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Genomics and crop plant science in Europe

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Contents

Preface

At a time when the new science of genomics is opening up all sorts of possibilities for practical advances in several major areas of activity, it is important that Europe is positioned both to participate in the science and to benefit from the advances. Indeed, Europe must be able not just to participate but to compete globally. This is particularly true for agriculture and plant breeding.

Europe is suffering serious problems in agriculture and the environment – weaknesses in the farming industry, uncertain consumer confidence in its products, damage to the environment from intensive use of fertilisers and pesticides. This report describes how genomics research provides a flexible resource to develop more productive and environmentally sustainable crop systems and new green industries dedicated to land reclamation, production of renewable energy and chemical feedstocks. The report concentrates on genomics research for conventional agriculture and plant breeding rather than for the genetic modification of plants through manipulation of individual genes, which is a separate issue that has already been widely discussed both in the scientific literature and elsewhere.

The strategic opportunities for agriculture may be greatly enhanced by scientific advances linking complex genetic traits to crop yield and quality. But fragmentation of European plant genomics research has led to duplication of effort and waste of resources. Innovation goals can best be achieved by appropriate funding and integration of research across the European Union (EU). In order to build competitiveness in plant breeding and to retain companies active in research and development within the EU, the report calls for a coherent vision in crop genomics, with improved coordination of multidisciplinary programmes alongside investment in model plant research, promotion of public-private partnership and attention to a range of important generic elements that underpin research and innovation. Our messages are directed to policy makers and opinion leaders in the Commission, Parliament and Member States. We recognise the commitment already made by the ERANet and Technology Platform initiatives.

EASAC – the European Academies Science Advisory Council – is a means for the science Academies of Europe to work together to provide expert, independent advice at EU level about the scientific aspects of public policy issues. This report, undertaken at EASAC's own initiative and expense and led on behalf of EASAC by the Accademia Nazionale dei Lincei, is a contribution to what we regard as an extremely important area of policy. We are distributing the report widely and will work further with the relevant institutions and individuals to stimulate discussion and resolution of these key issues for Europe.

On behalf of EASAC and the Accademia Nazionale dei Lincei, I should like to thank most warmly the members of the working group that produced this report (listed in Annex 2) and others who contributed to the project by submitting evidence, meeting with the working group and in other ways facilitating its progress.

Professor Edoardo Vesentini
Vice-Chairman, EASAC

Summary

EASAC launched this study on crop plant sciences in 2003 to highlight the contribution of genomics research to conventional plant breeding of food and non-food crops. Genomics research has the potential to open up new applications in both conventional agriculture and GMO-based agriculture. The promotion of a range of innovative approaches to plant breeding is fundamental to European needs for enhancing agricultural productivity and sustainability and for food security, diet and health, environmental safety and novel crops. In this report we concentrate on the issues arising from genomics research for conventional agriculture and plant breeding rather than for the genetic modification of plants through manipulation of individual genes, which is a separate issue that has already been widely discussed both in the scientific literature and elsewhere.

Advances in plant genomics research have opened a new era in plant breeding where the linkage of genes to traits inspires more efficient and predictable breeding approaches. European agriculture will take advantage of these new opportunities only if a coherent EU science and innovation strategy is developed to integrate currently fragmented research efforts, to tackle barriers to progress, to focus on reduction to practice, and to allow technology and information to be presented to plant breeders in a suitably practicable form.

The emerging research opportunities, coupled with societal and market demand, bring into range important new objectives for:

- improved plant breeding for diversified and healthy crops, and enhanced nutritive levels of food;
- sustainable systems, characterised by high yielding, high quality, low input agriculture, and preparing for climate change;
- new green industries dedicated to land remediation and reclamation, and to the production of renewable energy sources and chemical feed stocks, biomaterials, bioreactors;
- the establishment of partnership with developing countries.

In order to strengthen EU capabilities to attain these objectives, genomics research is required across a broad front:

- setting up high throughput technology platforms for genome sequencing, transcriptomics, proteomics, metabolomics, informatics, including procedures integrating functional genomics with cell biology;
- definition of target genes associated with plant processes and traits, and concerning growth, development, reproduction, photosynthesis, responses to environmental conditions and pathogens, and formation of specialised structures;
- characterisation of biodiversity, including its measure and application to search for new biologically active compounds of plant origin.

While these priorities may be equally recognised by other countries (particularly in North America and Asia), the EU must be actively involved in order to serve local needs in plant breeding and also to remain globally competitive. Several genomics research initiatives are currently running in EU Member States. Nevertheless, there is a pressing need for better, shared, awareness of the ongoing activities in order to identify the possibilities for improved coordination; joint, multidisciplinary, programmes; funding of gaps; and avoidance of unhelpful duplication. There must also be resolution of the inadvertent constraints on research activities and the application of the results, occasioned by other EU legislation (for example energy, chemicals, and recycling policies). Furthermore, promoting cohesion in public funding for the priorities of plant science, and the linkage to plant breeding, must be accompanied by attention to the generic elements that underpin efforts in research and innovation: building public trust, education and training, protection of intellectual property, promoting public-private partnership and the retention of R&D-intensive companies within the EU.

Main recommendations

1. A major opportunity exists for EU policy-makers, across the Commission, Parliament and Council of Ministers, to capitalise on the new era in plant genomics research by developing a coordinated strategy for identifying and resourcing multidisciplinary research priorities in crop biology and crop improvement. There are two major goals for the reduction to practice: from genomics research on model plants to crops; and from crop science to crop breeding.

2. We strongly recommend that a coherent European Commission research strategy be developed that integrates and balances the work carried out on enabling technologies, process-oriented goals (such as genome sequencing, construction of marker libraries) and problem-oriented goals (identification of genes related to particular functions and traits). DG Research should also outline a longer-term research strategy and set a benchmark for EU investment by comparison with projected North

American spending on plant science. The coordinated research agenda in support of European innovation and competitiveness will need to be supported by increased recognition of the importance of maintaining repositories of seeds, cultivars and varieties. We support calls for the establishment of a network of European and international Banks preserving cultivars and varieties of wild relatives.

3 We also strongly recommend that in addition to research dedicated to food crop breeding, a renewed effort to develop a coordinated policy in support of new green industries, based on transnational research and considering activities dedicated to remediation, renewable energy and natural product biosynthesis, be implemented. This strategic coherence will require the active involvement of several Directorates-General in addition to DG Research, eg Agriculture, Enterprise, Environment, Health and Consumer Protection.

4 We welcome and encourage the ERANet Plant Genomics (ERA-PG) Project goals of clarifying current individual national efforts and developing impetus for connectivity. Accelerating ERA-PG progress will require both DG Research and Member State commitment to identify and resolve impediments to coordination such as national differences in public-private sector relationships – as well as the means to build critical mass.

5 We also welcome the Plant Genomics Technology Platform and urge the European Commission together with the Council of Ministers to ensure that this is fully supported by stakeholders – to confirm priorities for social needs, and to develop options for facing key challenges such as consumer engagement and science-based regulation, as well as exploring research opportunities.

6 In consequence of ERA-PG and the Technology Platform, the Commission, led by DG Research, must now rapidly define priorities and resources for plant science in Framework Programmes 6 and 7, including options for training, involvement of the private sector and EU-international collaborations. More broadly, it is also timely to consider the basic research opportunities in plant science within the context of current developments on the European Research Area and European Research Council.

7 In making the case for new research investments, it is important for all funders and researchers to consider relative cost-benefit issues and whether current resources are appropriately structured – for example with respect to an appropriate balance between efforts in research institutions and university departments, and for the revival of public plant breeding activities.

8 In addition to identifying research priorities for new agriculture systems in the expanded EU, it will be important for both the Commission and Parliament to consider the potential for technology partnerships with developing countries, where they contribute to the achievement of EU objectives. Identification of how the EU can support skills and training as part of capacity building worldwide is particularly relevant.

9 It is essential to understand the potential for EU policy development in, for example, energy, chemicals and recycling, to have the unintended consequence of restricting research opportunities and their application (food and non-food crops). This is, again, an issue for multiple DGs and Parliament. These broader concerns must be incorporated within the ongoing work of the Technology Platform.

1 Introduction

European agriculture faces conflicting pressures – to increase farmers' income; to respond to consumer demands for food safety, quality and diversity; and to safeguard and sustain natural resources in general, and particularly those on which agriculture depends. The coming decades will require increasing global agricultural production, with reduced inputs, and with a smaller environmental footprint. Promotion of innovation is fundamentally important in addressing these needs for enhancing agricultural productivity and sustainability across a broad front – food safety and security, diet and health, environmental safety and novel crops – and for capitalising on a range of new opportunities in plant science (Porceddu, 1999).

The European Union faces strategic challenges in clarifying its agenda for research and application. The joint European Commission - US Task Force (US-EC Task Force on Biotechnology Research, 2001) noted that fundamental plant processes – growth, development, reproduction, photosynthesis and the responses to environmental conditions and pathogens – are central to nearly every agricultural issue facing society, and yet, surprisingly, little is known about the molecular biology behind these essential processes. Currently, several individual initiatives in genomics research have been proposed, but a better and shared awareness is necessary if the EU authorities are to determine the opportunities for coordination and partnership across Member States and between the public and private sectors.

To address some of these EU strategic issues, EASAC launched in 2003 this study on crop plant genomics – the set of knowledge and technologies that allows the understanding of structural and functional aspects of the crop plant genomes of greatest relevance to the EU. The study focuses on how knowledge of genomes of major crops contributes to conventional plant breeding for the generation of new cultivars with particular characteristics, for improving crop husbandry, and in support of post-harvest technologies (for example, food processing). The study does not concern the application of genomics research to the genetic modification of plants through manipulation of individual genes (a review of current R&D on GM plants in Europe was published by the European Commission, Joint Research Centre in 2003).

The terms of reference for the study were:

- to summarise the current state of genomics research related to the major crop plants in the EU, and the potential application of this research to conventional plant breeding, crop husbandry and post-harvest conservation and processing;

- to make recommendations about future research priorities and research requirements, particularly in the public sector, and to identify the key elements of an EU strategy for crop plant genomics over the next 15 years;

- to review the competitive position of the EU in the science of crop plant genomics and in its applications, and to make recommendations as necessary for strengthening capability in this area.

The study was carried out by a working group appointed by EASAC and chaired by Professor Gian Tommaso Scarascia-Mugnozza; the full membership is given in Annex 2. The members participated in their individual capacity and not as representatives of their organisations. The draft report was reviewed by the EASAC Council and Biotechnology Strategy Group. During the course of this study, a call for evidence was published on the EASAC website and key stakeholders were individually contacted. We are most grateful to those who assisted us in this way. The external feedback was incorporated during Working Group deliberations as part of the research on key issues.

2 Why is innovation in plant breeding important for Europe?

Global food production has doubled since 1960 (1961-1998 comparison for grain and oilseeds, International Food Policy Research Institute, 2001). The increase in productivity was built on successful interaction between crop husbandry and plant breeding, underpinned by publicly-funded R&D. In the absence of continued improvements in crop yield, quality and protection, additional untilled land will have to be converted to crop production to feed the growing global population (predicted to rise to 8 billion by 2030). However, only agriculturally marginal land remains for the expansion of food production, and some of the land, water and other natural resources are being diverted to other uses.

Genetic improvement of plants began in the Neolithic age with the domestication of cereals and pulses. Since then, a steady increase in plant yield has been achieved, with the last century having seen an impressive acceleration in the capacity to produce more food per unit of land. However, there is no guarantee that past increases in productivity can be extrapolated to the future. The principal systems of cereal crop cultivation (irrigation or rain-fed production of rice, corn and wheat in Asia, US, China and Europe) are still highly productive but it is uncertain whether they will prove sustainable in terms of future soil fertility (Joint Committee of the Italian National Academies of the Lincei and of the Sciences, 2003). Plant breeders in Europe do, nevertheless, continue their tradition of efficiently creating superior new field crops and horticultural varieties by conventional breeding approaches. One example is the tomato, wherein at least seven major genetic factors have been introduced from wild species into modern varieties in order to provide resistance against fungal, bacterial and viral diseases.

Plants are the planet's best chemical factories: with approximately 30 000 genes, higher plants synthesise more than 200 000 different primary and secondary metabolites. Thus plant genomics studies are likely to advance our knowledge in the fields of primary and secondary metabolism, and, in general, our 'green chemistry' capability.

The predictions for Europe over the next 10 years are that commodity food price will remain low (actually they will decrease for cereals and rice – European Commission, Agriculture DG, 2003) and that food security is not likely to be a major concern. But the EU economy must play a leading role in the global development of agriculture because of its trade balance interests. EU agriculture will also change in response to the reduction of production-based subsidies, because of the growing competition from the other States now joining the Community, and because of the emergence of social claims addressing the need of a better environment. Europe, moreover, cannot necessarily capitalise on R&D achieved elsewhere. Unlike medical and mechanical innovations that are often globally applicable, it is essential to elaborate agricultural innovation suitable to local conditions. For example, wheat, maize, sugar beet, soybean cultivations are based on day-length sensitive crop varieties developed specifically for European latitudes and climatic conditions. In addition, in Europe the cultivated land is inter-mixed with woody areas and pastures that constitute pest reservoirs, so that different crop varieties may be required, compared with the more uniform conditions that characterise other major world producer regions. Thus, it is important for the EU to develop and apply its excellence in science in this area, both in order to address local needs for plant breeding and to remain competitive at the global level.

The Life Sciences and Biotechnology strategy document from the European Commission (2002a) emphasised:

> *Life sciences and biotechnology are widely regarded as one of the most promising frontier technologies for the coming decades…In agro-food area, biotechnology has the potential to deliver improved food quality and environmental benefits through agronomically-improved crops.*

While GM crops still provoke European controversies, plant genomics research can greatly contribute to conventional plant breeding. The recent EURAGRI conference (European Commission, 2002b) expands on the challenge:

> *The citizen of Europe expects science to come up with answers to their concerns. In particular, they are concerned about food safety, the use of genetically modified organisms, exploitation of natural resources, the orientation of agricultural subventions and the future of world trade. The agricultural research agenda must address these questions and provide a sound scientific basis for decision-makers and consumers. Scientific information is particularly significant and abundant in the agricultural sector, and we need to develop this resource, while rendering scientific expertise more transparent, closer to the consumer and better co-ordinated at the European level.*

In articulating these challenges the EURAGRI conference identified four key interfaces: between agricultural sciences and other sciences; between scientists and consumers, between scientists and policy-makers, and between scientists and industry.

With this report, EASAC intends to inform and nurture these interfaces. Under-investment in plant genomics could result in the exclusion of the EU from advanced crop sciences – what is at stake is the ability of the EU to control the evolution of its agricultural sector. Public policy-makers in the EU cannot responsibly leave the R&D agenda to the private sector and to those outside the EU.

3 What has been the recent history?

Conventional crop breeding is time-consuming, requires a repetitive process of selection to modify the desired traits and has the drawback of a potential co-transfer of undesired genes. Conventional approaches are based on the exploitation of natural genetic variation available in crop land races and in related wild species and on its increase using induced mutagenesis. More empirical than scientific, previous approaches were restricted to natural recombination, were unpredictable and held decreasing prospect for significant advance. The advent of plant genomics within the last decade has inaugurated a new era in plant breeding by means of:

- the identification of genetic loci for key traits, including those affecting quantitative variation;
- the development of enhanced scanning methodologies for detecting useful genetic variation in crop plants and in their wild relatives;
- the more rapid transfer of knowledge and technologies from model to crop species, integrating new scientific discoveries in plant breeding;
- the acquisition of new tools to assist complex breeding programmes, defining a procedure known as Marker Assisted Selection (MAS).

If the initial investments in plant genetics and genomics can be sustained and well-integrated, the linkage relationships between specific genes and traits would be expected to inspire more efficient and predictable breeding programs in support of the EU strategic goals, including the consideration of industrial and societal needs. The GM controversy has obscured recent achievements of classical breeding (for example, conventional herbicide-tolerance and insect-resistant oilseed rape, cotton, soy and maize, and iron-rich rice cultivars). The new technologies, such as MAS, 'could offer to plant breeding what the jet engine has brought to air travel' (Knight, 2003).

Plant genomics research in the EU has been highly successful when focusing on reference genomes of yeast and *Arabidopsis*, which is a close relative to crop plants that belong to the *Brassica* genus. This activity has served as an assembly template for subsequent draft sequences of other genomes and to assign function to genes in particular metabolic pathways and to major events at the cellular, tissue and whole organism level of complexity (integrative or systems biology). European researchers now have the opportunity to be creative in integrating model and crop plant research. They can exploit model system research for understanding crop behaviour and performance, thus enhancing competitiveness, while crop priorities will increasingly feed back to highlight key targets for studies aimed at understanding the underlying fundamental biological processes relevant to crop improvement. However, many traits that are desirable in many other crops are often not represented in model organisms. Ongoing work in *Medicago* truncatula (a model plant for the legumes), rice, tomato, maize, wheat and *Prunus* is now needed to increase the understanding of the biology of crops of major economic importance.

Genomics is improving our knowledge of the genetic makeup of living organisms, by allowing characterisation of gene functions and interactions, and understanding of the complex frameworks among genes controlling specific metabolic pathways and their relationship to the phenotype. Most traits of plant breeding interest are complex and quantitative in nature: genomics will promote the identification of genes involved in the control of quantitative traits and the understanding of their functional and regulatory hierarchy. Thus genomics research will permit the modification of the plant phenotype by acting on a few regulatory genes through selection or by modifying their expression.

Research has just begun to unravel the complex molecular interactions that govern plant behaviour (US-EC Task Force on Biotechnology Research, 2001). However, crop research is more costly and requires more time than in the case of model plant species. While significant crop research has been undertaken in the public domain, this is now much surpassed by industry investments. In the present political situation of the EU, however, private companies are pessimistic about the future of plant genomics research and of its application in Europe. It is evident that they are reducing their in-house research located in the EU, with a consequent impact on the level of funding of university programmes and of joint venture/spin-off initiatives. Globally, public funding of agricultural R&D is declining (International Food Policy Research Institute, 2001) and there is perceived need to re-prioritise, as well as to capitalise on the research advances. Accordingly, the recent World Bank evaluation of the programmes of the Consultative Group on International Agricultural Research calls for a refocus on genetic research for enhancing productivity (Kennedy, 2003).

4 What are the opportunities for R&D in the EU over the next 10-20 years?

The development of sequencing techniques and the availability of genomics information on model organisms have greatly influenced the disciplines of plant and crop science. Crop plant genomics, by providing new tools for analysing gene variation and function at the population and ecological levels as well as the cellular level, will stimulate innovation in agriculture – but only if a coherent EU strategy across the key scientific disciplines and linking to innovation policy is developed to unify hitherto fragmented research efforts, while addressing clearly the current barriers to progress. Greater cohesion is vital, because:

- publicly funded plant genomics research must be integrated across multiple technologies, as described later in this report, including genomics information from non-plant species, animals and pathogens, to feed system biology;

- genomics research is expensive and duplication of efforts is wasteful; but the successful European yeast and Arabidopsis programmes show what can be achieved through integration and collaboration;

- current fragmentation of research hinders effective EU contribution in development of science and policy at the global level.

The objectives for the next two decades can be conceived as the combination of science push (bringing new research opportunities within range) with societal pull (addressing growing environmental and industrial issues). Rapid progress will require the coordination of work on problem-oriented goals (for example, the identification of genes associated with particular processes and traits), process-oriented goals (for example, sequencing of crop plant genomes (initiatives have been set up to sequence the genomes of tomato, potato, wheat, corn), genetic and physical maps, marker libraries, populations of mutants) and enabling technologies (for example, proteomics, micro-arrays, gene silencing tools, and bioinformatics). If this integrated strategy is to be successful, there must be emphasis on the genetic and molecular analysis of complex traits, particularly of those related to yield potential (under environmentally-sustainable farming systems), quality for human, animal and industrial end-users, sustainable stress tolerance and disease resistance. Achieving these objectives requires also the adoption of a 'reduction to practice approach', enabling technology and information to be presented to practising plant breeders in a form that can be applied.

What research is coming into range?

(i) *Knowledge-based crop breeding* – diversified agriculture systems with competitive and societal advantage, by:

- understanding fundamental plant biology aspects like perenniality, apomixes, asexual reproduction, sexual reproduction biology, domestication implications, crop architecture, flower and seed development, acclimatisation, adaptation;

- reducing levels of toxic and anti-nutritional compounds like alkaloids in lupins, lectins in beans, phytic acid in legumes;

- improving micronutrient (eg tocopherol, folic acid) and amino acid composition (for nutritionally-improved varieties);

- improving the efficiency of specialised crops, like trees, by understanding and modifying metabolic pathways and wood formation, and by reducing the duration of the juvenile stage, which is important in cultivation of fruit trees, variety development, in silviculture and in natural resource management.

(ii) *Sustainability* – for high yielding, high quality, low input agriculture, an approach requiring also the study of the interactions with other organisms and the information on related genomics, by:

- understanding of the genetics of pest and pathogen resistance, of symbiosis, nutritional use efficiency and stress tolerance (drought, high salt, mineral);

- development of crops enabling decreased application of pesticides. Not only does resistance to pests need to be understood, but also tolerance to pest damage, an approach that should not endanger other species or promote resistance;

- decreasing inputs of chemical fertiliser (less polluting, more cost efficient), for example by capitalising on information from specialised association between legumes and micro-organisms to fix atmospheric nitrogen and to make soil phosphate available to plants;

- designing major crops adapted to foreseeable climate changes by understanding the genetic control and molecular events of vernalisation and changes in pathogen distribution, and identifying scientific options for improving the desired traits;

- designing forest trees specialized in the sequestration of CO_2 and of other atmospheric gases.

(iii) *New green industries and premium agriculture* – potentially attractive economic alternatives to generating food surpluses.

- Remediation and reclamation - tackling environmental pollutants, for example by sequestering heavy metals. It is estimated that approximately 1.4 million contaminated sites exist in the EU, with projected clean-up costs of 400 billion Euro. Phytoremediation is currently encumbered by limitations precluding widespread application, and only metal hyper-accumulating plant species are able both to tolerate and to sequester high concentrations of metals. Most of these species are slow growing and produce a low biomass (Department for Environment, Food and Rural Affairs, UK, 2002).

- Renewable energy sources – plants can substitute for fossil fuels in the form of biomass. However, photosynthesis is inefficient, converting only 1% of incoming solar radiation to biomass energy; small improvements in the efficiency of this photochemical process could make energy crops an economically viable option (Department for Environment, Food and Rural Affairs, UK, 2002). Commitment to science push is restricted by lack both of market pull and of awareness of end-users. Biodiesel (esterified rapeseed oil) is a proven diesel substitute whose merits were perceived unfavourably by some EU Member States a decade ago but which should be examined in the light of changing views on energy security, oil price, CAP changes and best practice. Bioethanol is also proven as a potential constituent of transport fuels, but currently only 5% of EU ethanol production is so used. The fermentation technology from sugars and starches is relatively mature and there are additional opportunities to utilize other feed stocks (for example, wheat straw, sugar bagasse, pulp and paper waste, wood) that require further dedicated research and a specific type of development.

- Renewable chemical feed stocks replacing petrochemicals – mainly to generate commodity polymers from olefins, particularly thermoplastics. The current industry trend is moving away from the EU to regions where cheap hydrocarbon feed stocks are available. The recent commercial development of polylactic acid from cornstarch provides proof of principle on the economics of polymers production from crops (Chemical Industries Association, 2003). Higher plants produce a spectrum of fatty acids useful as starting materials for a wide variety of industrial chemicals (paints and coatings, detergents; see chapter 9). There will be greener industries (for example, less factory solvent use), and environmental criticism for such initiatives on principle is misplaced.

- Bioreactors – improved production and delivery vehicles of natural products (new medicinal agents, vitamins, pigments, fragrances and flavours). Many of these complex chemicals are chiral and difficult to produce synthetically. Examples of plant-derived chemicals for which demand currently exceeds supply (Department for Environment, Food and Rural Affairs, UK, 2002) include cancer chemotherapy drugs such as taxol, artemesinin (a novel anti-malarial drug with particular potential for developing countries), opiates as painkillers and the beta acids of hops, which have anti-microbial activity useful for disinfection of food production systems. Some of the new production processes may utilise high mass bioreactors such as micro-algae (for example, *Haematococcus pluvialis* for ketocarotenoid astaxanthin production) rather than crop plants. Although underpinning advances in plant genomics research will be broadly applicable, the pathways of application will be vulnerable to technological change.

- Nutraceuticals – which require considerable further scientific and regulatory consideration. Some estimates suggest that the nutraceutical market in Europe could reach 300 billion Euro within 10 years (Ronchi, 2003). Nutraceuticals might be generated in bioreactors, although their direct production in plant matrices (seeds, fruits, vegetables) – known as 'biofortification' – appears much simpler from the regulatory viewpoint and economically more convenient.

5 Current state of plant genomics research

The ERANet Project on plant genomics (ERA-PG, 2003) proposes to survey EU Member State efforts in comparison with current and emerging competitor countries (for example, US, China, Japan, Canada, Brazil). Outside Europe other countries are committing considerable strategic resources to this research area. For example, Australia has recognised the importance of focusing on the discovery of plant mechanisms of salt and drought tolerance. The Australian Centre for Plant Functional Genomics aims to broaden the genetic understanding of crops and provide new resources to transfer the results of academic research to plant breeders. The USA has multiple Government Department research funders supporting genome research, including USDA, DoE, NIH, USAID and DoD, in addition to large charitable contributors as Rockefeller, Noble and Hughes. The major US initiative is the National Science Foundation-funded Plant Genome Research Program, part of the cross-Departmental National Plant Genome Initiative whose ultimate goal is 'to understand structure and function of all plant genes at levels from molecular to the organismal and to interactions within ecosystems' (National Science Foundation, 2003). Approximately $350 million has been spent since this programme started in 1998 and it has been estimated that the objectives for the next 5 years will require $1.3 billion. This estimate, providing a benchmark for EU spending, includes $400 million for genome sequencing (finished sequences of rice and maize and draft sequences of gene-rich regions of other key species); $200 million for functional genomics (Arabidopsis and rice international collaborations); $300 million for translational genomics supporting a broader scientific community with a specific interest in plant biology; $250 million for data management and informatics; and $125 million for training, education and outreach.

Country	France	Germany	Netherlands	UK
Programme and funding	Genoplante € 200M for 5 years (1999)	GABI € 50M for 4 years (1999)	Centre for Biosystems Genomics € 50M for 5 years (2003)	GARNet € 16M for 3 years
Partners	Research institutes (INRA, CNRS) companies, Government	Government, companies	Universities, research institutes, companies	Universities, research institutes
Species	Arabidopsis, rice, corn, wheat, oilseed rape, pea, sunflower	Mainly barley, Arabidopsis, also rape, sugar beet, potato, rye, maize, poplar	Potato, Tomato, Arabidopsis	Arabidopsis in GARNet and other plant species in CropNet

Table 1 Individual European Member States are committing significant resources in plant genomics

GABI = Genome analysis of the plant biological systems; GARNet = Genomic Arabidopsis resource network

Other EU Member State national plant genome programs are found in Spain (24 million Euro /5 years) and Sweden (50 million Euro /5 years), while Belgium, Finland, Italy and Norway have currently much smaller programs (ERA-PG 2003). In Greece, the Hellenic Scientific Society for Genetic Improvement of Plants promotes plant breeding, and research teams at the Universities of Athens and Thessaloniki are working on molecular genetics and plant breeding. The total EU spending from the provisional ERANet data is about 80 million Euro annually.

In general, EU Member State programmes combine functional analysis of model plant genomes with specific research on traits or problems related to the most important crops for Europe. Progress is being made in linking basic and applied research and in catalysing public-private interactions. Operational goals cover developing expertise and competitiveness in plant genomics, standardising research tools, creating national networks to access technology platforms, technology transfer and transfer of results into breeding practice, and international cooperation. While these individual efforts and commitments to cooperate are commendable, much remains to be done in identifying duplications and/or omissions, in aligning and integrating research objectives, and in managing mutual interests with centres of excellence outside the EU.

Some enthusiasm is evident for bilateral and multilateral collaboration across the EU. The pioneering example is the Genoplante-GABI integration active since 2001 (now also including Spain), centred on Arabidopsis research. Unrealised opportunities for joint wheat and Solanaceae programmes exist and, in general, an imperative for each

Member State is to evaluate the prospective benefits of integrated programmes.

We recognise that ERA-PG will achieve significant clarification and impetus for coordination, identifying common priorities and existing efforts that, if aligned, would have a significant added value. ERANet aims to develop the common knowledge necessary for a coherent generation of policies and efficient use of limited resources. This programme may become the basis for EU joint programmes and for strengthening the foundations of a crop science European Research Area. We welcome ERANet as an instrument in building connectivity and synchronisation. But in order to accelerate the implementation of the conclusions reached by ERANet, it will be necessary to establish research groups with a critical mass (including scientific education and training), to turn goals into tangible actions, to formulate and implement joint research plans, and to pursue research priorities including the options for new research structures. The ERANet experience, moreover, should help to identify barriers that currently hinder collaboration in research across the EU Member States (for example, varying practices in university-industry relationships), and to clarify what is best done at national level and what at EU level. We assume that most Member States should have a stake in research on model plant genomes of Arabidopsis, Medicago, Rice, Prunus, Poplar and in the development of technology platforms, also coupled to national/regional activity translating available results to crops of local importance (see table 1). Looking ahead to EU enlargement, we do not see major needs for research on other crops: the new challenge resides in the increasing competitiveness from accession states agriculture systems.

In the meantime, the research community must also draw on the resources of Framework Programme 6. Some topics proposed by the Framework are of interest to plant science, albeit they are less apparent than in Framework Programs 4 and 5. Despite an increase of the life science share of the total funding, it is disappointing that in the 6th Framework no specific plant thematic priorities are mentioned. Nonetheless, the recently approval of the 15 million Euro project on legume genetics is encouraging, as well as the commitment to develop a Technology Platform in plant genomics (see below).

6 Research priorities: technologies

Genomics enables the comprehensive study of the overall expression of genes, proteins and metabolites in a functionally relevant context and facilitates new discoveries in biology. To support the goals identified in this report for plant science, and taking into account current national efforts, it is urgent for the EU across the Commission and Member States (national funding agencies) to identify and allocate the appropriate level of resources and facilities necessary for integrated activities of genomics, proteomics and metabolomics developing high-throughput (automated, miniaturised), cost-effective technologies and efficient management of large amounts of data. Broadly, the initiatives described in chapter 5, together with the research priorities outlined in chapters 6-8, must be led by DG Research. But it is also important for the research community to build commitment in support of the innovation goals from other relevant DGs – eg Agriculture, Enterprise, Environment, Health and Consumer Protection – and the European Parliament.

(i) *Genome sequencing*. The in-depth analysis of the known and predicted coding sequences of model genomes has provided an invaluable resource to begin a basic resolution of the plant genome. Limitations, nevertheless, exist in extrapolating the available results to crops. For example, more than 70% of known maize proteins do not match any *Arabidopsis* protein. Gene information deficit is particularly evident for plants that form specialised structures like tuber in potato, fleshy fruit in tomato, root development in sugar beet, bulb development in onion, foliage structure and fruit ripening in fruit trees, and wood formation in woody plants. Comparative genomics becomes increasingly informative as additional species are sequenced, and it is vital that much of this activity is carried out within the public domain. Priorities should be selected according to genetic tractability, genome size and complexity, genome fraction represented by repetitive sequences and complexity, and the potential for transfer of data and tools to agronomically important relatives.

However, while sequencing technology continues to develop rapidly and costs to decrease significantly, the complete analysis of a large genome still requires major financial resource and technical limitations may also restrict progress. The estimated size of plant genomes range from 130 million base pairs for *Arabidopsis*, 430 for rice, 550 for *Medicago truncatula* and poplar, 770 for apple and 950 for tomato, to 5000 for barley, 16 000 for wheat and 18 000 for onion. It is still unrealistic to use current technologies to sequence the larger genomes of crop species most important for the EU, and the current goal should be to progress draft sequences for gene-rich genomic regions, or the sequencing of expressed sequences (ESTs). For this purpose physical maps of several crops are currently being constructed. These maps will form the starting point for selection of the gene-rich genome regions. While it should be appreciated that genomic approaches used to circumvent cost and technical limitations may not reliably capture weakly expressed genes (for example, transcription factors and regulatory genes, or genes located in heterochromatin or highly methylated regions), major advances in enabling technologies – such as the generation of libraries of genetic markers, or the creation of dedicated microarrays – are becoming available in a range of crop species. The use of markers in combination with novel physical and linkage mapping techniques has led to the assembly of dense genetic maps for many crop species and to the location of genetic factors important to these crops, such as those supporting vernalisation, delayed senescence, day length insensitivity, dwarfism, disease resistance and stress tolerance, bread-making quality. All of these agronomic traits now require detailed study through molecular approaches.

The research opportunities are exciting and rapid progress will be facilitated by international collaboration. Individual research groups might focus on sequencing chromosome segments most relevant to local interests and expertise, with a coherent strategy to support and facilitate development and integration of technology platforms and research outputs.

(ii) *Proteomics*[1]. The systematic analysis and documentation of proteins is an emerging research area that addresses not only questions concerning the abundance and distribution of proteins (within cell, tissue, organism) but also their functional roles. Advance in proteomics depends heavily on new application and standardisation of techniques such as two-dimensional gel electrophoresis and mass spectrometry. Several proteomic platforms are already active in Europe. A need is evident to coordinate current and future proteomic projects dedicated to EU crops and to allocate to them sufficient resources to access existing platforms.

It is common knowledge that almost every protein function relies on the transient or stable formation of protein complexes. Therefore, comprehensive information about protein interactions and interaction networks provides a valuable contribution to the understanding of protein function on a genomic scale. Powerful new technologies have been

[1] An approach that seeks to identify and characterise complete sets of protein, and protein-protein interactions, in a given species.

developed that facilitate the systematic large-scale identification of protein-protein interactions. Different experimental approaches proved reliable and efficient for genome-wide interaction mapping. A necessary step will be the integration of appropriate bioinformatics tools to analyze the vast quantity of interaction data and to extract biological meaningful information.

(iii) *Metabolomics*[2]. This recent 'omics' technology proposes a comprehensive, unbiased, high-throughput analysis of complex metabolite mixtures that require integrated procedures for optimal sample extraction, metabolite separation, detection and identification, automated data gathering, analysis and quantification. There is no single analytical technique that visualises the metabolome because the chemical complexity and biological variance are too large. Nevertheless, metabolomics is being driven primarily by advances in mass spectrometry coupled with chromatographic separation procedures. Adoption of other standard technologies (in particular, NMR) also shows promise, but the major limitation to applying these techniques is the absence of high throughput analytical processes.

As with genomics, the first tasks for proteomics and metabolomics were associated with the analysis of human, animal and pathogen samples, often driven by the prospect of biomedical applications. Proteomics and metabolomics are now being applied to plant systems but research is in its infancy and there is critical need for sharing of reference material, standardisation of research tools and sustained bioinformatics support. Such challenges can, again, be faced effectively only through coordination and collaborative effort at the European level. Extensions of standard metobolomic platforms to crop plants are still major problems in Europe .

(iv) *Bioinformatics*. EASAC is currently engaged in a separate initiative to identify the strategic opportunities and challenges for bioinformatics in the EU. Bioinformatics is of central importance in crop plant genomics research, linking genetic and phenotypic data and underpinning all of the technology platforms in plant sciences and plant breeding. A broad challenge is facing the EU plant community in generating and handling large data collections and the growth of large-scale computing resources. The issues for plant sciences may best be addressed as part of the broader resolution of the bioinformatics concern. Among the needs identified in the other, ongoing, EASAC work are :

- providing sustained support for informatics infrastructure and progressing collaboration between the European Commission and other science funding agencies like EMBL, ESF, Member States;

- identifying and resourcing cooperative mechanisms to build new cross-disciplinary research strengths, particularly IT-mathematics for computational biology, and modelling and simulation of complex systems;

- database design and mining (intelligent analysis), including protein structure prediction and protein functional analysis;

- database integration with common standard and interfaces for crop genomes, and creating tools for communication between heterogeneous datasets, organising and disseminating information (open access).

(v) *Transfer of knowledge to crop improvement: molecular breeding*. Useful alleles are accumulated during crop selection. The molecular characterisation of these alleles has stimulated new approaches to mapping quantitative trait loci (QTL) and to the understanding of the natural variation in the genes concerned. A limited number of QTL have been described, but acceleration of their rate of discovery is expected with the progress in genomics studies. This will ultimately provide a science-based approach to crop breeding (Morgante and Salamini, 2003).

[2] The large-scale study of the full complement of secondary metabolites produced by a given species in all its tissues and growth stages.

7 Research priorities: definition of target genes and traits

Use of the technologies described above to understand inter- and intra-specific variation in plants, in order to effect rational improvement in the productivity of crop species, will cover a wide range of problem-oriented goals:

- identification of expressed genes controlling complex plant structures and understanding of their coordinated interactions;
- understanding of molecular mechanisms that regulate plant morphogenesis;
- identification of cellular processes underlying plant growth and accumulation of dry matter;
- description of molecular mechanisms by which plants coordinate their response to external signals such as light, water, ions, pathogens, insects;
- description of biosynthetic pathways of primary and secondary metabolites;
- mode and routes by which storage materials (protein, starch, and oil) are stored in specific cellular bodies.

Rapid progress is being made in a number of the other areas listed, such as the biology of pathogen resistance (non-self recognition and synthesis of defence proteins) (Dangl and Jones, 2001). This is a vital topic for Europe, given the impact that fungal diseases had on human societies. Examples are potato blight in Ireland in the 1840s and downy mildew on vines in France in the 1870s. Surprisingly, after more than 150 years, late blight, *Phytopthora infestans*, is still the most devastating pathogen in potato. High doses of pesticides are applied to control this disease, with a current global expenditure of about 3 billion Euros. If developing countries had the funds to apply the amounts of pesticides actually needed, this expenditure would increase to 9 billion Euros annually. Developing novel late blight resistant varieties would, therefore, have significant impact on productivity worldwide.

The state of the art and potential for progress can be illustrated further by the opportunities for studying the response to environmental stress. Understanding and improving plant tolerance to abiotic stresses is of central relevance for the EU. The need to improve productivity in the less hospitable regions, characterised by problems of water limitation and soil salinity and compounded by the predicted impact of climate change (for example, declining mean rainfall in the Mediterranean regions and increasing frequency of extreme climate events), will stimulate demands for plant varieties with improved stress tolerance. Despite the prominence of yield losses in agriculture due to abiotic constraints, progress in improving stress tolerance in crop plants has been relatively slow, primarily because of the polygenic nature of tolerance and the difficulty of reproducing stress situations under standardised conditions.

What then are the new opportunities arising from plant genomics applied to plant stress resistance?

(i) *Exploitation of natural diversity*. Plant evolution under domestication has led to increased productivity of crop species, but at the same time has narrowed their genetic basis. Fortunately, wild relatives of crop plants exhibit vast genetic diversity for adaptation to stressful environments such as frost, drought and high salt and metal, and also to the presence of pathogens and pests.

Examples are salt resistance in tomato, drought tolerance in rice, aluminium tolerance in wheat and barley (acid soils have high soluble aluminium content that limits cereal productivity) and resistance to *Phytophtora infestans* in potato. Also, the non-crop species *Arabidopsis* is an excellent model because of its wide range of geographic isolates ('ecotypes'), which differ in various quantitative traits and can be used to identify genetic quality determinants and components involved in the adaptation.

Exploration of the rich genetic diversity present in *Solanaceous* crops as tomato, potato, pepper, aubergine, petunia and tobacco and their wild relatives provides a basis to enrich varieties with novel genes that enhance their performance. This approach is both a complement and an alternative to the GMO strategy for improving the quality and quantity of food output.

Genetic variation present within families is currently the basis for further crop improvement by breeders. The observation that research with related wild species can contribute to improvement of crop plants has led to the establishment of large collections of genetic resources. In addition to providing useful genes, these collections can be used to understand quantitative traits of agricultural value including resistance/tolerance to (a)biotic stresses, as well as genes responsible for the many compounds detectable in individual plants that are related to quality aspects such as taste, health and food safety.

Recently the International crop *Solanaceae* Genome Projects have been initiated with the aim of sequencing the tomato genome as a reference for *Solanaceous* plants as well as plants from other related taxa. Similar projects have been organised for maize, wheat, rice, *Prunus, Medicago*. Over the coming ten years these projects will integrate diverse disciplines and research groups from around the world to create a coordinated network of knowledge about these plant families. This will lead to a deeper understanding of the genetic basis of plant diversity and how this diversity can be used to meet better the needs of society in an environmentally friendly and sustainable manner.

(ii) *Comparative genomics*. Components of the stress resistance mechanisms are shared among different plant species. Studies on model species, particularly on *Arabidopsis*, have provided new insight into the perception of environmental signals and molecular mechanisms of stress responses, subsequently confirmed in crops such as wheat. Comparative genomics is thus important to reconstruct the stress response of crop plants. Building on the identification of those genomic regions involved in stress tolerance and using the recently developed tools for genome-wide expression analysis, progress can now be made in linking the tolerant phenotype to the molecular response to stress.

(iii) *Improvement of crop stress resistance*. Marker-assisted selection, based on improved understanding and chromosomal location of the loci involved in tolerance, will be a major tool in developing stress tolerant varieties of major crops. The feasibility of this approach will largely depend on the number of genome regions involved in the control of resistance, while for a new variety the goal will be the accumulation of as many stress tolerance genetic factors as possible. This research endeavour, while still in its infancy, has a revolutionary potential.

Improved varieties could also be bred by plant transformation based on genes having a critical role in the expression of the desired trait. Molecular engineering of metabolic pathways in plants (for example, controlling synthesis of soluble sugars or limiting the accumulation of reactive oxygen species) can lead to improved stress tolerance. Transgenic plants have been produced exhibiting tolerance to water deficiency and salt stress. In general these molecular engineering approaches have received considerable public attention and generated the current European public controversy on GM food which has not yet been solved. To reiterate - the purpose of the present report is to show how crop plant genomics as a research area has a major role to play in conventional plant breeding, without commenting on the production of GM crops.

8 Research priorities: definition of genomics targets for biodiversity

Biodiversity has often been considered as encompassing all variations in living organisms, from genes to ecosystems, and, as such, difficult to quantify. Expressed in terms of species and populations, the current loss of biological diversity is a matter of great concern (Purvis and Hector, 2000). Continuing growth of human populations will induce further contraction of natural ecosystems in favour of cultivated land, in circumstances where agricultural activities already generate serious environmental concerns (European Environment Agency, 2003). For example, in recent summers, the Baltic Sea has been infested by toxic micro-algae and cyanobacteria as a result of high fertiliser use in adjacent soils dedicated to agriculture. Furthermore, many of the natural ecosystems of Europe – fragmented and disturbed – are now confined to marginal and poor soils, and because of this they are particularly sensitive to the effects of climate change. It is estimated that flora and fauna are losing biodiversity at a rate faster than those reported for mass extinctions in previous geological eras, a loss potentially incompatible with evolutionary organisation of the life on the planet.

Plant communities rich in biodiversity have superior biomass yield and better adaptation to the environment than communities of single species. Moreover, their richness in plant species promotes the diversity of other organisms, while providing a higher resistance to genetic invasion. An integrated approach to preserving biodiversity demands new methods to describe, characterise and measure organismal taxonomy. It also demands definition of the needs and modes of biodiversity conservation, based on the combination of molecular, morphological and physiological information within the broader context of population biology (population genetics plus ecology).

(i) *Molecular systematics and taxonomy*. The classic unit for measuring biological variation has been the species, a concept that has been corroborated by appropriate definitions based on reproductive isolation and crossability. The molecular approach to species systematics, eg the evolution of wheat or the search for wild relatives of maize, based on measuring and comparing DNA sequences and on characterising and comparing genome regions, has brought new light in the understanding of the evolutionary history of plants. Nevertheless, it is still necessary to integrate the information obtained at the level of gene, organism and population when considering the evolution of a species. Common technology platforms underpin the modern study of biodiversity while also serving the search of target genes supporting crop traits as described above.

(ii) *Applications in characterising biodiversity.* Progress in understanding plant species and population diversity is expected to generate information relevant to crop breeding as follows.

- Plant molecular evolution. Plant kingdom diversity can be revised at all hierarchical levels leading to novel interpretations of the evolution of plant characteristics, such as flower and fruit formation.
- Plant and organ development. The variation in the structure of homologous organs in plants that are taxonomically different may lead to the discovery of general principles of organ origin and evolution;
- Speciation analysed by molecular markers. Tracing the evolution of crop plants from annuality to perenniality (or vice versa), or monitoring the evolution of a trait contributing to colonisation ability, should improve strategic thinking in plant breeding.
- Evaluation and use of intraspecific variability. Molecular markers allow us to follow processes of domestication from wild populations and all key steps enabling the transformation of plant breeding from an empirical activity to a science-based process.
- Conservation of biodiversity. Molecular fingerprinting is becoming a standard tool in managing germ plasm collections for crops or endangered species. Programmes of biodiversity conservation need not only to maximise the number of protected taxa but also to guarantee the conservation of the highest possible level of diversity within taxa. Molecular systematics and adoption of appropriate molecular markers provide the scientific basis for conservation management programs, both *ex-situ* and *in-situ*, possibly also for entire ecosystems.
- Discovery of novel therapeutic agents. The search for biologically active compounds of plant origin is based on the analysis of plant diversity. Genomics helps in establishing relationships between the collected taxa and also provides links between plant systematics and the understanding of the pathways involved in the production of secondary metabolites, supporting new cost-effective methods to identify and screen candidates for new medicines.

(iii) *Seed banks and their international role*. In addition to adopting a coherent strategy for the use of the functional genomics technology platforms, it is essential to create internationally coordinated facilities and common standards for the curation and quality control of collections of seeds, explants and plants. Dedicated resources require the capacity to conserve and grow taxa requiring different environmental conditions. An EU commitment to biorepositories (plant samples plus their genomic data) could become a central part of a global network of Biological Resource Centres, as proposed by OECD (European Commission, 2001) and would be augmented by the shared databases envisaged by the Global Biodiversity Informatics Facility (www.gbif.org). This GBIF is conceived as an inter-operable network of biodiversity databases and analysis tools. Its value lies not just in the dissemination of data and in the sharing of best technical practice, but also as a route to cross-disciplinary training, to reinforcement of EU-US-other international networks and to the generation of new collaborative programmes.

It would also be relevant for the EU to evaluate the impact of the Convention on Biodiversity on germ plasm use in plant breeding. It is important to ensure, when trying to protect developing country interests in medicinal plants and local crops, that the international collection of genetic resources necessary for agricultural progress is not inhibited. The impact of the new International Treaty on Plant Genetic Resources for Food and Agriculture should also be assessed, in this respect (Kennedy, 2003), as a responsibility of the Commission.

9 Policy constraints on novel applications: non-food use of crops

As discussed in #4(iii) (new green industries), there is a broad range of other potential applications of crop biosciences that may support and create new EU industries. This chapter discusses additional examples in order further to illustrate the danger of promising applications being curtailed, not only because of insufficient or uncoordinated research investment in plant science, but also as unintended consequences of other EU policies.

The Common Agriculture Policy (CAP) has often been criticised for constraining industry uptake of agricultural raw materials, thus distorting market prices and supply of commodities. If the new green industries are to prosper, a secure and predictable framework for the supply of raw materials is essential. This supply should not depend on government subsidy but is competitive on world markets. Recent CAP reforms have been beneficial in introducing 'set-aside' regulations for arable crops, permitting non-food crops to be grown on this land and, thereby, stimulating the novel energy and industrial supply uses. We welcome this process of reform.

EU legislation also restricts the desirable use of renewable raw material in other ways. For example, the use of natural fibres as composite materials is undermined by recycling quotas, as highlighted by the work of the UK Government-Industry Forum on non-food uses of crops (see below). In some cases, the scientific priority is for more R&D (although not necessarily in genomics) but in others the priority is for the informed scientific community to work together with policy-makers to explain, to potential end-users, what is already achievable in novel applications. What is needed is a coherent strategic viewpoint and supportive legislative framework, as described in this report, to encourage the major opportunities for non-food uses of crops across the EU. This will require attention by multiple DGs and the European Parliament and, possibly, might be addressed in the first instance as a broader issue by the Technology Platform (see chapter 12). The identification of yet more opportunities will depend on continuing investment in plant sciences.

(i) *Biopackaging*. Globally, only about half the packaging used in the world is derived from renewable materials. Increasing this proportion would conserve resources and decrease the disposal of waste to landfill sites; but it is important to avoid increased production costs and energy consumption when using renewable materials.

Less than 0.1% of European polymer production is currently from biological materials (mainly starch). R&D is necessary to address why biomaterials have a poor performance. Changes in the EU quota (for example of potato starch) might be necessary to support market pull.

Environmental advantages will accrue if packaging waste from industry and from domestic uses is identified for composting where appropriate, rather than for disposal in landfill sites. Biomaterial colour coding could be mandated and segregated procedures supported by incentives/tax penalties.

In addition to the R&D agenda for optimising starch-based and oil-based polymers, it is important to initiate lifecycle economic comparisons of conventional and bioplastics, for example in terms of the fossil fuel consumed during manufacture.

(ii) *Wheat secondary products*. In furthering the aim of total utilisation of major crops, various new applications are foreseen for wheat – bioethanol, starch – and wheat-straw for paper pulp and for construction material and composites.

Industrial applications of starch range from packaging to cosmetics, surfactants, adhesives and coatings – generally, where significant industrial R&D in the fine chemical area exists and the opportunities are being exploited.

Wheat straw used as structural building blocks and infill for walls offers low environmental impact and energy consumption. But it is unfamiliar to the construction industry, consumers and regulators across the EU, and is further hampered by lack of skill in using the material. What is needed is EU leadership to raise awareness.

(iii) *Composite materials*. Natural fibres from hemp, flax, jute and plant leaves offer advantages over traditional materials (glass and, to an extent, wood) in terms of reduced weight and environmental sustainability.

Industry demand is led by the automotive sector, about 30 000 t (60% in Germany), estimated to grow to 100 000 t by 2010 (100 million Euro market). But the End of Life Vehicle Directive, which sets recycling targets, may constrain market development.

To promote use of renewables, the cited Directive should be reviewed. Enhancing productivity and functional performance of crops also requires re-examination of CAP subsidy support and current legislative constraints on planting area, permitted varieties and harvest date (to allow cultivation most appropriate to local climate).

10 Providing the right conditions for crop plant genomics research and its applications

(i) *Cost-benefit issues for choice of public investment in research*. Policy-makers in both the Commission and Member State funding agencies must respond to the claim (International Food Policy Research Institute, 2001; International Service for Agricultural Research, 2003) that too little is being invested in plant sciences. A slowdown – or reversal – in growth of agricultural R&D over the past 20 years is a matter of concern because the under-investment gap is growing (International Service for Agricultural Research, 2003). We endorse the view that there should be diversity in types and sources of funding. There must be sustained and stable support to nurture long-term approaches (both to model species and to crops of EU relevance), together with shorter-term, responsive-mode, grants. However, we are concerned about inefficiency when the culture of the research funders differs (for example, between national research councils and government departments). Competitive peer review of investigator-initiated research proposals should rightly remain fundamental to project management, and a case should also be made for longer-term support to address interdisciplinary aspects and the longer experimental cycle in crop systems.

Although many of the pleas for increased investment in plant and crop science emphasise the potential for agricultural innovation, economic feasibility is seldom addressed. Agriculture is an example of a fragmented sector in which market forces generally fail when it comes to the generation of new technologies. The individual private benefit is too small to constitute an incentive to invest the substantial capital required. The outputs of plant genomics research have classic 'public good' characteristics – even though the near-term goal is innovation – and joint action/government intervention is needed to overcome the market failure.

(ii) *Supporting private investment and meeting EU competitiveness goals*. In addition to understanding the economic costs and benefits of research, it is important to consider possibilities for incentivising the private sector and for optimising market structure. Broadly, the actions needed to increase R&D investment and to attract and retain companies within the EU, include (International Service for Agricultural Research, 2003):

- support for technology development (investment in basic science; training of researchers; improving access to knowledge);
- promoting economy of scale (joint R&D projects; international collaboration);
- enhancing industry structure (anti-cartel legislation to discourage monopolies; patent systems to stimulate private investment);
- sharing best practice for R&D efficiency (structures, management and organisational effectiveness);
- optimising adoption rate (consideration of market structure);
- addressing risk and uncertainty (clear, science-based, regulatory measures to incorporate the principle of substantial equivalence for new plant varieties and to relate to the public concerns for the environment; horizon scanning of future developments).

(iii) *Education and training*. Human resources are an important part of the infrastructure needed if the EU is to strengthen its capability. The increasing requirement for skilled researchers is not just in genomic technologies, important though those are, but also in plant taxonomy, systematics, physiology, biology and quantitative methods. We recommend that the EU consider undertaking an initiative corresponding to the one introduced successfully by the NSF in USA: targeted post-doctoral fellowships in plant science. There is a need for similar initiatives at the PhD level based on longer training programmes including interdisciplinary rotations and joint training programmes across university and industry, and across North–South collaborations.

It is particularly important to disseminate informatics training and resources: by programmes focusing on plant science; by identifying the needs for both young (basic user skills) and established scientists (mid-career training awards); and by organising workshops to inform the research community on accessing tools and databases.

More in generally, across the Member States, there must be mutual acceptance of national training standards, so as to facilitate exchange of young scientists, with promotion of mobility (drawing on best practice in Marie Curie Fellowships). There is also considerable scope for sharing best practice in distance learning and day release schemes for delivering industrial and conversion course training, and in teaching plant breeding as an undergraduate discipline. New university positions are needed at interdisciplinary interfaces, and improved career pathways and recognition for technical support staff.

(iv) *Public-private relationships and knowledge transfer*. Issues for public-private sector partnerships, as for education and training, are similar for crop plant genomics, plant breeding and other areas of life science. Indeed, valuable lessons can be learnt from best practice in other sectors: for example, the value of multilateral partnership developed within the SNP (Single Nucleotide Polymorphism) Consortium supporting biomedicine. Plant science has already benefited from pooling of public-private sector genomics information, in the case of the creation of a rice genome draft sequence.

However, these particular developments of the public-private relationships in plant science are in part stimulated by the disappearance of government funding of plant breeding research, both in the USA and EU (Knight, 2003). The example of the UK may be particularly instructive: here privatisation of plant breeding severed the emerging link between breeders and molecular geneticists. At the same time, agribusiness has undergone major consolidation and restructuring, leading to globalisation of priorities and focusing on added-value output traits in the major cash crops such as maize and soybean. Thus, as described, there are relative gaps in R&D invested in field crops and horticultural crops of importance to the EU, particularly concerning input traits that are desirable for a coherent EU strategy but have weaker commercial potential (for example, nutrient and water use efficiency). As plant breeding becomes more science-driven over the next two decades, there must be renewed connections between crop plant genomics research and breeding. This necessitates more 'public good' oriented plant breeding activities, since plant breeding is not very profitable but delivers great value to society. For example, current estimates suggest that the UK wheat seed market is less than 3% of the total farm gate value of wheat, so that increasing wheat yield has relatively little impact on the profitability of seed companies. Public-funded plant breeding efforts would also help to improve public confidence in the use of genomics research for crop improvement (see #10 (vi) below); revitalise training efforts at the plant science/plant breeding interface, and exert a proper control over private sector.

The options for publicly funded plant breeding across EU Commission and Member States now need to be explored, in terms of creating new centres or new networks. But the issue for knowledge sharing is not one only for the public-private sector interface. Within the public sector, there is need to do more at the EU level to share and incorporate best practice relating to the balance of effort in universities, research institutes and applied research organisations. There is an important mission-driven role for the institutes to provide dedicated infrastructure and long-term coherence to crop breeding research. Universities supply a complementary function in research, teaching and training, and access to a wide range of disciplines. Crop scientists are less well connected, by comparison with the *Arabidopsis* research community, and it is thus important to promote connectivity across research bodies.

(v) *Intellectual property rights*. While the need for public investment in plant genomics and plant breeding research is clear, the magnitude of resources required makes private sector participation essential. The private sector can be induced to invest in crop plant genomics research only if to some degree it can appropriate the results of its research.

The application of intellectual property rights (IPR) to plant varieties has been a relatively recent phenomenon. Plant variety protection (PVP) systems that have emerged over the last three decades allow new plant varieties to be protected on the basis of morphological distinctness, uniformity and stability in time. Given the sequential and cumulative nature of innovation in plant breeding, PVP systems generally allowed for researchers' exemption, so that a variety can be used as initial source of variation in the follow-on development of new varieties, without the permission of the titleholder. This does significantly reduce the appropriability of returns from a plant variety innovation and, consequently, PVP has been considered a relatively weak IPR measure. Efforts have been made to strengthen PVP to allow breeders to secure a larger share of the returns from their innovation. In the USA, Japan and Australia it is now possible to obtain utility patents for plant varieties. This development has, however, been perceived as damaging to public plant breeding programmes.

Protection of genomic information per se has also been controversial. During the early phase of technology development, numerous gene sequences were patented with excessively broad claims (and some feared an undermining of the traditional distinction between an invention and the discovery of a principle of nature), Conversely, *Arabidopsis* patent claims extended only to *Brassicas*, although extra work might have enabled expansion of claims to other crops. Patent authorities are now applying more stringent examination of claims for function, novelty and inventive efforts.

The rise in patenting of genomic information has been particularly marked in the US and Japan and covers gene sequences, tools and technologies. It has been estimated that US entities (companies, research institutes, universities) own 90% of US agrobiotechnology patents and more than 50% of European patents (Kalaitzandonakes, 2000).

Patent policy can have many impacts: it provides incentives to innovate and disclose new knowledge, but a proliferation of patents and licences may also cause increasing difficulties for start-up companies and public institutions to participate in leading innovation (International Food Policy Research Institute, 2001). It should also be admitted that some universities have been weak in their negotiations with companies, when granting exclusivity without guarantee that the patent will be effectively worked. If ownership of IPR is diffuse and uncertain, multi-lateral negotiation becomes difficult and the invention is under-exploited because of the high costs of the access. The Royal Society (UK) has recently emphasised that if patents are too broad in scope, they block other researchers from carrying out related work, and the Society recommends that public authorities should make explicit to patent offices their duty to examine patent applications appropriately rather than to strive to grant as many patents as possible (The Royal Society, 2003).

It has been proposed (Knight, 2003) that the power of conventional plant breeding will be boosted by marrying it to genomics and other molecular genetic technologies only if there is a concerted effort to break at least in part the current proprietary approach to IPR. This concept of open access to genomic information was seen as particularly applicable to US R&D efforts (Knight, 2003), but equivalent issues can be raised for the EU.

We recommend that these issues continue to be reviewed as part of the European Commission watching brief on biotechnology patenting and impact analysis of the current Biopatenting Directive. An additional access issue exists: plant breeders need to have access to a comprehensive and wide pool of genetic diversity, but are currently inhibited by the Seeds Directive. This risks reducing the number of vegetable and fruit cultivars remaining in cultivation because registration of a cultivar under the Directive is costly, and there is little incentive to register rarer, less commercial cultivars.

(vi) *Building public trust*. There has been concern – shared by scientists, industry and public policy makers – that the controversy over GM crops will hold back advances in other areas of plant genetics and genomics including applications that can improve conventional plant breeding. In order to capitalise on expected research advances in plant science, it is essential to progress public engagement on both scientific and socio-economic issues across a broad front: plant genomics and genetics, plant breeding, food production, food security, novel applications (European Commission, 2003). For example, it is poorly appreciated that use of genomics research as a tool in 'fast-track' breeding could increase and not decrease genetic diversity. While advances in plant genomics research open up applications for both conventional agriculture and GM crops, this report has concentrated on the former. It is important for the public to recognise the difference between the approaches exemplified in this report and GMO/transgenic approaches.

We recommend that the issues for plant science continue to be considered as a priority for the European Commission initiative Science and Society. However, while trust is essential to the success of any relationship (including those key interfaces identified by EURAGRI), it can be argued (O'Neill, 2002) that the recent culture of accountability, intended to increase trust, in fact does the opposite, through excessive bureaucracy and contradictory or unrepresentative targets. What is required, instead, is better governance without unnecessary centralised micro-management.

11 The global policy domain

The strategic issues for EU capability in plant science and crop breeding must be considered within the context of global policy developments. According to the 'positive reform agenda' (OECD 2003), encompassing trade liberalisation, the Uruguay Round, and promotion of environmental sustainability, there will be an increasing pressure to reduce forms of agriculture support that distort markets or require trade protection. The challenge is to find ways for agriculture efficiently and profitably to produce sufficient and safe food (and non-food crops), without harming the environment and degrading natural resources.

Traditionally, CAP provided substantial production-linked support, with mixed effects on environmental quality. The reform of agriculture policies and trade liberalisation has started to alter the signals to EU farmers – and these changing policies can capitalise on the research advances outlined above, if a coherent innovation strategy across the EU is implemented. However, the immediate influence of CAP is likely to lead to an intensification of farming practices in the accession countries, unless the EU rapidly prioritises sustainable farming (European Environment Agency, 2003). Moreover, the cohesive policy objectives must extend far beyond research and agriculture, for example to encompass energy, chemicals and recycling policies in the context of novel applications for non-food crops.

Some scientists perceive a substantial part of the justification for investment in crop plant genomics research to be the potential benefits that might accrue for developing countries. This report makes clear that crop plant genomics research will be of direct relevance and benefit to EU agriculture. But it is also important for the EU to consider the potential of research for developing countries (European Commission, 2002a), especially with regard to crops that may not be of interest to the private sector. However, in examining the benefits for developing countries, the heterogeneity of these countries, in terms of their research capacity, needs to be acknowledged.

Byerlee and Fischer (2002) propose a typology of national agricultural research systems (NARS) that classifies developing countries in one of three groups. Type 1 NARS include countries such as China, India, Mexico, Brazil and South Africa, with strong capacity in molecular biology, that can develop the new tools for their specific needs. Type 2 NARS only have the capacity to apply molecular tools developed elsewhere, while a large number of countries (Type 3) have no capacity in molecular biology and very fragile capacities in plant breeding.

EU crop plant genomics research would benefit the three categories of countries in different ways. Type 3 NARS will benefit from EU research only if this research produces plant varieties that can be directly introduced – so the benefits will materialise only if the EU deliberately prioritises this objective. For example, the EU might champion applications for improving 'orphan' crops such as cassava and tuberous legume species of South America. By contrast, Type 1 and 2 NARS are likely to benefit from EU plant genomics research through the use of newly developed tools. This will depend on the level of access to these tools that the regulatory environment will permit. The challenge for the EU is to consider developing countries as partners in technology generation/transfer (European Commission, 2003) and to promote access to genomic information and research tools, even as they become increasingly subject to private ownership and control within a strengthened and harmonised regulatory regimen.

It is important to learn from best practice in current partnerships using EU funding – for example, the projects with Indonesia, Malaysia and the Philippines that have promoted the molecular linkage maps for coconut and oil palm, and from initiatives in training (for example, the University of Ghent Institute of Plant Biotechnology for Developing Countries). The EU should consider the potential for global collaborative research initiatives exemplified by the recent donation of the Gates Foundation in support of innovation in traditional plant breeding methods (HarvestPlus with IFPRI – especially wheat, rice, cassava, legumes, maize; enrichment targets for vitamin A, iron and zinc). We also endorse the general points made by the recent report from the InterAcademy Council (Inventing a Better Future, 2004), which emphasises both the importance of building capacity in science and technology in agriculture and the importance of coordinating international efforts. This InterAcademy Council report is recommended as a comprehensive discussion of the broad approaches needed to build capacity and as an introduction to the practical opportunities available to achieve those ends.

12 Developing the strategic framework

When considering how crop plant sciences can contribute to EU competitiveness and sustainability, many drivers in addition to science push have to be taken on board: public expectations, changing demographics, regulatory developments, litigation, new competitor countries, market structure. But sound science must be at the heart of policy-making.

We greatly welcome the Plant Genomics Technology Platform announced at the Heads of State European Council meeting in 2003. We support the aims of the Platform in mobilising all stakeholders (researchers and funders, farmers, industry, NGOs) to identify the opportunities for Europe and prepare the ground for political acceptability by showing how this technology can and will affect our futures. We hope that our report will help to inform and take forward this Platform – not just at the EU level but also at EU Member State level, and in collaboration with other international partners. We urge the Platform to consolidate new thinking across a broad front:

- building on ERANet, with immediate effect on Framework Programme 6 funding choices and seeding ideas for Framework Programme 7;
- developing the strategic options for the private sector;
- confirming the priorities for societal needs: food quality, environment (and remediation), biodiversity, developing countries assistance, novel applications;
- facing key challenges: informing consumer views, appropriate science-based regulation of markets, coordinating R&D initiatives.

EASAC should be involved in these continuing efforts.

One of the issues for the Platform and related efforts is how success should be measured. Many different performance criteria are available and a portfolio approach to measuring outputs, outcomes and impact is recommended: publications, patents, citations; trained staff and their mobility; development of new technologies, tools and standards; uptake of research by companies; reduction to practice in plant breeding; value creation from the new applications; rural income, infrastructure, employment and economic development; contribution to balance of trade.

In publishing this report, EASAC confirms that there is a major opportunity for the EU to generate new knowledge on crop plants, to apply that knowledge to plant breeding and, thereby, to contribute to competitiveness and other societal goals. The EU will succeed in this strengthening of its capability only if it is committed to identifying the highest priorities for excellent research, what is feasible and what are the best pathways with which to pursue those priorities. Crop biology and crop improvement should be the overarching themes, with twin goals for the reduction to practice: translating from genomics research on model plants to crops, and from crop science to plant breeding. To achieve this, the EU will need a coherent strategy for generating new knowledge, bringing together the different research communities, sharing best practice and clarifying what added value can be delivered at the European level.

In this report, we have discussed some specific research priorities: for genes and traits, technology and tools, and for addressing societal needs and market opportunities. It is important to take a long-term perspective in order to make the case for the emerging research agenda, but also to be aware of likely new competitor countries. We have also highlighted the importance of addressing the wider framework that is necessary for EU innovation: building in the necessary elements for human resources, public engagement, regulatory regimes, technology assessment, intellectual property protection and cost-benefit analyses.

We have focused on major crops. There is more to be done to identify research priorities and policy issues for other areas, for example pasture and forest trees, where there may be more variability between Member States. What we have also not attempted here is the detailed analysis necessary to quantify R&D investment requirements and the potential impact on competitiveness, because we do not wish to pre-empt either the thorough ERANet review of Member State activities and opportunities for alignment or the collective debate across all stakeholder groups that will drive the progress of Technology Platforms. But, as a first step, by identifying research priorities and applications across a broad front, EASAC intends that the present report will help to stimulate ongoing discussion across Europe.

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