ESRC genomics policy and research forum

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Plant Genomics Workstream
Working Paper: Genomics, Farming and the Bioeconomy (March 2007)

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The following notes focus on the theme of farming and the bioeconomy, and are intended to stimulate discussion rather than provide a comprehensive overview. The Genomics Forum website contains additional working papers relating to the Plant Genomics workstream[1].

I. Overview of biotechnology, farming and the bioeconomy

The global agricultural landscape is likely to change noticeably over the next 20 years in response to a variety of social, economic and environmental factors. These include:

- increasing pressure to maximize yield from existing agricultural land to feed a growing world population, while reducing the 'environmental footprint' of farming (for example, by reducing the intensive use of fertilizers, pesticides and irrigation) and promoting sustainable development.
- a desire for increased food security, or the ability to maintain stable agricultural output in the face of threats including climate change and current and emerging plant pests and pathogens. Maintaining sufficient genetic diversity in planted populations is necessary for crop plants to resist disease and adapt to changing environmental conditions.
- changes in the standards and requirements of consumers (for example, increasing recognition of the link between diet and health is resulting in a push for improved nutritional value of foods).
- Common Agricultural Policy (CAP) reform in the EU and the increased emphasis on treating farming systems as part of wider agro-ecosystems.
- increasing demands for renewable products and energy sources. The derivation of energy from biomass is currently a popular policy option for reducing dependence on fossil fuels.

Given this rather complicated picture, maintaining the status quo does not seem a viable option for agriculture. The so-called 'Green Revolution' of 1960s and 1970s boosted agricultural productivity and yields largely through improved mechanization, irrigation and use of agricultural chemicals. Now, scientific advances (especially at molecular and genetic levels) are improving our fundamental understanding of plant development, metabolism, physiology and health, and future gains in productivity are predicted to depend increasingly on genetic and genomic technologies (Briggs, 1998; BBSRC, 2004). However, translating basic knowledge into practical applications to help meet targets for sustainable development, environmental protection and agricultural productivity will be a key challenge, and will require new partnerships among funding bodies, policymakers, academic scientists, industrial entrepreneurs, farmers and other stakeholders.

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[1] See http://www.genomicsforum.ac.uk/default.aspx?pageId=116.

As alluded to above, the future agricultural landscape will almost certainly not be restricted to growing crops for food and animal feed, but will also include plants grown for non-food uses such as bioplastics, pharmaceuticals, biofuels and building materials. Indeed, such uses for biological materials have led to the concept of the 'bio-based' economy, or **bioeconomy**, which can be broadly defined as an economy for which the raw materials and basic building blocks for energy, industry and growth are derived from biological, renewable resources. Improvements in our ability to harness biological processes for practical applications will almost certainly affect sectors as diverse as health, industry, environment, agriculture, energy and security. Rather than assuming traditional divisions between these sectors, the OECD has identified a need to consider the convergence and integration of "research domains, technologies, economic infrastructures, and government practices", and is currently working on a long-term roadmap for policy formulation relating to the bioeconomy (OECD report, 2006). Furthermore, the report identifies that "the policy and regulatory frameworks that currently govern bio-science based activities are often unsuited to the economic, social, and ethical issues now emerging" (p.5). Developing more appropriate frameworks will be a key challenge.

How might governance frameworks best support the development of an environmentally sustainable, bio-based economy?

II. Plant biotechnology for the farming and the bioeconomy

If desired, plant biotechnology could make a valuable contribution to farming and global food production, and is likely to become increasingly important for the bioeconomy and sectors including phytoremediation, energy production and the pharmaceutical industry. It should be possible to develop improved crop varieties with a host of tailored traits, including higher yield, increased drought and salinity tolerance, better pest and insect resistance, increased biomass, more efficient photosynthesis, and altered carbohydrate and metabolite compositions. Below is a brief exploration of possible avenues for plant biotechnology in years to come. Any new regulatory frameworks developed should be consistent with the wide range of possible applications for plant-derived products.

Farming for health and well-being

Plant breeding for agriculture has traditionally been oriented towards crops with high agronomic yield, easy and consistent processing, and disease and pest resistance. However, increasing recognition of the link between diet and health is leading to demand for more nutritious foods (Morris & Sands, 2006). Examples might include food crops with higher vitamin content, modified starch levels, or lower allergenic potential.

Food safety and biosecurity

Genomics and other '-omics' technologies (particularly metabonomics) may prove useful for monitoring purposes to improve quality control and traceability of products through the food supply chain, feeding into more robust regulatory frameworks that hopefully improve consumer confidence. Similar approaches can be used to improve safety testing of plant-derived non-food products, including pharmaceuticals and chemical products.

'Green chemistry' and the chemical industry

Higher plants synthesize more than 200,000 different primary and secondary metabolites, but the chemical potential of plants is largely unexplored. There are great possibilities for new plant compounds to be discovered and exploited by the chemical industry for products such as biodegradable plastics, flavouring agents, and packaging and construction materials (Hatti-Kaul *et al*, 2007).

Phytoremediation

Phytoremediation makes use of plants' natural ability to contain, degrade or remove toxic chemicals and pollutants from contaminated soils and water (Pilon-Smits, 2005). Phytoremediation can be used in combination with other techniques to clean up metals, pesticides, solvents, explosives, crude oil and other contaminants. Several fungi, algae and higher plants (including sunflower, poplar and duckweed) are currently under investigation for their phytoremediation potential.

Plants as an energy source

In coming decades, the necessary switch from a fossil-fuel-based economy to an economy relying on alternative sources of energy means that plants will almost certainly provide a higher proportion of global energy requirements. The conversion of biomass into energy is an area receiving both private and public sector investment[2]. Using artificial photosynthesis to harness solar energy is also an area of current research[3].

Pharmaceuticals

Plant products have long been important to the pharmaceutical industry: about 25% of all commonly prescribed medicines are directly or indirectly derived from plants. As well as sampling natural genetic diversity to find new therapeutic compounds (sometimes referred to as 'bioprospecting'), several dozen companies worldwide are currently working with plants as vehicles for producing vaccines and other pharmaceutical products — a process sometimes termed 'pharming' (Fox, 2006). There is already some concern over the use of food/feed crops for growing pharmaceutical products, as there is a realistic possibility of food supply contamination.

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[2] See working paper on bioenergy, http://www.genomicsforum.ac.uk/documents/pdf/BioenergyPaper0307.pdf.

[3] The Swedish Consortium for Artificial Photosynthesis is one of the leading research networks in this field, see http://www.fotomol.uu.se/Forskning/Biomimetics/consortium/index.shtm.

III. New technologies for the bioeconomy: Current initiatives in plant genomic research

There are several ongoing genomics initiatives relevant to farming and the bioeconomy, including:

- Vascular plant genome sequencing projects (three genome sequences completed[4], a further six underway, and many more genetic maps and large-scale EST[5] databases being generated for principal food crops, model organisms and other plant species[6])

- Fungal genome sequencing projects. For example, the genome sequence of the maize fungal pathogen *Ustilago maydis* has just been published (Kämper *et al*, 2006). *U. maydis* is a well-established model organism for the study of plant–pathogen interactions, and should help to shed light on mechanisms of fungal pathenogenicity in plants.

- Bacterial genome sequencing projects. Recently published genome sequences include *Ralstonia eutropha* H16 (a bacterium widely used to produce natural polyesters) (Lee, 2006) and *Candidatus* Accumulibacter phosphatis, a microbial organism prevalent in the sludges used for treating wastewater (Mino & Satoh, 2006). These genome sequences provide a starting point for engineering optimal metabolic pathways and bioproduct synthesis.

- ‘Metagenomic’ profiling of soil samples to generate microbial ‘fingerprints’ that may help to better understand the plant–soil interface (Gewin, 2006)

- Marker-assisted breeding projects to develop new cultivars or plant varieties that fulfil agricultural, consumer and/or environmental needs (see section IV).

- The establishment and maintenance of *ex situ* germplasm and seed banks (e.g. the Millennium Seed Bank at Kew and the new seed storage facility being build in Svalbard, Norway) to document and preserve natural genetic diversity in plants.

- Development of so-called second- and third-generation GM crops. Second-generation GM crops are intended to provide benefits for both farmers and consumers, and will be designed for traits such as herbicide, pest and pathogen resistance, drought, salt and extreme temperature tolerance, improved nutritional quality, increased supermarket shelf life, and elimination of allergens. Third-generation GM crops are predicted to make increasing use of functional genomics to manipulate and control traits such as plant architecture, flowering time, fruit/seed size, seed quality and number, photosynthetic efficiency, and nutrient assimilation (Vasil, 2003).

Genomics is essentially an information-providing tool. Understanding how to collect, organize and interpret genomic information, and to integrate it with knowledge gained through other disciplines, will be key to driving innovation in farming and the bioeconomy. Together with other ‘-omics’ approaches, genomics should help to promote a holistic or *systems-level* understanding of plant development and function. This gradual shift to a systems-based understanding of organisms has several parallels at a larger scale, including the increasing recognition of the need to manage agroecosystems at the ‘landscape’ or ‘ecosystem’ level (see section V).

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[4] The model organism *Arabidopsis thaliana*, *Oryza sativa* (rice), and the poplar tree *Populus trichocarpa* (as of November 2006).

[5] EST: expressed sequence tag

[6] See http://www.ncbi.nlm.nih.gov/genomes/PLANTS/PlantList.html for a list of ongoing projects.

IV. New technologies for the bioeconomy: from GM to genomics

> *"The much-debated genetic modification (GM) of plants is one of the biotechnologies used, depending on the specific challenges to be addressed, but we should not make the fundamental mistake of equating agricultural and plant biotechnology with GM alone. Genetic modification of plants is not the only technology in the toolbox of modern plant biotechnologies."*
> – European Commission report *Plants for the Future* (2004, p.9)

Public debate on the use of plant biotechnology for farming and the bioeconomy has to date centred largely on the production of GM crops for agriculture. However, the future of plant biotechnology in Europe will not rely solely on conventional genetic modification — as stated above, traditional GM is only one of several biotechnologies that can be used to manipulate plant traits[7]. Tissue-culture techniques such as micropropagation, anther culture and embryo rescue are well-established and routinely used by plant breeders in both the developed and developing world (Dhlamini, 2006). Genomics also is emerging as a powerful tool in plant breeding, with molecular techniques such as marker-assisted selection (MAS) that allow scientists to exploit genomic information to enhance the conventional breeding of plants. The flexibility and breadth of applications accessible through genomics makes it an attractive tool for the development of innovative, customer-targeted products. However, manipulation of plant traits, whether by conventional GM, genomics or other means, is only one facet of plant science for the bioeconomy — epidemiological and population modelling studies, as well as practical agroecosystem management strategies, are also required to manage plant–environment interactions in a holistic and sustainable manner.

Marker-assisted selection is increasingly cited as an alternative method to conventional GM for plant breeding. From a technical perspective, however, both conventional GM and MAS have advantages and disadvantages, and are not interchangeable techniques (Pollack, 2001). Compared to GM, which is only possible if the gene of interest is known and isolated, MAS can be used even if the specific gene has not been identified. MAS also offers the advantage of being able to select plants for multiple traits, instead of the one or very few traits possible with conventional GM, and promotes the use of natural genetic diversity present in wild relatives of crops (see Giovannoni, 2006). This being said, MAS is limited to traits that are already contained within a crop and its wild relatives, meaning that some projects are simply not feasible using MAS alone[8]. Furthermore, breeding by MAS is inefficient compared with GM, as it involves the crossing of entire parental genomes. MAS requires a longer timescale than GM, but a shorter timescale than conventional breeding. It has so far proved a fairly difficult and expensive technique, but the cost is likely to decrease as more genomes are sequenced and associations between markers and traits are mapped out in more detail.

Technical considerations aside, perhaps the greatest advantage of MAS compared to conventional GM is a *political* one (in Europe at least, and possibly in parts of the developing world). MAS does not involve the artificial transfer of genes between organisms, which many opponents of GM technology identify as 'unnatural' and posing a risk to both human health and the environment. As such, MAS is not expected to provoke resistance from consumers[9] (Pollack, 2001). In fact, known critics of GM and biotechnology have spoken out in favour of MAS, including Jeremy Rifkin, Greenpeace and the Soil Association (Stokstad, 2006). At present, plant varieties generated through MAS avoid the regulatory reviews required of GM crops, and it is even possible to use plants generated by MAS in organic farming. Despite being a slower and more expensive technique than conventional GM, many plant breeding companies are turning to MAS as a socially acceptable way to develop new plant varieties. Should plant varieties developed through MAS be treated identically to conventional plant varieties, should they be subject to similar regulatory standards as GM crops, or should the regulatory standards fall somewhere between the two[10]?

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[7] Adoption of a particular method will depend on the aim of the given project and the available resources.

[8] For example, the development of 'Golden Rice' containing vitamin A would not have been possible using MAS.

[9] Is this merely an assumption, or has any formal research been undertaken to validate this claim? Is the general public aware of the distinction between crops generated through conventional GM and marker-assisted selection?

[10] Arguably, some of the traits selected for using MAS will be characteristics often associated with ecological fitness and invasive species (for example, rapid growth rate, efficient photosynthetic mechanisms, efficient water use, etc). Some ecological assessment of new plant varieties generated through MAS might be advised.

V. Funding and research strategies for plant science in the UK and Europe

> *"Along with the overarching concern to improve agricultural competitiveness, the agenda for agricultural R&D now includes a greater and growing emphasis on issues such as the environment, genetic diversity, food safety, value adding, human health, the structure of agriculture and animal welfare. These issues will compete for funds against the more traditional agenda of productivity enhancement, economic growth, farm incomes and food supply."* – RIRCD Corporate Plan, 2003

The UK's future competitiveness in the global marketplace for agricultural and other plant-derived products will depend increasingly on its ability to harness science and technology to develop innovative, *customer-oriented* products. Several recent reports on the future of plant science in the UK and Europe[11] stress the need for more funding, and notably, increased coordination and the development of a coherent strategy for European plant science research in order to meet future needs (Hughes, 2006).

The 2004 EC *Plants for the Future* report highlights an emerging gap in plant genomics and biotechnology innovation between the EU and countries including the US, China and Japan, in part owing to the more restrictive political and regulatory framework in Europe. This report estimates that private and public funding in European plant science will have to exceed €45 billion over the next ten years if Europe is to remain competitive. The 2004 EASAC report suggests a number of possible reasons for the marginalization of European plant science research in recent decades. These include (1) difficulties in translating advances in basic understanding of plants into better crops, (2) complacency in the developed world about food security, and (3) controversies regarding transgenic plants, which have led to public pressure to move away from plant biotechnology and towards more organic, 'natural' methods of achieving sustainable agriculture.

New plant cultivars and plant-derived products are likely to occupy increasingly important niches in the 'knowledge-based' bioeconomy. Plant genomics and biotechnology can be seen as flexible resources or tools for developing more productive, customer-oriented and environmentally sustainable crop systems, and in the above reports are highlighted as central to Europe's competitiveness in the agricultural and food processing industries. The perceived importance of plant biotechnology more generally is reflected in at least three of the nine themes outlined for EU funding through Framework Programme 7, including (1) food, agriculture and biotechnology, (2) energy and (3) environment[12]. Within the food, agriculture and biotechnology theme, the main funding priorities[13] seem to map fairly well onto the future requirements for agriculture and the bioeconomy outlined in section I.

Some coordination and integration of research strategies is seen as necessary in order to maximize the potential benefits of plant biotechnology research. To this end, the European Plant Science Organization (EPSO) launched a technology platform in 2004 called 'Plants for the Future' that will bring together relevant stakeholders to reach a consensus on common priorities and develop action plans. A European Research Area on Plant Genomics (ERA-PG)[14] was also set up in 2004 under the FP6 programme. ERA-PG is a network of research funding organizations that aims to foster coordination and cooperation between national research programmes, and currently has 15 member countries. A number of other ERA-NET projects are also relevant to plant biotechnology[15].

Will it be enough to ensure reasonable coordination and cooperation among existing funders and plant biotechnology research centres, or might there be value in rethinking the structure of plant

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[11] These include the European Commission (EC) 2004 report *Plants for the Future: 2025 a European Vision for Plant Genomics and Biotechnology*, the European Academies Science Advisory Council (EASAC) 2004 report *Genomics and Crop Plant Science in Europe*, and the BBSRC's 2004 *Review of BBSRC-Funded Research Relevant to Crop Science*.

[12] FP7 will run from 2007–2013; see ftp://ftp.cordis.europa.eu/pub/fp7/docs/ec_fp7_amended_en.pdf#page=20.

[13] The main funding priorities are listed as (1) sustainable production and management of biological resources from land, forest and aquatic environments, (2) 'fork to farm': food, health and well-being, and (3) life sciences and biotechnology for sustainable non-food products and processes.

[14] http://www.erapg.org/everyone

[15] Details of ERA-NET projects can be found on http://cordis.europa.eu/coordination/era-net.htm.

biotechnology funding in Europe and developing new funding mechanisms? New production and supply chains are likely to emerge in the bioeconomy (with biofuels, for example), and new R&D strategies may help to exploit the agricultural research base in Europe for the development of new bio-industries.

Arguably, a new research strategy for European plant science should place society's needs at the centre, and consider how best to harness science & technology to achieve these needs. Such a strategy would ideally take a holistic view of the entire R&D chain, from basic science through to the delivery of customer-specific products in both agricultural and other bio-based industries. Challenges in managing a successful holistic strategy include (1) achieving an appropriate balance between basic and applied research, especially given the growing cost of research and the challenge of increased interdisciplinarity, and (2) managing public and private investment along the entire chain, to help link basic research with deliverable products. New modes of engagement between stakeholders may be required to achieve this.

Government–industry partnerships may help to encourage the translation of basic research findings into customer-specific products. Defra's LINK scheme[16] is a small-scale (£5 million/year) but fairly successful example of a joint government–industry initiative. The Australian government has been running a larger scheme for over 15 years, through the Rural Industries Research and Development Corporation (RIRDC)[17]. The RIRDC oversees and funds priority research for the rural economy in Australia, and relies on **matched funding** from industry to foster the development of new rural industries, manage investments for established industries, and address cross-sectoral issues facing the rural sector. Are there other examples of funding models that may help to exploit the existing S&T base in Europe to deliver innovative products for the bioeconomy? How should the success of any such schemes be measured?

Comparing strategies for Europe and the developing world

Funding for agricultural research in the developing world is increasing. China, Brazil, India and South Africa have made large investments in agricultural biotechnology research in the past decade, and African Union governments have pledged to devote at least 10% of their budgets to agriculture by 2010. Initiatives to foster biotechnology research have been set up in recent years, including CGIAR's Generation Challenge Programme on 'Genetic Diversity for the Resource-Poor'[18]. A number of international collaborations and research institutes have also been established — these tend to be in the form of 'North–South' and public–private partnerships. A recent article by Ayele *et al* (2006) concludes that such agbiotech partnerships in sub-Saharan Africa are often poorly oriented to end users, fragmented in scope and aid-dependent.

Similar to the considerations outlined above for the UK and Europe, new and innovative funding and research strategies may also prove valuable for the developing world. Are there specific research programmes and/or strategic approaches that would have tangible benefits for both the EU and the developing world? The immediate priorities for farming world would seem to be reasonably different at first glance. In the developing world, high levels of chronic malnourishment and a lack of food security are key issues to address. Major constraints on crop production include drought and the presence of fungal diseases (such as *Phytopthera*) and parasitic weeds like Striga. Improving the yield and nutritional value of crops are key areas of focus in the developing world. In contrast, the UK and Europe seem more concerned with decreasing farming *inputs* than increasing agricultural *output*. The main debates concerning farming in the UK and Europe are not centred on issues of crop yield, but instead on matters relating to land management, biodiversity conservation and sustainable development[19]. Over time, there has been a shift away from breeding for high yields in the UK, and the adoption of less intensive, wildlife-friendly farming techniques has been supported by government measures including the new Environmental Stewardship scheme launched in 2005 (POSTnote, 2005). The Genomics Forum working paper on biodiversity, conservation and land use contains a more detailed discussion of the links between farming and the environment in the UK.

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[16] See http://defrafarmingandfoodscience.csl.gov.uk/linkprogrammeoverview.cfm.

[17] See http://www.rirdc.gov.au/.

[18] CGIAR is the Consultative Group on International Agricultural Research. This particular programme has an annual budget of $8 million to support genomics and marker-assisted selection breeding programmes in the developing world.

[19] Take for example the prominence of RELU (rural economy and land use) in the UK policy agenda.

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