gene transfer have therefore been explored (JAUHAR [7]).

Agricultural biotechnology - modern plant breeding

Biotechnology in agriculture has two categories: (1) "improvements" to existing crops and livestock, and (2) development of entirely new uses for both plants and animals (Biopharming) So called "improvements", include 'input traits' such as crops with extra resistance to insect attack and improved weed control. These "GM" or "GMO" crops, are modified food crops made more commercially viable, e.g. "Roundup ready" soya, "Starlite" corn, or "Frost-tolerant" tomatoes (<http://www.molecularfarming.com/about.html>).

The plant biotechnology era began in the early 1980s with the landmark reports of producing transgenic plants using *Agrobacterium* (Bevan & al.[22]; Fraley & al.[23], Herrera-Estrella & al.[24]). Recent biotechnological tools of direct gene transfer help engineer into plants new characters that are otherwise very difficult to transfer by breeding programs. The world's major crops are being transformed by direct DNA delivery by microprojectile bombardment and other methods of direct gene transfer (Jauhar [20]).

Molecular marker systems for crop plants were developed soon thereafter to create high-resolution genetic maps and exploit genetic linkage between markers and important crop

traits (EDWARDS & al. [25], PATERSON & al. [26], TODOROVSKA & al.[27]). During the past 25 years, the continued development and application of plant biotechnology, molecular markers, and genomics has established new tools for the creation, analysis, and manipulation of genetic variation and the development of improved cultivars (SHARMA & al.[28], ABUMHADI al.[29]; VARSHNEY & al.[30], COLLARD & al.[31]). Molecular breeding is currently standard practice in many crops, with the following sections briefly reviewing how molecular information and genetic engineering positively impacts the plant breeding paradigm (MOOSE & al. [9]).

- Genetically modified plants

Now, genetic engineering has opened up new possibilities by allowing the transfer of individual, known genes, even from completely unrelated organisms such as fungi or bacteria. Genetic engineering thus provides a supplement to classical breeding approaches. This chapter gives examples of crop traits that have been or are being conferred by means of genetic engineering (http://www.gmo-compass.org/eng/agri_biotechnology/breeding_aims/):

- Herbicide resistance

The discovery of herbicide-resistant weeds in the early 1970s triggered an interest in mimicking this unintentional development for use in crop breeding. The concomitant progress in molecular genetics made it possible to incorporate resistance genes from unrelated organisms into an otherwise susceptible crop. In other words, we were now able to adapt the biology of the crop to the chemistry of a herbicide, whereas we previously had to adapt chemistry to biology. It must, however, be noted that herbicide-resistant crops (HRCs) were first produced by methods of traditional breeding, whereas the major current HRCs have been produced by genetic engineering, the technology which has unintentionally placed these crops in a fierce debate between those in favour, and those against, the introduction and commercial use of genetically modified (GM) crops (for references see MADSEN & al.[32])

- Pest resistance

Past debates about the use of new technologies for agriculture have tended to adopt an either/or approach, emphasising the merits of particular agricultural systems or technological approaches and the downsides of others. This has been seen most obviously with respect to genetically modified (GM) crops, the use of pesticides and the arguments for and against organic modes of production. These debates have failed to acknowledge that there is no technological panacea for the global challenge of sustainable and secure global food production. Crops genetically engineered for pest resistance are enabling a shift away from our reliance on broad-spectrum insecticides. This could provide a safer, more biologically sustainable way of managing insect pests. Experience has shown that crop yields can be maintained or increased while decreasing spraying (for references and details see SRIDHARA [33], WANG & al.[34], YUDELMAN & al.[35], JAMES [36]).

- Disease resistance

Diseases have an impact on loss of crops, pre and post harvest. There is a cost associated with their control through crop-protective chemistry and resistant varieties. Significant losses are caused to crop yields from a variety of fungi and oomycetes (microscopic fungus-like organisms), bacteria and viruses across a range of crops. Plant diseases are a major agricultural problem, with losses sometimes reaching 90 percent. Virus infections can be especially difficult to prevent, and treatments for plant viral infections do not exist. Plants can suffer from infections caused by fungi, bacteria, viruses, nematodes, and other pathogens. Various high-tech approaches have been proposed to protect plants from

harmful afflictions. To date, most interest has been focused on virus resistant transgenic plants, but using biotechnology to confer resistance to fungi, bacteria, or nematodes has also been gaining attention (for references and details see Royal Society [37]).

- Stress resistance

More and more research is addressing intensifying global concerns over water scarcity. Salt, heat, and drought resistant crops could play an important role in meeting emergency food needs in the developing world and stabilising crop yields in industrialised nations (for reference and details see Plant Breeding for Stress Environments, <http://www.plantstress.com/Breeding/Breeding.htm>)

- Altered composition

With the advent of genetic engineering, food enhancement and processing could take on a new dimension. Instead of adding new ingredients to foods in the factory, beneficial substances can now be put into the crops themselves. Both industry and consumers have much to gain from crops like "designer oilseeds" or starch crops custom tailored to specific applications JAMES [36]).

- Pharming: Production of Pharmaceuticals, Enzymes and 'Bio' Raw Materials

The world's plants are capable of producing an enormous spectrum of useful substances. With genetic engineering, the potential also exists to modify plants to efficiently produce valuable pharmaceuticals, biodegradable materials for industry, or enzymes that can improve animal feed. This technology is sometimes known as molecular farming or biopharming.

Researchers are currently developing transgenic plants that efficiently produce vaccines. Many researchers hope that such strategies could facilitate immunisations in the developing world. Projects are targeting viral and bacterial causes of diarrhoea, HIV, rabies, and hepatitis B.

In addition, other medically important proteins such as growth hormones, insulin, blood substitutes, and trypsin inhibitor have been produced in transgenic plants. If such plants ever make it to open fields, extreme care would have to be taken to ensure that the novel gene responsible for producing the active substance does not accidentally spread to the environment or to the food supply. Scientists will need to use containment strategies to prevent the out-crossing of transgenes. (http://www.gmo-compass.org/eng/agri_biotechnology/breeding_aims/150.pharming.html).

- Improved animal feed

Phosphorous overabundance in poultry manure is a common environmental problem in areas of intensive livestock production. When added to animal feed, the enzyme phytase can alleviate this problem by reducing phosphorus discharge by up to a third. Scientists have genetically modified the forage crop alfalfa to contain high levels of phytase (JAMES [36], THE ROYAL SOCIETY [37]).

- 'Quality traits'

Some of these new "quality traits" are already in use in the US, while others are well advanced in development. For the time being, no approval applications for GM plants for producing specialty substances have been submitted in the EU. However, the EU produces many important enzymes with the help of genetically modified microorganisms. Transgenic plants can be used to produce an array of substances including pharmaceuticals, silk proteins, biodegradable plastics, or industrial enzymes. Such crops are only intended for industrial use and are not to be used as food (JAMES [36], THE ROYAL SOCIETY [37]), ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT (OECD) [38].

- Elimination of pollutants

Genetic engineering has given plants the ability to clean-up soils polluted with heavy metals or petroleum products. Such strategies can offer cheap and sustainable solutions to dangerous environmental problems (JAMES [36], THE ROYAL SOCIETY [37]).

- Genetically Modified Plants and the Environment

Are genetically modified plants a threat to the environment? Up until now, genetically modified crops have not caused environmental problems. But each new genetically modified plant needs to be closely examined to find out if negative impacts on the environment could be possible down the road (For references and details see The Royal Society [37], FAO [39], LHEUREUX & al. [40], also <http://www.gmo-compass.org/eng/home/>)

DNA marker assisted selection

Plant breeding is a well established method for improving the performance of crop plants by making defined crosses between genetically distinct parents, screening progeny for desired trait combinations and selecting preferred individuals with better combinations of characteristics that can then be bulked and developed into lines and varieties. The procedures for screening progeny for desired traits are often the most challenging stages in conventional plant breeding because many plant lines have to be tested for phenotypes that may be difficult to assay. Disease resistance, for example, can normally be identified only after extensive testing of multiple plants in each line for susceptibility. Similarly, yield enhancements cannot be identified by collecting the products from a single plant; the products from several plants need to be combined and measured accurately in replicated tests. The advances described below allow these screening procedures to be streamlined. Breeders and geneticists can often show that defined traits are conferred by specific genes, or are associated with quantitative trait loci (QTL)—stretches of DNA strongly associated with the gene for a particular trait. These traits are often difficult to measure, requiring laborious and incompletely reliable assessment methods. It therefore makes breeding easier if instead of measuring the trait, a molecular DNA genetic marker linked to the QTL can be monitored in progeny. This method is cheaper and more reliable. In addition, undesirable traits are often genetically linked to desired traits. This is known as linkage drag. DNA markers help identify rare plants in a breeding program in which the desired trait is retained but deleterious traits are left behind. This is referred to as marker-assisted selection (MAS). DNA marker technology has evolved through several stages. In its most advanced form, it is based on a genome sequence and generates dense genetic maps in which the markers are very close to, or may actually represent, the gene of interest. More complex applications of MAS involve selection for traits affected by multiple genetic loci. An example of the application of MAS is in the development of submergence-tolerant rice. In rice, the major genetic determinants of flooding tolerance have been identified and, using this information, MAS has been employed to develop flooding tolerant varieties. Many other examples of MAS suggest that this approach will be increasingly important in breeding as genome sequence data become available for more crop plants (The Royal Society [37], BABU1 & al.[41], MISZTAL [42],

Proceeding from the assumption that the molecular plant breeding as the foundation for 21st century crop improvement, we need radically rethinking agriculture for the 21st century. In this paper we look for the biotechnology and genomics as the most promising tools for addressing new agricultural challenges.

Future challenges: system biology (next “omics”) development

Yuan & al. (2009) defined the systems biology as the study of interactions among biological components using models and/or networks to integrate genes, metabolites, proteins, regulatory elements and other biological components.

'Omics' research approaches have produced copious data for living systems, which have necessitated the development of systems biology to integrate multidimensional biological information into networks and models. Applications of systems biology to plant science have been rapid, and have increased our knowledge about circadian rhythms, multigenic traits, stress responses and plant defenses, and have advanced the virtual plant project (YUAN & al. [43]).

The practice of integrating physiological, morphological, molecular, biochemical and genetic information has long been applied to biological research, and in diverse fields such as plant breeding and ecology (TREWAVAS [44]). The development of modern systems biology was driven by the need to assimilate the large amounts of data generated by genome-scale studies into biologically meaningful interpretations. Nevertheless, the definition of systems biology is still contentious; some researchers emphasize the role of dynamic modeling, whereas others stress multidimensional data analysis. Considering the infancy of the field, this dichotomy is not surprising (KIRSCHNER [45]).

The advances in the field of life sciences during the last 20 years have been tremendous. Our knowledge for the functioning of the genomes of living organisms has grown to a degree allowing us to use them in a sustainable way. The technology development has allowed the researchers to simultaneously study the function of thousands of genes, metabolites and proteins. As a result new scientific fields have emerged called genomics, metabolomics, proteomics and bioinformatics. These new scientific fields provide the opportunity to evaluate the biodiversity in order to protect it and to use it properly for the constantly growing demands of the humankind. Via utilizing our knowledge we can create better plants, animals, food, cosmetic and pharmaceutical products while preserving the natural resources and biodiversity.

Systems biology is composed by omics technology

Systems biology is related but not synonymous to the postgenomics omics technologies such as microarrays for high-throughput generation of large-scale data (YUAN & al. [43]). Genome sequencing enables functional or comparative studies of plant genomes (BEVAN & al. [46]). Genome information also leads to the study of the mRNA transcripts and proteins of an organism as a whole, which are referred to as transcriptomics and proteomics, respectively (GALBRAITH [47]). Research of all or most of the metabolites in an organism is referred to as metabolomics (HALL [48]). The study of genome-scale interactions among proteins is referred to as interactomics (LI [49]). The advances in RNA interference and other mutagenesis technologies have enabled high-throughput phenotype screens for genes; this is referred to as phenomics (ALONSO & al. [50]). With the recent advances in analytical techniques, the list of omics is growing to include, for example, glycomics, fluxomics and ionomics (SALT [51], SEKIYAMA & al. [52], TURNBULL & al. [53]). Regardless of which omics techniques are used to generate data, the goal for systems biology is to define the structure, dynamics and control of biological systems. Thus, systems biology extends beyond the omics list of genes or proteins to the functional whole plant, which requires bioinformatics to model suites of biological data into networks, which are representations of the actual plant. Bioinformatics, then, is the key for successful integration and presentation of systems biology data. Considering the complexity and diversity of biological systems, the computational models for different applications are expected to be diverse.

- **Genomics for Food and Feed Crops Improvement**

The identification of the genomes of all the major crop plants, the ability to utilise beneficial genes from closely related or diverse species and the application of new breeding techniques is expected to lead to the development of sustainable, higher yielding food crops

offering a wide variety of beneficial characteristics and requiring lower inputs, including a reduced dependence on pesticides and fertilisers.

Current work has sequenced the genomes of model plants and by ten years from now all key crops and pathogens are expected to be sequenced. This will lead to more intelligent and predictive plant breeding and give access to many more beneficial genetic and genomic resources within those plants. China has sequenced two rice genotypes, which puts them ahead through the resulting creation of an F1 hybrid. Future programmes will examine the synergistic links to animal and microbial models, will create new technologies and develop integrative biology.

Crop breeding has moved from an art to a science and will facilitate the development of new crops and new diversified agricultures. Complete gene tool-kits will be available soon, which, through special promoters and homologous recombination, will allow genes to be placed, and switched on, in the appropriate part of the plant, much more specifically than current random insertion. More basic plant models than *Arabidopsis* will be developed to generate understanding of pathways and how plants behave. Genomic analysis of heterosis will identify the key genes involved in hybrid vigour. These are different for different crops, which will provide a basis for improving yield in future.

Integrating molecular biology with population dynamics and plant physiology will permit the identification of the genes conferring beneficial heritable properties on plants under field conditions. Some products will be emerging that have been produced by the engineering of apomixis, to enable the production of seed from a hybrid crop through to subsequent generations.

Crop breeding is a two stage process with, firstly, the identification of useful genetic variation and, secondly, the assembly of desirable gene combinations in commercial lines. Genomics shows that current conventional breeding, based on accessible natural genetic variation, is, to a high degree, unpredictable, suffers from the linkage drag of undesirable traits, and can take up to 10 generations to recover the elite lines with ingressed traits. Genomics will have a very significant impact and allow: enhanced identification of genes for key traits; enhanced scanning for useful genetic variation; more rapid transfer of genes and knowledge between species (e.g. amongst different cereal species); and enhanced tools for molecular tracking in complex breeding programmes. GM assisted breeding will facilitate the transfer of only the desired genes, rapid recovery of elite lines with inserted traits, better gene combinations and a clear targeted strategy.

This will allow supplementation of available genetic variation with: precisely tailored genes; gene pyramiding; genes from related species; and novel genes - GM breeding technology but not necessarily GM end-products. Many developments will be impossible without GM technology. Others will be scientifically difficult or uneconomic in competition with GM. Current costs of ~\$100m to launch a new GM-based variety will fall significantly by 2020 (ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT (OECD) [38]

- Genomics for Non-Food and Non-Feed Uses

Of equal importance is the equivalent application to non-food crops, in particular in light of the limited reserves of fossil fuels. Plant biotechnology and genomics offers the opportunity to contribute to providing renewable alternatives to petrochemical outputs in terms of energy sources, polymers, plastics, pharmaceuticals and other added-value materials. These applications of biotechnology to non-food crops are potentially much more “environmentally friendly” than current petrochemical processes.

A combination of new types of biomass (e.g. specifically designed as a renewable resource) combined with new approaches to bio-processing may well provide the opportunity

to create a sustainable platform for the future. The knowledge and understanding of genome sequences, gene function, gene expression, protein interactions, and metabolic control mechanisms, will allow a sound scientific basis for further major improvements in primary production and in bio-processing. The acceptance and integration of such developments will contribute to a more sustainable future.

Currently materials like wood, starches, vegetable oils, cotton and flax represent about 5% of raw material input to industry. Almost all of the rest is from non-renewable fossil fuels. It is necessary to act now to ensure an orderly transition to a more sustainable economy. Plants can be developed to replace petrochemicals through:

1. Increased utilisation of existing materials: residues from forestry, crop and processing residues, and municipal waste.
2. Developments based on these materials to enhance their industrial value.
3. Agronomic adaptation of existing crops (crop protection programmes already in place).
4. Domestication of new industrial crops.
5. Introduction of novel materials: “plants as factories”:
6. Drugs and pharmaceuticals.
7. Vaccines.
8. Advanced plastics.
9. Components for nanotechnology.

We don't have much time to make the required changes in industrial platforms. Taking the known reserves today and making a simple mathematical calculation based on the global consumption rate of oil 29 bb l/year indicates that we will run out in 35 years.

- Renewable Energy

We can envisage a number of future sources of renewable bioenergy, including the utilisation of plant sugars in direct conversion units (analogous to eating calories). However, at present we have several opportunities that are still expanding and could be improved further. The major types are biodiesel and ethanol.

Designed crops for ethanol involve altered starch content and type (amylose:amylopectin ratio, extractable level, etc). However, most work to-date has been on engineering the enzymes and organisms used to process starch to glucose and subsequently to ethanol. Further biotech-based improvements in source modification and bio-processing are in the development pipeline.

- Bio-based industrial Products

Transgenic plants can be used to produce biodegradable plastics such as polyhydroxybutyrate (PHB). Researchers have taken two genes from the bacterium *Alcaligenes eutrophus*, which encode enzymes responsible for synthesising the naturally occurring plastic PHB, and introduced them into plants. PHBs are 100% biodegradable and are physically similar to polyethylene. PHB and other related plastics are already produced commercially by bacterial fermentation. Known commercially as Biopol™, they have a wide range of uses from medical implants to shopping bags (http://www.gmo-compass.org/eng/agri_biotechnology/breeding_aims/150.pharming.html).

Currently, a number of bio-based products are made from various parts of different crops. The classic example is pulp/paper from lignocellulosic biomass. Others include specialty fibres, adhesives, boards, veggie-candles, crayons, and additives. However, to-date, and with the exception of paper, most have been small niche products due to difficulties in processing and/or product performance issues. Biotechnology really opens several new doors to creating “natural” bio-based products that are viable in contributing to a more sustainable future (Lheureux [37]).

In addition to a broad range of materials, chemicals, and polymers that may be derived from existing streams of agriculturally-produced carbohydrate, protein, and oils, there is now a possibility to expand production of useful natural substances that could not previously be harvested effectively. There are several examples such as a) the repetitive amino acid units found in polyaspartate - found naturally inside oyster shells and can be used as a descalant in water pipes; b) mussel adhesives - work well in aqueous situations and could have significant medical uses.

- **BioProcessing & BioProspecting**

Due to biotechnology, a significant opportunity exists to create a bio-processing system (rather than a thermocatalytic processing system) that will be friendlier to the products and the environment. The basis for such a system is the ability to develop new biocatalysts, commonly called enzymes. For many years, enzymes have been used in selected processes (e.g. making alcohol) but the extent and efficiency of use were limited by what was considered the physical features of enzyme molecules. Genomics studies have now clearly shown that enzymes can be found with properties in a much broader range than previously envisaged: e.g. wide pH range, high and low temperature, and activity in organic solutions. These enzymes have often been found in micro-organisms under unusual but natural conditions, such as hot springs (thermophiles) or in other harsh environments (extremophiles).

Currently, we have a rudimentary understanding of less than 5% of all the species on earth. Genes for interesting functional materials, for new biocatalysts, and for nano-molecular structures that may impact sustainable development, are likely to be uncovered as we explore more of the diversity of life on earth. Consequently, it is important that structural and functional genomics be applied to move forward in:

- Bio-prospecting for genes that improve primary production of biomass (all types).
- Bio-prospecting for new types of biocatalysts (extremophiles and extremozymes).
- Bio-prospecting for novel chemicals and materials.

System biology (next “omics”): perspectives

Developmental biology aims to identify mechanisms that govern cell proliferation and differentiation in the body plan formation of multicellular organisms. In the past, developmental biologists described how anatomy and morphology are established during ontogenesis, and developmental geneticists identified many developmental regulators. In contrast to the traditional approaches that mostly focus on one or a few genes at a time, highly parallel profiling technologies have been developed for use in biological research over the past decade. Such parallel profiling technologies probe many genes, transcripts, proteins or metabolites at once. In this review, we expose the growing impact of transcriptomics, proteomics, metabolomics and modelling on plant developmental biology. Novel profiling technologies will not make traditional gene-centred approaches obsolete but should instead complement forward developmental genetics (HENNIG [54]).

There are three domains that must be addressed to take full advantage of plant systems biology: (i) omics technology development; (ii) data integration into usable formats and (iii) data analysis within the domain of bioinformatics. Among these, bioinformatics probably needs the most attention because it is essential that biological data be normalized, standardized and visualized to build integrated models (TOKIMATSU & al. [55], BORNHOLDT [56], VENTURA & al. [57])(Figure 2).

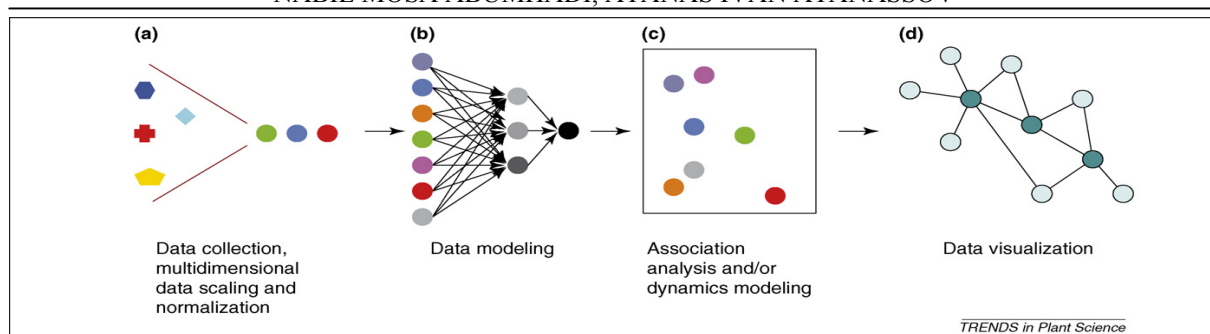


Fig. 2. Bioinformatics applications in systems biology. (a) The normalization and scaling of the multidimensional omics data. Data from the different omics technologies are expected to have diverse formats and numerical scales of data, and thus should be considered to be multidimensional – that is, beyond two or three dimensions that can be simply visualized. To perform informative analyses, the multidimensional data from different omics techniques should first be integrated and normalized. (b) Data modeling for normalized data. (c) Constructing interactions or dynamics based on the data modeling. (d). Data visualization. From steps (b) to (d), the normalized data are modeled to estimate the level of interaction and association, and are then visualized. All steps might not be necessary for a given systems biology study. In (a), the different shapes indicate the different types of biological data; in panels (a), (b) and (c), the different-colored circles symbolize the variables representing the data; and (d), the circles represent the elements in the model. Lines represent relationships among the elements.

The limitation of systems biology is greatly tied to data modeling, in which analysis always involves generalization, simplification and assumptions. Therefore, networks in systems biology might never completely represent the actual biological system. The interpretation of systems biology data needs to be ever cautious and systems biology approaches can be complemented by reductionist approaches. Nevertheless, plant systems biology has come of age, given its potential to provide crucial understanding of the regulatory networks controlling developmental, physiological and pathological processes in plants. Advances in plant systems biology are needed to take full advantage of the ever-increasing numbers of omics technologies (YUAN & al. [43]). However, as the field matures, the key tasks will likely become clearer, and the requirements and limitations of current visualization methods will become better understood (SARAIYA & al. [58]). This process will also be aided by insights from the emerging field of visual analytics (THOMAS & al. [59]), which specifically studies the role of visualization in the larger process of understanding and interpreting data. Visual analytics methods have begun to be applied to studying the connection between visualization and analytical reasoning in systems biology (SARAIYA & al. [58, 60], GEHLENBORG & al. [59]).

Advances are needed for both basic plant biology and also the discovery of the key regulatory genes for agricultural purposes. We currently ask crops to serve more purposes than ever before and we also expect rapid genetic improvement. By understanding systems integration, we should be able to accelerate crop adaptation for food, feed, biofuels, and industrial and pharmaceutical production (YUAN & al. [43]).

Breeding and agronomic improvements have, on average, achieved a linear increase in food production globally, at an average rate of 32 million metric tons per year (ALSTON & al. [62]). However, to meet the recent Declaration of the World Summit on Food Security (FAO [63]) target of 70% more food by 2050, an average annual increase in production of 44 million metric tons per year is required (Fig. 1), representing a 38% increase over historical increases in production, to be sustained for 40 years (Tester & al. [62]). This scale of sustained increase in global food production is unprecedented and requires substantial changes in methods for agronomic processes and crop improvement (TESTER & al. [64]).

Achieving this increase in food production in a stable environment would be challenging, but is undoubtedly much more so given the additional pressures created by global environmental changes.

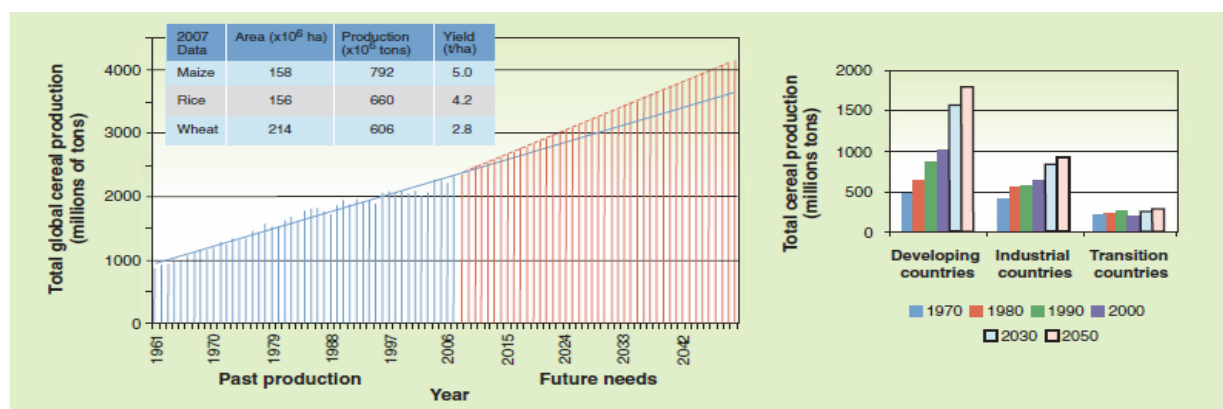


Fig.2. Cereal production targets. (Left) Global cereal production has risen from 877 million metric tons in 1961 to 2351 million metric tons in 2007 (blue). However, to meet predicted demands (3), production will need to rise to over 4000 million metric tons by 2050 (red). The rate of yield increase must move from the blue trend line (32 million metric tons per year) to the red dotted line (44 million metric tons per year) to meet this demand, an increase of 37%. The inset table shows the 2007 data for the three major cereals. Data are from the FAO: <http://faostat.fao.org/>. (Right) The greatest demand for yield increases will be from countries in the developing world.

Global environmental changes in the biophysical environment caused by human activities include: (1) land cover and soil (2) atmospheric composition (3) climate variability and means (4) water availability and quality (5) nitrogen availability and cycling (6) biodiversity (7) sea currents and salinity and (8) sea level

Climate change has important implications for agriculture. The European heat wave of 2003 killed some 30,000 to 50,000 people (BATTISTI & al.[65]). The average temperature that summer was only about 3.5°C above the average for the last century. The 20 to 36% decrease in the yields of grains and fruits that summer drew little attention. But if the climate scientists are right, summers will be that hot on average by midcentury, and by 2090 much of the world will be experiencing summers hotter than the hottest summer now on record. The yields of our most important food, feed, and fiber crops decline precipitously at temperatures much above 30°C (SCHLENKER & al. [66]). Among other reasons, this is because photosynthesis has a temperature optimum in the range of 20° to 25°C for our major temperate crops, and plants develop faster as temperature increases, leaving less time to accumulate the carbohydrates, fats, and proteins that constitute the bulk of fruits and grains. Widespread adoption of more effective and sustainable agronomic practices can help buffer crops against warmer and drier environments, but it will be increasingly difficult to maintain, much less increase, yields of our current major crops as temperatures rise and drylands expand. Climate change will further affect agriculture as the sea level rises, submerging low-lying cropland, and as glaciers melt, causing river systems to experience shorter and more intense seasonal flows, as well as more flooding (FEDOROFF & al. [66]).

Society is on a collision course: population increase and environment loss.

Food production has not kept pace with population growth over the last 20 years in 49 developing countries, yet up to 75% of the world's population depends on plants for food. By 2020 the key drivers for commercialisation will be: over population (up from six billion to eight billion); increased longevity; health/fertility/disease; resource demand for water and raw materials; imbalance between the developed and the developing world with food insecurity in developing countries; climate change; and world order and conflict. The EU moratorium on GM crops will have been ended and uptake will be retailer led. The need for increased sustainability demands action and leadership now to avoid serious social disruption. Improvements in human and animal health will require nutritional enhancement, reduced allergens, reduced myco-toxins, functional foods and a shift in emphasis from curative medicine to preventative medicine. Both conventional plant breeding and GM plant

transformation will be dependent on molecular techniques and functional genomics: the former to allow better varieties faster and the latter to introduce new traits.

The lest but not the last the synthetic biology approach which open the door to construct soon the first artificial microorganism capable to meet challenges related with higher efficiency of environmental pollution degradation, faster biomass convention for bioenergy products etc.

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