MISTRA
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Sustainable Development of Agriculture and Food Systems using Biotechnology as a Tool

The Mistra International Planning Committee
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1. Summary

Swedish agriculture and food systems face major challenges over the coming decades. A Mistra programme on "Sustainable Development of Agriculture and Food Systems using Biotechnology as a Tool" would provide a substantial platform for the development of biotechnologically-related knowledge, products and services with a 20-40 year time horizon. This would contribute to environmental, economic and social sustainability associated with agrifood production and strengthen Swedish competitiveness. Such a programme should be multidisciplinary, building on relevant natural and social sciences as well as ethical inquiry.

The report outlines four major research themes that proposals should address:

- Biotechnologies for future Swedish agriculture
- Biotechnologies for sustainable use of resources
- Consumer choices
- Developing Swedish competitiveness

The focus should be on Swedish agriculture and food systems, and expected outcomes should address how the knowledge generated will be transformed into products and services, or contribute to policy development. Stakeholder engagement in the design and execution of the programme will also be an important characteristic.

2. Assignment and the Planning Process

In June 2009, the Mistra Board decided to start planning for a new programme on the use of biotechnology for a sustainable future with a focus on agriculture and the food system, including societal and ethical aspects. Mistra had commissioned a pre-study by Professor Torbjörn Fagerström (Swedish University of Agricultural Sciences, Uppsala) and Mr. Peter Sylwan (science journalist, Stockholm), which was presented in April 2009 ("With Nature's Own Methods", in Swedish).

Professor em. Thomas Rosswall was contacted by Mistra in the autumn of 2009 and agreed to chair an international Planning Committee "Biotech Food". As a first step, a few Swedish scientists were invited to a seminar at Mistra on 14 January 2010. The seminar included presentations by Professor Sven Ove Hansson (The Royal Institute of Technology, Stockholm) on "Social and ethical aspects of green and white biotechnology", Professor Janne Bengtsson (Swedish University of Agricultural Sciences, Uppsala) on "Future Agriculture", and Dr. Anders Nilsson (Swedish University of Agriculture, Alnarp) on "Plant Breeding".

The participants were invited to suggest names for members of the Planning Committee. Based on these submissions, and in consultation with Thomas Rosswall, five additional members were invited to serve. The Planning Committee (Annex 1) held its first meeting in Stockholm on 20-21 September 2010 at which time members agreed on a broad definition of biotechnology and seven themes for research. The work was guided by Terms of Reference (Annex 2).

Swedish scientists and representatives of key institutions were invited to a seminar at Mistra on 16 December to discuss a draft of the report from the Planning Committee. The agenda and list of participants are included in Annex 3.

Based on the discussion, the Planning Group decided to concentrate on four, rather than seven, themes. The final version of the report was agreed subsequent to a second meeting in Stockholm on 21-22 February 2011.

The Terms of Reference for the Planning Committee specified that a summary of current scientific understanding should be prepared, including key references. Each member was invited to submit 5-7 key references and Mistra commissioned a summary of the current knowledge based on these references. This report ("Biotechnology for Sustainable Food Systems – a brief summary") by Andreas Nilsson, Vetenskapsjournalisterna, is included as Annex 4. It should be noted, however, that the report was commissioned based on references provided by Planning Committee members prior to their first meeting. During the course of planning, the scope of biotechnologies has been significantly broadened, with increased focus on prospective, rather than retrospective, activities. Thus, in the annexed report, there is more focus on public concerns over Genetically Modified Organisms (GMO) rather than all forms of biotechnology discussed in the report from the Planning Committee.

3. Setting the scene

3.1 Introduction

The Terms of Reference for the planning took the global situation as the point of departure. Due to a growing population and rising living standards, global food demand is estimated to rise by about 70% by 2050. However, total arable land cannot be increased to any great extent without causing considerable environmental impact. In addition, changing consumption patterns are boosting demand for livestock products. Therefore, future increase in food production will have to come largely from sustainable ways of increasing crop yields and animal production on present-day agricultural land. Moreover, people need a healthy diet, rather than a mere increase in calorie intake. Part of the solution to meet the demand for sustainable production of healthy food can be genetic improvements of crops and livestock.

A growing concern is that climate change will negatively affect crop yields and increase harvest variability, especially in smallholder agriculture in developing countries. Climate change may be beneficial for agricultural production in other regions and will change the geographic location of growing zones for individual crops. Challenges to agriculture and the food system also include contributions to greenhouse gas emissions, where agriculture and forestry contribute about 1/3 of the total global emissions. Use of fertilizers must also be managed better to avoid runoff and leaching, resulting in eutrophication and groundwater pollution. Societal concerns about herbicide and pesticide use will also continue to be a challenge to the farming community. Again, biotechnologies can contribute to the development of more sustainable agriculture and food systems.

In the planning, focus has been on Swedish agriculture and food systems and the competitive advantages that Sweden could have, while putting such developments in a global perspective.

3.2 Swedish food systems

There are many challenges facing Swedish agriculture. In 2004, about 1.4% of the Swedish labour force earned their living in agriculture compared to more than 50% at the beginning of the 20th century and about 20% in 1950. Most farmers are elderly, and many small farms do not have a successor waiting to take over. Most Swedish farmers are small landowners, who also support themselves through forestry and other activities.

About 8% of the land area in Sweden is classified as arable land. In 2007, there were about 72,000 holdings with more than two hectares; a decrease of 24,000 compared to 1990. It is primarily the number of farms of <10 ha that has become smaller.

Grains (oats, wheat, barley, rye and oilseed rape), potatoes and other root crops, vegetables and fruit are the major agricultural products. Over the past ten years, the number of dairy herds has decreased by almost 50% and the number of dairy cows by 25%, while the average yield per cow has risen substantially. Structural changes towards larger farms have occurred at the same time as increased investment in machinery and specialization in grain, milk production or pig rearing. The livestock sector contributes almost half of the value generated in Swedish agriculture.

Unlike farmers in many other European countries, Swedish farmers, via their co-operative associations, are involved in the further processing and marketing of their agricultural products. The co-operative Scan Group, for example, slaughters about 80% of the cattle produced in Sweden. In the dairy sector, the predominance of co-operatives is almost total and co-operatives are also major grain processors.

Overall production exceeds domestic consumption, but a considerable amount of food and feed is imported. The total revenues of the agricultural sector were equivalent to about 2% of GNP (1996) but the food sector is important for the Swedish economy because one in four industrial jobs is in the food sector.

Swedish food exports consist primarily of surplus grain but also of, for example, butter, pork and vegetable oil. In 2009, Swedish export of agricultural products and food totalled SEK 50 billion (fish, cereal and cereal products, beverages and processed food), while imports were SEK 93 billion (fish, fruit and vegetables, meat and beverages). Imports consist primarily of goods which are not produced in Sweden.

Swedish agriculture faces many challenges. The Ministry for Agriculture has recently been renamed the Ministry for Rural Development to underline that successful agriculture and forestry policies are needed to create more jobs and a flourishing countryside. The government considers that improving the competitiveness of Sweden's farmers is one of the most important issues for the creation of new jobs, both in rural and urban areas. The vision of the Minister for Rural Development is that of 'Sweden – the new culinary nation', an initiative that he hopes will create up to 20,000 jobs.

In the context of agricultural development over the next 20-40 years, modern biotechnologies can have an important role to play. Swedish agriculture and food systems can compete by developing niche and high-value products that address consumer needs by utilizing appropriate biotechnological techniques. They can probably benefit as a result of the global warming process.

3.3 Biotechnologies for agriculture and food systems

Biotechnology comprises both cell and molecular biology tools. Biotechnologies can be used for structural and functional genome, transcriptome, metabolome and proteome analysis, providing information that helps in mapping the major physiological, agronomical and quality characteristics of crops and animals. Today, genomes have been sequenced, e.g., for rice, maize, sorghum and soybean, as well as for chicken, cow and pig, and other genome projects are in an advanced state. Used in combination with high-throughput phenotyping, this information could enhance our understanding of interactions between genes and their associations with phenotypes of plants and animals. Furthermore, the increased understanding of the modes of action of pests and pathogens emerging from genomics offers new possibilities for achieving durable disease and pest resistance and novel control measures.

In modern breeding technology, desired traits are marked at gene level. This enables "marker-assisted" selection, or so-called genomic breeding, which provides greater selectivity and possibilities for simultaneous selection for more traits than conventional breeding based solely on phenotype selection. Another technique is genetic modification (GM) that allows selection and insertion of a specific gene or set of genes that control a desirable trait directly into the genome of a target plant or animal cell. Several techniques have also been developed for growing and manipulating plant or animal cells and tissues in laboratories. Methods such as cell cloning, cell culture and regeneration, interspecific hybridisation and crossing of distantly related species can be applied in agricultural research and variety development.

Public acceptance of, and priorities for, the development of different forms of biotechnology, applied to sustainable food production is an important element in the development of policy and commercialisation, within Sweden and beyond. Sustainable food production may be defined as including the maintenance of a supply of healthy and secure foods, as well as those which deliver environmental advantages. For this reason, improved healthiness, safety, and availability of foods need to be considered in any discussion of biotechnology and sustainability related to foods and food choice.

Other factors, such as price, or people's tendencies to make habitual food choices, or context will influence consumer decision making. Individual differences in terms of the economic status of households, or related to an individual's value or attitudinal system, stage in their life cycle, or priorities for different types of food attributes all influence whether sustainable consumption choices are adopted. In addition, people's perceptions of the relation between agrifood production and the Swedish landscape may also need to be taken into account, in particular when introducing novel plants or animals into agricultural practices.

Novel functional foods (for example, those which have been biofortified, or deliver other human or animal health benefits) may be developed either through traditional breeding, or through other forms of biotechnology. For example it is known that the balance of fatty acid classes may have an effect on blood pressure and cardiovascular diseases, and that the fatty acid composition of nutritional oil can be improved by breeding. Personalised nutrition has potential to improve consumer health in line with individual differences in health status. Such health benefits can only be realised if developed in conjunction with effective (and targeted) information interventions, providing relevant information to those groups in the population who will benefit most from a particular innovation.

3.4 The agricultural biotechnology industry

Introduction of legislation that enables developers to privatise intellectual property rights in agricultural biotechnology has been followed by a consolidation process that has worked to the advantage of a few large companies whose research tends to focus on major crops and large markets. Yet there may be potential gains in agricultural biotechnology for niche products and specialized agriculture in high-income countries. To meet these demands, there may be a role for public initiatives to promote research and applications that are not attractive to the major corporate players but have potential for a significant impact on food security or sustainable production.

A serious Swedish thrust in agricultural biotechnology must be planned in the context of the established advantages of some other countries and multi-national corporations in some major sectors of biotechnology, and the evolving regulatory regimes around the world. It must be addressed to Swedish environmental conditions, the structure of Swedish agriculture, the perceptions and attitudes of Swedish consumers and citizens toward food, agriculture, and landscape, and any comparative advantages that Sweden may enjoy in the area of agricultural research and technology.

4. Definition of biotechnology

In this context, biotechnology is defined as the use of genomics technologies, breeding and genetic markers, genetic modification (GM), as well as technologies for cell and tissue culture and animal cloning.

5. Vision statement

The programme will contribute significantly to the sustainable development of Swedish agriculture and food systems by utilizing the most appropriate biotechnological tools in ways that are societally acceptable. As a result, innovative new products, services and knowledge will strengthen Swedish competitiveness.

6. Scientific issues and key research questions

The research programme envisaged here will be conducted by a consortium of research organizations capable of completing a major programme of interdisciplinary research covering the four major themes elaborated below. Contributions from the natural sciences, the social sciences, and ethical inquiry will be integrated to identify and develop promising directions for a Swedish programme in agricultural biotechnology.

The four major themes of the proposed programme are closely linked. A common thread is how Sweden can become more competitive and how the science can catalyse innovation in business, industry, policy and regulation over the coming decades. In order to set priorities, it is important to have a clear vision of how the Swedish food system might be expected to develop. Foresight analysis could provide a common framework for the necessary integration across disciplines and definition of priorities for research. Although forestry is excluded from the new programme, any scenario exercise needs to consider competing uses for available land, including the future of forests and forestry, which are important in the current, and future, Swedish economy.

A systematic review of current knowledge, perhaps including meta-analysis of research results where sufficient data exists, could provide a framework for assessing future research directions. To develop and establish these "ways forward" for increasing competitiveness and reducing the environmental impact of agriculture and the food chain in Sweden would be valuable for its own sake, but could also provide a Swedish comparative advantage in the knowledge sector, i.e. exporting Swedish agricultural and food biotechnologies.

Ensuring a sustainable Swedish food supply will also require the availability of healthy foods. Thus, research may address approaches to ensuring sufficient availability at a low price of foods conducive to health. In addition, novel functional foods (for example, those which have been biofortified, or deliver other human or animal health benefits) may be developed through the use of appropriate biotechnologies.

The development and application of emerging food technologies requires careful analysis of consumer perceptions and attitudes (including perceived risk and benefit perceptions, and perceptions of associated uncertainties) and consumer priorities for specific benefits, which should be incorporated early enough in the innovation process to influence final product delivery. Research focused on enhancing the effectiveness and impact of public and stakeholder engagement in the process of technology implementation and product development is needed, and requires interdisciplinary collaboration between social scientists, natural scientists, ethicists and food technologists.

Opportunities for Swedish competitiveness in the agricultural biotechnology sector of the knowledge industry extend beyond products and technologies to include regulation and policy. Sweden could aspire to leadership in developing regulatory frameworks that protect against potential risks to human health and environment without unduly impeding technological innovation, and biotechnology policy frameworks that serve as models for Europe and beyond.

The four themes are elaborated in more detail below. Within the themes, the ideas offered are intended only as suggestions – to be more explicit, the suggestions are not intended to provide a checklist of tasks expected to be included in proposals.

6.1 Biotechnologies for future Swedish agriculture

Sweden's early entry into research focused on sustainable production systems coupled with an enviable, international reputation for environmental protection are reasons to believe that Sweden could develop a novel niche for the application of biotechnologies in sustainable food systems that would find international resonance. This element of the programme will provide research to underpin the development of advanced biotechnologies based on the evolving techniques of gene discovery and application through breeding programme. With a 40-year perspective it is necessary to target production systems using inputs efficiently using the best available science, technologies, crop plant and farm animal species and varieties/races.

Increased production per unit is an important global objective in the coming decades, so developing ways forward for reducing the environmental impact of production practices on the food chain in Sweden will be an attractive package for export of Swedish agricultural biotechnology. Technologies that promote human and ecological resilience are essential. Changes of land-use and landscape shifts may not only affect the public`s perception or appreciation of landscapes, but could also lead to substantial changes of flora and fauna including a loss or substantial and destructive shift of biodiversity even including extinction of species. Such detrimental changes need to be foreseen and avoided.

Since about 45% of the arable land in Sweden is used for animal feed and animal products are almost 50% of the economic output from Swedish agriculture, food and feed crop production must be considered together with forage and animal production as a whole. The improvement of aquaculture through biotechnology is also included in this programme although forestry is not. It is recognized that agriculture and forestry are closely associated geographically, economically and socially so that in any scenario exercise, the future of agriculture will be considered in that context.

The impact of new biotechnologies can be seen well beyond the farm gate and will affect other important elements of the food system such as prevention of damage of fresh produce during transportation, ease of processing and retention of desirable organoleptic properties in processed foods, attractiveness in shops and restaurants, and development of affordable functional foods of high nutritional benefit.

The key question of this theme in the programme is: What can biotechnological tools contribute to food systems and where might Swedish competitive advantage lie in this field? Emphasis will be put on the potential value and use of biotechnologies for Swedish crop production, animal husbandry, fisheries and the Swedish food sector as a whole.

Key research issues and examples of research questions involving biotechnology include:

- Enhance diagnostics and vaccine development to reduce infectious diseases of farm animals and disease "costs" so that energy can be used, e.g., for growth, milk or egg production.
- Use reproductive biotechnology techniques like sexing, embryonic genomics, etc. for improved reproductive performance of farm animals; poor reproductive performance (long generation intervals or blunt breeding procedures) costs energy without returns.
- Genomic selection, ideally combined with reproductive biotechnology, for a more efficient selection of sustainable and high performance farm animals, resulting in a better input/output ratio per unit produced food.
- Combining animal genomics and physiology with feed selection for better feed conversion resulting in more efficient use of energy and essential micronutrients.
- Advanced genome analysis of (crop) plants to unravel the genetic and physiological basis of major input traits (e.g. stress resistance) and output traits (product quality) of crops relevant to Sweden's agricultural sector, e.g. with particular protein, starch or oil contents and compositions.
- Increasing the yield potential of crops particularly adapted to or prevalent in Sweden by marker-assisted breeding, genomics-based selection or genetic engineering which is considered essential for major improvements.
- Breeding crop plants adapted to Sweden for generating high-value, agricultural products such as vegetable protein as supplements for human nutrition (e.g. grain legumes, oilseed rape).
- Adaptation and domestication of valuable native "Swedish" plant species for the production of novel products (e.g. nutraceuticals, pharmaceuticals, new materials), by combining different strategies, including molecular breeding and GM technology.

6. 2 Biotechnologies for sustainable use of resources

In Europe, there is widespread debate as to how land should be used to deliver the multiple services (e.g. food, forest products, water purification, recreation etc.) required of it, and some land that was formerly in agricultural production might be used for other purposes. Whatever production system is employed, though, to produce crops and animals, there is a need to use resources efficiently and to minimise off-site effects which may compromise the ability of land and water bodies to deliver other services.

In the past 60-70 years, the increased crop yields obtained in many parts of the world have been accompanied by increasing inputs of chemical compounds including fertilisers, pesticides and herbicides. Such compounds are dependent on fossil fuels either directly as a feedstock for synthesis or indirectly as energy during the manufacturing process or both. As fossil fuels become less easily extractable and as agriculture is called on to make its contribution to reduce the emissions of greenhouse gases, there is a growing demand to examine alternative ways of achieving the levels of yield obtained using chemical compounds and simultaneously improving the efficiency with which all inputs (energy, water and chemicals) are used in agricultural production systems. Life cycle assessment of food systems to highlight the major energy and carbon costs is being developed as a research tool, and could assist in the selection of sustainable production practices and in systems that both use resources more efficiently while simultaneously reducing waste.

Globally, prices of fossil-fuel energy are projected to rise so that nitrogen fertilisers are likely to become more expensive. Sources of high-quality rock phosphate are also being depleted through mining, and competition for water for domestic and industrial use will both have impacts on agricultural systems. In the context of Sweden, water scarcity is probably not a major issue but other inputs are widely used.

Biotechnologies that deliver new genotypes with durable disease resistance or greater physiological efficiency of nutrient use, or both, provide means to take this agenda forwards but, in addition to these individual component approaches, research that adopts a systems approach to improve agricultural production and food systems will also be required. For example, approaches that result in the development of biologically-based rather than chemically-based systems will be welcome as will interventions in food systems based on life cycle approaches to reduce energy use and the production of greenhouse gases.

Forage crops are widely grown in Sweden and underpin systems of animal production. Past research has focussed on the development of fodder and feed mixes to enhance production but, in future, this approach should broaden to develop products that will serve to improve the organoleptic or health qualities of the final product, that use nutrients more efficiently and that minimise greenhouse gas emissions such as methane. In addition there are opportunities to develop novel fodder crops that maintain animal health by in-plant production of medicines and vaccines.

Work should focus on the use of biotechnologies to develop biological processes and systems to either replace current chemical inputs with biologically-derived inputs in crop production systems, or increase the efficiency with which inputs are used in crop and animal systems. Whichever route is taken, control of diseases and pathogens is a key step in reducing inefficiency in the use of resources, and the technologies developed must deliver no less value than the present system.

Key research issues and examples of research questions involving biotechnology include:

- The use of biotechnologies to identify and deploy traits, genes and markers that can be employed in breeding programme to deliver genotypes (varieties and races) that use nutrients more efficiently.
- Biotechnological approaches to the development of genotypes (varieties and races) with durable disease resistance.
- Development of new biotechnologies to modify rhizosphere behaviour and optimise the benefits arising from symbiotic and non-symbiotic organisms. Such biotechnologies could increase fixation of nitrogen, reduce emissions of nitrous oxide, increase the bioavailability of soil phosphorus, and improve disease resistance.
- Biotechnological approaches to the development of vaccines in grass and other fodder crops to sustain healthy animals, and the modification of feed quality to improve P utilisation and reduce methane emissions in animal production systems.
- Reducing energy use and carbon emissions in the food system, and the development of crops and cropping systems that enhance the sequestration of carbon.
- The development of integrated systems of environmental performance of food systems so that trusted and robust accreditation systems can be developed and consumers can make choices about sustainability and quality assurance.

6. 3 Consumer choices

Research is needed to understand how attitudes towards emerging food technologies directed towards improved sustainability in the food supply are developed, their relation with actual food choice behaviours, and if and how communication and other interventions influence consumer selection of foods in the direction of increased sustainability. In addition, other factors such as the organoleptic properties of foods, and household economic factors need to be assessed as potential determinants of sustainable food decisions. For example, consumers' willingness to pay for sustainable food produced using biotechnologies, or their tendency to purchase the same products repeatedly in the retail environment independent of production attributes, may represent important barriers to the development and implementation of a commercialisation trajectory for novel, biotechnologically produced, sustainable foods.

An important issue relates to how consumer perceptions and attitudes translate to actual behaviours regarding sustainable consumption. A successful commercialisation trajectory linked to biotechnology and sustainable production will depend on foods developed aligning with lifestyle requirements and sensory preferences of consumers. Given that not all food choices occur in the domestic environment, it is also important to understand how to effectively communicate relevant food choice information across the range of Swedish retail and catering environments.

An important part of any development and commercialisation trajectory involves ensuring that consumer priorities for specific benefits are incorporated early enough in the innovation process to influence final product delivery. Research focused on enhancing the effectiveness and impact of public and stakeholder engagement in the process of technology implementation and product development is needed, and may require interdisciplinary collaboration between social scientists, ethicists, natural scientists and food technologists, as well as the food industry, if appropriate. Issues to be considered may include biotechnology applied to production process, as well as end-product attributes and consumer priorities for these, as well as issues related to the Swedish agricultural landscape and ethical concerns.

From the consumer health perspective, there is a requirement for studies of how the use of breeding and other forms of biotechnology could improve the nutritional quality of food products. A specific area of interest here will be on personalised nutrition focused on the needs of population groups with (genetic or phenotypic) risk profiles, which may be explored by nutrigenomics and related technologies. Concerns about potential negative side effects of the resulting products on good eating practices and food habits may also need to be understood. An important issue relates to consumer priorities for, and acceptance of, functional food attributes. This will link to the development of high value products which will also contribute to Swedish economic development and competiveness.

Key research issues and questions include:

- In order to map existing knowledge, and gaps in understanding regarding consumers and biotechnology applied to sustainable food consumption, systematic review of previous research is required (including meta-analysis of existing data if available and appropriate). This will provide information about how perceptions and attitudes vary across different consumer segments according to predictable individual differences, and with time, as well as identify gaps in knowledge, in particular in relation to recent developments in the area of biotechnology. Of particular interest is the interrelationship between perceptions, and food choice behaviours with respect to biotechnology, sustainability and food production.
- Consumer decision-making about food choices is likely to depend on simultaneous consideration of various food attributes (for example, risk and benefit perceptions related to sustainability and health, attitudes to biotechnologies, cost considerations, trust in key food chain actors, sensory factors and food choice contexts). The extent to which different determinants contribute to sustainable and healthy food choices, and how these vary across the Swedish population, is needed if targeted intervention strategies are to be developed and implemented to encourage sustainable, healthy food choices. Assessment of consumer willingness to pay for more sustainable, or healthier, foods, developed by the use of biotechnologies, is also required if an effective commercialisation strategy is to be developed.
- Sustainability claims, in addition to health claims, need to be delivered across a range of food choice environments (for example, in the retail environment, in restaurants, and in school canteens). Due consideration of process (which biotechnology application is used) and impact (in terms of improved sustainability, health, or other benefit) is required as part of the development of labelling strategies, as well as how labelling information complies with existing and emerging) regulatory requirements.
- It is important to understand the various kinds of concerns which may underlie consumer and public attitudes to applications of various forms of biotechnology in food production and to be able to present different ethical frameworks for allowing these attitudes to be discussed.
- Consumer and other end-users of biotechnology applied to sustainable food production need to participate in the technological innovation process. Information about their priorities and preferences for innovations relevant to sustainable food production is needed. More effective approaches to public participation need to be

developed, and methods identified to explicitly demonstrate how outputs are utilised in biotechnology application and product development.

6. 4 Developing Swedish competitiveness

For Sweden, competitiveness refers to success in the marketplace, improvement in the Swedish quality of life, and a positive Swedish influence on policy and regulation in Europe and the rest of the world. A serious Swedish thrust in agricultural biotechnology must be planned in the context of the established advantages of some other countries, the dominance of multi-national corporations in some sectors of biotechnology, and the evolving regulatory regimes around the world. It follows that Sweden's best opportunity may be to succeed as a serious niche player in areas where it faces special challenges or has special advantages, and that are compatible with its society and culture. Sweden should seek to identify niches underserved by corporate biotechnology where a Swedish comparative advantage exists or can potentially be developed.

The idea of Sweden becoming a serious niche player in developing agricultural biotechnologies raises several kinds of research questions:

- Is this a goal that should be given high priority given the needs, the potential for success, and the alternative opportunities available to Sweden? How can the appropriate niches be identified? What resource commitments and basic infrastructure for research in agricultural biotechnology should Sweden provide? How can creative approaches to financing the necessary investments be developed? What roles might be played by public-private partnerships and creative approaches to intellectual property rights? How can entrepreneurship in agricultural biotechnology be encouraged, and how can a Swedish agricultural biotechnology programme be designed to stimulate the development of businesses with international competitiveness?
- How can niche biotechnologies addressed to the particularities of the Swedish case be identified and developed? What traits in what crops, animals, or products should be given high priority for introduction, given identified needs and the potential for success? How can productivity be enhanced for crops and food animals where Sweden enjoys an advantage, and what traits should be introduced to relax the constraints that impact Sweden disproportionately (e.g. traits that increase production despite a short growing season)?
- How can agricultural biotechnologies be developed to improve the Swedish public goods environment and quality of life? How can particularities in what and how Swedes value the environment and quality of life be identified and turned into opportunities for a Swedish agricultural biotechnology sector?
- Can Sweden develop smart ways of using biotechnology and export the knowledge (know-how and technologies) rather than the agricultural products?

New approaches are needed for the governance of modern biotechnology for sustainable food production. Public-private partnerships may have a role in marshalling the necessary intellectual and economic investments. If intellectual property rights to new niche developments remain in public (or public-private partnership) hands, they may help finance further research and development. New forms of stake-holder involvement and public participation may allow biotechnology development that is more stakeholder-driven and thereby more attuned to Swedish society and perceived as more acceptable. Key research issues and questions include:

- What approaches might advance public and consumer acceptance of agricultural biotechnologies: focusing on more acceptable products (for example, food products with medicinal properties, and food products and/or production processes with reduced environmental impact), providing more complete information and more opportunities for consumer choice, and/or more inclusive and effective public participation in decision-making processes? What other strategies might be added to this list?

To reduce the risks of allergies and other health problems, as well gene drift, weed resistance and biodiversity depletion, GM products are regulated with respect to field trials and final market introduction. While too little regulation may expose us to too much risk, too much regulation, or the wrong kind of regulation, may deny us the benefits of innovation. It follows that regulations should be designed to provide adequate protections against risk, instil consumer and public confidence and, at the same time, avoid unduly restricting technological development and raising its costs. Sweden's adherence to EU legislation must be taken into consideration in the research proposal. Key research issues and questions include:

- How can regulatory approaches be designed that achieve a better balance between regulatory costs and delays on the one hand and serious risks to human health and environment on the other? What are the regulatory constraints and what research is needed? Does a regulatory focus on biotechnology products rather than processes advance this objective?
- How can inclusive governance procedures be developed, to effectively include stakeholders and end-users in framing risk-benefit assessments, developing more appropriate regulatory approaches, and setting the overall innovation strategy for sustainable agricultural biotechnology?

Gaps, overlaps, and inconsistencies among nations in policy for agricultural biotechnology may present opportunities for Swedish leadership. How can more effective, efficient and equitable policies be framed? How can inclusive governance processes be adapted to development of policy frameworks for agricultural biotechnologies?

7. Proposed Scope of a Mistra Programme

The appropriate use of biotechnologies in the agricultural sector and food system can benefit Swedish competitiveness by developing quality products and services while minimizing environmental impact in the move towards a sustainable society. For that reason, Mistra is planning to finance a full research programme on "Sustainable Development of Agriculture and Food Systems using Biotechnology as a Tool" for a total of eight years providing a mid-term evaluation is positive.

Sustainable development will underpin the approach and consider the integration of environmental, economic and social sustainability. Proposals should include natural and social sciences as well as ethical inquires and take a food systems approach considering relevant aspects of the food chain between farm and fork (e.g., producers, food industry, retail and consumers).

Mistra is looking for innovative solutions for the future aiming at a 20-40 year-long time perspective. The programme should catalyse significant change and contribute substantially to the development of innovation in Swedish agriculture and food systems. Other important aspects of the proposed programme are:

- It is important to consider Swedish competitiveness both with regard to sustainably driven business development as well as knowledge support for policy-making. Swedish competitiveness should be increased through the development of new innovative products and services and scientific knowledge that will provide leadership in an international context.
- While the food system is increasingly global, the emphasis of the programme will be on Sweden.
- In order to focus the programme, and taking other Mistra programmes into account, forestry and forest products will not be included. The use of biotechnologies for production of materials and energy will also be excluded.
- The expected outcomes of the programme should address how the result will be translated into products and/or services. Outcomes could also address policy needs in the private and public sector. This will require proposals to demonstrate how institutions informing and developing policies and business/industry will be engaged both in the detailed planning for the programme and its implementation.

Annex 1

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Annex 2

Terms of Reference for the Mistra Committee "Biotech Food" (Dnr FOR 2007/89)

Mistra

The aim of the foundation is to support research of strategic importance for a good living environment. The foundation shall promote the development of robust research environments of the highest international class that will have a positive impact on Sweden's future competitiveness. The research shall play a significant role in solving major environmental problems and contribute to the development of a sustainable society. The potential for achieving industrial applications shall be realised as far as possible.

Mistra distributes about SEK 200 million a year to environmental research. Mistra funds and organises research aimed at solving strategic environmental problems. A Mistra programme is considered a success when scientifically advanced research has been put to practical use in companies, authorities or other organisations. Mistra funds about 20 major programme, each of which should have a time span of between six and eight years. Major investment in interdisciplinary research programme stimulates innovation, new options and new forms of cooperation, benefiting both Swedish environmental research as a whole and Sweden as a nation.

Why Mistra take an interest in biotechnology

Mistra has for several years invested in inter- and transdisciplinary research in biotechnology. Examples include the Mistra programmes Greenchem, PlantCom, MASE, DOM and MAT 2 (www.mistra.org). Mistra would like to invest even more in this area due to the potential benefits we foresee for the use of biotechnology. Our hypothesis is that application of biotechnology in various components of the food system can contribute to sustainable development of the environment and society. We foresee that Swedish scientists and companies can contribute to our scientific understanding of the safe use of biotechnologies both at national and global levels.

There are several future challenges to ensure food security such as increase of global population, climate change, increased competition for the use of land, water and other resources (fertilizers, pesticides etc) and lifestyle change leading to new consumption patterns. Biotechnology can offer partial solutions to address these challenges. However, there are barriers towards applications of biotechnology in various components of the food system. There are social and ethical issues, including public acceptance of new technologies, potential health risks, regulatory requirements as well as lack of public investments in biotechnological research, etc. Failing to approve new technologies that benefit consumers carries its own set of risks. Undesirable conventional agricultural production practices may result in overexposure to chemical pesticides or inefficient pest management abatement, negatively impacting food safety.

Mistra Decision
The Mistra Board of Directors decided in June 2009 to develop a programme proposal about biotechnology for the environment including social and ethical aspects of applying biotechnology. Further discussions resulted in a focus on agriculture and food systems. It was also decided that the definition of biotechnology shall be broad. The Planning Committee is appointed to assist Mistra in the development in a call for proposals on possibilities and constraints of using biotechnology in various components of the food system.

Overall goals
Mistra's goals for a new programme will be to:
- Contribute to sustainable development of agriculture and food systems using biotechnology as a tool. The benefits must be substantial for the environment and humankind while the disadvantages and risks are limited.
- Develop excellent research environments and build capacity in Sweden especially regarding the use of biotechnology for sustainable food systems based on the best natural and social science noting also the need to consider, as appropriate, humanities, e.g. philosophy.
  Increase knowledge of the advantages and constraints for the use of biotechnology in support of the private sector and policymakers with focus on risk management and public perception.

Framework for a new programme
The programme "Mistra Biotech Food"
- shall address biotechnology as a tool for improvement in agricultural and food systems;
- shall specifically address future scenarios and challenges in a changing world with increased population, change of lifestyle, climate change, change of land-use, etc.;
- will look beyond today's problem and address solutions for the next decades;
- shall strengthen Swedish competitiveness, but be considered within a global context;
- must be interdisciplinary and include natural sciences, social science and humanities as appropriate. Social and ethical aspects of biotechnology need to be addressed;.
- must engage the international scientific community; and
- must be conducted with a participatory approach involving users (companies producing food and selling food, consumers, policymakers, authorities etc.).

Assignment
The Committee is appointed to develop
- A proposal for a Mistra programme call for proposals in the area of biotechnology and food systems; and
- A summary of the current scientific understanding to support the Mistra call for proposals including key references to further inform the scientists that wish to apply for Mistra funding based on the call.

Membership

Mistra will appoint a Planning Committee of 5-6 members with expertise from major disciplines necessary to develop a convincing call for proposals. The Planning Committee will be chaired by Professor em. Thomas Rosswall and Britt-Inger Andersson will be the key contact with Mistra.

Remuneration of the members of the Planning Committee will be decided on by Mistra.

Timetable

The assignment starts in early 2010 and ends when the call is announced in December 2010/January 2011

- First planning meeting (2 days) late April or May in Stockholm
- Second planning meeting (2 days) in September in Stockholm
- Mid-October submission of the report to Mistra

Ola Engelmark	Britt-Inger Andersson
Chief Executive, Mistra	Director of Idea Development

Annex 3. Programme for seminar on 16 December 2010 and list of participants.

Sustainable Development of Agriculture and Food Systems using Biotechnology as a Tool

Date and time: 16 December 10.00-15.30 incl. lunch
Place: Mistra, Gamla Brogatan 36-38, Stockholm

Mistra is planning a possible new research programme on "Sustainable Development of Agriculture and Food Systems using Biotechnology as a Tool". It has appointed an International Planning Committee.

To further define the scope of a possible new programme you are invited to attend a seminar to discuss the preliminary conclusions of the Planning Committee. A first draft description developed by the Planning Committee is distributed, see *"Background paper version 1"*. The result from the discussions on 16 December will be of major importance shaping the final document. Mistra has also commissioned a report based on scientific literature references given by the Planning Committee. See the attached report *"Biotechnology for Sustainable Food Systems – a brief summary"*, A. Nilsson 2010.

Programme: Moderator Thomas Rosswall

1. Welcome (Thomas Rosswall)
2. Self-introduction of members of the International Planning Committee and participants
3. Why Mistra wants to invest in this area (Britt-Inger Andersson)
4. Introduction of the possible research areas, issues and discussion
   10 minutes per research area and 20 minutes discussion

- Introduction (Thomas Rosswall)
- Biotechnology for future Swedish agricultural landscape (Thomas Rosswall)
- Biotechnology and food security (Lynn Frewer)
- Sustainable use of resources (Thomas Rosswall)
- Waste management in the food systems (Britt-Inger Andersson)
- Inclusive governance for sustainable biotechnology in the food system (Peter Sandøe)
- Biotechnology for healthy foods (Peter Sandøe)
- Consumer choices, food, sustainability and health (Lynn Frewer)

5. Conclusions

Welcome!
Thomas Rosswall Britt-Inger Andersson

Participants

Sven Ove	Hansson		KTH
Thomas	Rosswall		CGAR Consultative Group on International Agricultural Research
Helena	Åberg		Göteborgs Universitet
Heléne	Ström		Jordbruksverket
Peter	Sandoe		Köpenhamns Universitet
Bo	Gertsson		Lantmännen SW Seed
Leif	Bülow		Lund University
Peter	Söderbaum		Mälardalens högskola
Margareta	Hökeberg		MASE Lab
Christopher	Folkesson Welch		MASE Laboratorierna
Britt-Inger	Andersson		Mistra
Britt-Marie	Bertilsson		Mistra
Lars-Erik	Liljelund		Mistra
Magnus	Börjeson		MistraPlantCom
Klas	Hesselman		SIK
Erik	Andreasson		SLU
Jan	Bengtsson		SLU
Torbjörn	Fagerström		SLU
Sebastian	Håkansson		SLU
Ulf	Magnusson		SLU
Anders	Nilsson		SLU
Ingrid	Öborn		SLU
Per	Sandin		SLU
Sten	Stymne		SLU
Ingmar	Börjesson		Stiftelsen Cerealia FoU
Maria	Magnusson		Uppsala Universitet
Lynn	Frewer		Wageningen University

Annex 4

Biotechnology for Sustainable Food Systems — a brief summary by Andreas Nilsson, Vetenskapsjournalisterna

Introduction

This paper is an overview of current scientific understanding in the field. It is based on references supplied by the International Idea Planning Committee for *Biotech Food Systems* (preliminary name), a Mistra potential research programme. No exhaustive overview of all relevant research in the field is feasible and, for example, this paper covers the uses of biotechnology in livestock production only briefly.

Our agricultural systems produce more food than ever before. Plant breeding has resulted in new high-yielding crops. Combined with agrochemicals, irrigation and machine-intensive practices, they have given farmers a steady rise in productivity. Cereal yields, for example, have tripled over the past 50 years in many parts of the world, including Asia and Latin America, according to the Food and Agriculture Organization of the United Nations (FAO). Despite this 'green revolution', around one billion people are hungry and undernourished.[25, 28] Productivity benefits have not reached the farmers, especially in Africa, who need them most.

Demand for food is, moreover, set to rise further. The world's population is forecast to reach nine billion by 2050. According to FAO estimates, this will involve a rise of at least 70% in global food demand. However, total arable land can hardly be increased to any great extent without causing environmental problems, such as accelerated deforestation and further pressure on biodiversity. Any increase in food production will therefore have to come largely from higher yields on present-day agricultural land.[28]

Besides population growth, there are several other drivers of food insecurity. Rising income and changing consumption patterns in developing countries are boosting demand for livestock products; the World Bank predicts an 85% rise in demand for meat by 2030. Climate change could cause more harvest variability. Productive soils are being damaged by industrial pollution and physical compaction. There will also be more competition for agricultural land owing to urbanisation and rising demand for biofuels. All these trends are exerting pressure on food prices and may exacerbate global inequity.

Moreover, what people need is a healthy diet, rather than a mere increase in calorie intake. Besides giving higher yields, agriculture must meet the challenge of malnutrition in large populations due to consumption of staple crops, such as rice or cassava, of low nutritional value. Fruits, vegetables and animal products that are rich in essential micronutrients are often not universally available. Deficiencies, especially from vitamin A, zinc and iron, result. As many as three billion people are at risk for zinc deficiency, while two billion suffer from anaemia due mainly to iron deficiency and 150 million are deficient in vitamin A.[25]

Concerning environmental impact, agriculture, though reliant on ecosystem services like pollination and crop protection by pests' natural enemies, is a major factor in biodiversity decline. Farming practices are also dependent on heavy machinery that uses fossil fuel, as well as on nitrogen fertilisers based on energy-intensive production that lead to emissions of nitrous oxide. This makes agriculture a major contributor to climate change, accounting for over 10% of global greenhouse-gas emissions.[3]

Societies have the power to meet these challenges, partly by using biotechnology. The World Bank estimates, for example, that gains from biotechnology in terms of improved crop and livestock production can bring increased yields and better nutrition while reducing environmental impact. However, it is equally important to understand, and take into account, economic and social impacts in developed and developing countries alike.

Biotechnological tools used in agriculture

In this context, 'biotechnology' is defined as the use of genomics, breeding and genetic markers, genetic modification (GM), as well as technologies for cell and tissue culture and animal cloning in the food system.

Genetic improvements in crops and livestock are achievable by means of modern breeding technology and GM. Biotechnology can also be used for DNA and gene analysis, providing information that may help in mapping the biochemical and physiological characteristics of various crops and animals.

Examples of biotechnological tools with applications in agriculture are listed below. Some of the technologies concerned build on existing knowledge, while others will require a great deal of further research and development.

Genetic sequencing and profiling tools

Thanks to the introduction of new sequencing technologies, the cost of generating full DNA sequence data for an organism is falling. Ten years ago, the genome of the plant species *Arabidopsis thaliana* was the first to be sequenced. This contributed to a molecular understanding of several plant functions. The genomes of several crops, such as rice, maize, sorghum and soybean, have now been sequenced and genome projects for wheat, potato and tomato are under way. As for livestock, chicken, cow and pig genomes have been sequenced. In conjunction with new methods of assigning functions to genes and high-throughput technologies for analysing proteins and small molecule metabolites, information from genome sequences provides a powerful framework for studying complex biological processes in crops and animals. Coupled with computer analysis, sequencing information permits gene expression profiling of thousands of genes. Used in combination with phenotypic investigations, this information could advance our understanding of interactions between genes and phenotypes in plants and animals.

The complex relationships between genes and phenotypes can also be enhanced by the development of systems biology. Building mechanistic models based on the information from genome sequencing and profiling tools could lead to a broader understanding of complex functions, such as plant photosynthesis.

Tools for improved breeding

Improving the performance of crops by plant breeding includes making defined crosses between genetically distinct parents, testing plant lines for the desired phenotypes and selecting individuals with preferred characteristics that can be developed into crop varieties by further crosses in several stages. However, conventional plant breeding is slow: it takes ten years or more before seeds can finally reach the market. The same problems apply to animal breeding.

Marker-assisted selection (MAS) and similar tools for marking the desired traits on gene level have allowed these screening procedures to be streamlined. This applies especially to traits that are difficult to measure from phenotypes. With MAS, specific DNA strains in proximity to the trait of interest are marked with specific markers. The traits can be either genes or relatively long strands of DNA. After breeding, hybrids are analysed and the markers guide

selection of those that are suitable for further development.
The number of markers for different traits is steadily increasing, and MAS gives greater selectivity and reliability than conventional breeding, which relies on phenotyping alone. Thus, MAS and other similar modern breeding techniques may have a positive impact on crop and livestock development.

Genetic modification (GM)
Instead of more or less randomly mixing genes, as in conventional breeding, GM lets a specific gene or set of genes that are associated with a desirable trait to be selected and inserted directly into the DNA of a cell. Several techniques can be used for the insertion. For example, the gene can be introduced by means of a DNA-splicing bacteria or viruses, or be physically inserted into the cell nucleus with a gene gun.
These methods circumvent the crossing cycle associated with conventional breeding. Novel genes can be introduced either individually or in small groups to develop new plant varieties or livestock with various positive traits. The genes inserted may either be from the same or related species (cisgenics) or from another species (transgenics). In transgenic organisms, new traits not present in the gene pool of the species or its relatives can be introduced. Commercially available GM crops mainly use genes from other species, but more recent developments include the use of cisgenics.

Cell and tissue culture engineering
Several techniques have been developed for growing and manipulating plant or animal cells in laboratories. These methods can be applied in many disciplines of agricultural research. They include screening of traits in cells rather than whole organisms; cell cloning and other techniques for producing large numbers of identical individuals; hybridisation and crossing of distantly related species; and manipulation of cell chromosomes to accelerate breeding. The technologies used for animal cloning are still at an early stage, which is clear from the low success rates. A capacity to reproduce animals that are highly productive or have other desirable traits could be valuable in livestock production.[20]

Constraints on future food production
In the quest to produce more and better food on available arable land without exacerbating environmental stress, there are key global constraints that limit sustainable food production.

Weeds, insects and diseases (biotic stress)
For major crops, estimated production losses due to weeds, insects and diseases are as high as 30–40%, and would be even higher without the various crop-protection practices in use today. Losses also occur in post-harvest storage or during transport, often because of insects or fungal infections, and these losses are estimated at 20% for many crops.[28]
Today's crop protection is dominated by application of various chemicals, as well as some mechanical weed control.
Disease is also a major limiting factor in animal production. It accounts for estimated losses of 15–50% in livestock farming, especially in developing countries.[3]

Abiotic stress and climate change
Various factors, such as heat, drought, flooding and soil salinity, result in reduced or unstable yields. Farmers in developing countries are often more affected by these abiotic stresses than elsewhere, because of greater weather variability and more limited access to irrigation and other risk-reducing technologies.
Climate change will further aggravate the pressures on crops and livestock production. If the variability of rainfall increases, this will exacerbate the risk of drought in many rain-fed

regions. There may also be additional risks of flooding in some regions. Increased temperatures may result in crop losses because pollination is a temperature-sensitive process in many crops and heat stress can adversely affect grain filling.

Declining water resources
Yields of crops are restricted by water in most environments and water availability is also vital for increasing livestock production. Agriculture currently accounts for around 70% of annual use of global freshwater resources according to FAO. Based on presents farming practices and future food demands, water use for crop production will increase by 70–90% by 2050.[3] However, water resources are limited. Water levels in many major regional aquifers and groundwater levels in many regions have fallen to unprecedented levels. Already, 1.2 billion people live in areas affected by limited access to water.[3]

Limited nutrient resources
The availability of nitrogen and phosphorus are crucial determinants of sustainable crop and fodder yields. However, production of synthetic nitrogen fertilisers accounts for a large share of the fossil fuel used in agriculture. The use of fertilisers also results in atmospheric emissions of nitrous oxide, which is an important greenhouse gas. Phosphate rock is a non-renewable resource that will probably, if present trends continue, be severely depleted during this century.[35]
Nitrogen and phosphorus loss from soils into water bodies contributes to eutrophication, which affects ecosystems around the world and is a key factor underlying loss of biodiversity in rivers, estuaries and coastal waters. The negative effects of nutrient losses from land are predicted to double or triple with a doubling of food production up to 2050.[3]

Biotechnology aimed at agricultural constraints

Using biotechnology could potentially raise agricultural productivity significantly and ensure that enough food is available for the growing world population. The annual increase in yield of major cereals, especially rice and wheat, has been slowing over the past 20 years.[25] In managing a yield increase sufficient to keep pace with predicted population development, tapping into genetic knowledge of crops and livestock has a major role to play. Expectations in the industry are high. The agricultural company Monsanto estimates, for example, that maize yields can be doubled in the US by 2030, mainly with the use of MAS and GM. This includes both present-day traits for crop protection and new traits for drought tolerance and other yield-improving traits.[9]
On the other hand, breeding efforts are still needed to produce successful local varieties of new crops that can be brought to market in seed form. Thus, in practice, the 10 years or more between gene discovery and seed sale to farmers would be hard to reduce significantly even by means of GM and MAS, especially for more complex traits than those related to pests and diseases.[1] There are also concerns that new technologies mainly benefit today's industrial agriculture and have a smaller impact on food security in developing countries.[2]
Examples of biotechnology used for future food security are listed below. The aims are durable disease/pathogen resistance and weed control to reduce crop losses, crop improvement for more efficient use of resources and improvements in livestock production.

Durable disease/pathogen resistance and weed control

Crops with better pest and pathogen resistance have the potential for higher yields, while reducing the need for pesticides. Owing to technical and economic constraints, actual losses are higher in developing than in developed countries because of higher pest pressure and often less effective control measures involving chemicals and tilling,. Conventional breeders use varieties or wild relatives in trying to develop plants with natural pest-resistance traits. GM techniques offer new opportunities by allowing a much wider gene pool to be used. Tolerance to certain herbicides (HT) and insect resistance (IR) were among the first GM crop traits to be commercialised. The HT trait comes from insertion of a gene from herbicide-resistant bacteria that makes the plant tolerant to glyphosate and similar herbicides. IR plants express proteins that are toxic to certain insects, such as maize borer in maize, and this trait is derived from bacteria that express these proteins.

Experience of herbicide-tolerant and insecticide-resistant GM crops

Adoption of HT and IR crops has expanded rapidly, with the largest areas under cultivation in the US, followed by Argentina and Brazil.[23]

HT soybeans and HT maize, combined with application of glyphosate, are reported[34] to have allowed farmers to replace some relatively toxic herbicides and to move to minimum or conservation tillage practices. The effective weed control with herbicides has enabled a shift to reduced tillage, thereby reducing soil erosion as well as saving energy. For farmers who grow HT crops, the main advantage has been reduced costs of weed control, rather than increased yields. Weed control relying on a single herbicide has, however, caused nine glyphosate-resistant weeds to emerge in the US since 1996. In the rest of the world only seven glyphosate-resistant weeds have evolved since 1974.[34] This is a cause for concern, since combating these weeds could necessitate a return to tillage and more environmentally harmful herbicides.

IR maize is reported to have reduced insecticide use in the US. Moving away from use of broad-spectrum insecticides means that fewer beneficial insects are killed, thus mitigating adverse effects on biodiversity. IR crops have made higher yields possible, owing to reduced losses and lowered insecticide costs. A few populations of pests have evolved resistance to IR crops, but refuges with non-IR plants, to slow down this process, are being tried by GM farmers.

Future solutions for crop pest control

Many plants are naturally resistant to various diseases and pests, and this trait is often related to specific genes. Conventional breeding is used to transfer resistance from crop varieties or wild relatives to food crops. Biotechnological tools can be used to identify genes associated with resistance and speed up this process. One disease where this strategy is used is UG99, a new form of stem rust that threatens 20% of the world's wheat, in Africa and Asia. Some genes associated with resistance have been identified and screening is under way for additional UG99 resistance traits.[28]

Organisms targeted with various chemicals are likely to develop resistance to them. Careful management is therefore required to prolong the useful life of pesticides. One strategy to mitigate this problem is to make pest adaptation less likely by developing crops with multiple protection mechanisms. For example, several natural resistance genes can be added to crops. Another strategy is to introduce genes for several toxic proteins in IR crops. IR maize expressing six different toxic proteins has been developed. Using mixtures of seeds with different crop protection traits is another solution for preventing resistance arising in weeds and insects.

Profiling tools that afford a better understanding of plants' natural defence systems could be used to develop a novel class of crop protection chemicals, targeted at the plant rather than the pest. Analysis of various plant chemicals could allow those that trigger defence mechanisms in the plant to be identified. This strategy could eliminate the risk of resistance arising in weeds or insects.

It is also worth noting that methods not based on biotechnology could be highly successful. The East African 'push-pull' system, for example, uses agricultural practices to combat moths and the weed striga in maize farming. The method, based on attracting natural enemies to weeds and pests, has boosted yields by 100%.[28] This shows the potential for a better understanding of crops and their role in ecosystems, and agricultural research — including biotechnology — can provide valuable knowledge.

Plant tolerance to abiotic stress

Using biotechnological tools could help develop higher plant tolerance to abiotic stresses such as heat, drought, flooding, cold or soil salinity. New crop varieties could contribute to higher and also more stable yields, especially in regions affected by erratic weather conditions. The first drought- and heat-tolerant GM crops are, for example, expected to be commercialised within the next five years.[25] However, stress adaptation and responses to other relevant threats are controlled by several genes, each of which has a relative small individual effect. This is a challenge to GM and the use of MAS in breeding programmes. There is also an increasing need for rapid crop adaptation to changing climate conditions. Developing cultivars with increased tolerance to abiotic stress and changeable weather conditions, by either breeding or GM, is crucial to mitigate a decrease in yields due to climate change. For maize and soybean, ongoing private breeding programmes using modern technologies could secure high rates of crop adaptation. For other major crops such as wheat and rice, however, no such strong private or public programmes exist.[9]

Drought tolerance

Improved drought tolerance would reduce effects of sporadic water scarcity in rain-fed areas. In breeding programmes aimed at drought tolerance, methods have been developed for modifying such variables as flowering and maturity dates, spike fertility, quantity of dead leaves during stress and canopy temperature. The latter is especially important since it regulates transpiration, which accounts for more than 90% of water loss in plants.[1]

Genes controlling canopy temperature and, in part, photosynthesis and water status have been identified in wheat and could be used in GM and breeding. GM also makes it possible to introduce traits outside the natural gene pool of crops, such as those related to cell-dehydration tolerance or capable of suppressing drought-induced leaf death.

Plant traits based on improved stress-resistant strategies are advantageous in terms of survival. However, they are often associated with a yield penalty in non-stress situations that reduces their value. GM might serve to circumvent this dilemma by permitting introduction of traits that induce stress tolerance only in response to actual drought.[1]

An indication of potential benefits is shown in estimates of future effects in research on drought tolerance in eight low-income countries, both from GM and conventional breeding.[18] Yield increases are presumed to be substantial for maize, wheat and rice, leading to benefits such as lower production costs for farmers and lower prices for customers. Drought tolerance is also expected to bring considerable benefits in terms of reduced yield variability, especially in India and Bangladesh.[18]

Submergence tolerance

Many crop development projects using MAS indicate that it is an approach that will be increasingly important in breeding for tolerance to abiotic stress, as genome-sequencing data become available for more crop plants. One example is development of submergence-tolerant rice. The major genetic determinants of flooding tolerance have been identified in rice. Based on this information, MAS has been employed to develop flood-tolerant varieties.

For example, a gene from flood-tolerant rice has been bred for in other varieties, resulting in improved yields on more than 15 million hectares in Asia.[27]

Tolerance to salt and other undesired minerals

High concentrations of some mineral elements in soil can inhibit plant growth and reduce yields. These minerals include manganese and aluminium, which can occur in acid mineral soils, while sodium and chlorine occur in saline soils. For crop production on these soils, expensive measures are needed to mitigate falling yields. Crop varieties that can tolerate these minerals would bring benefits. For example, MAS is being used to develop salinity-tolerant rice and is estimated to save several years in the breeding cycle.[2]

The presence of aluminium in soil solution inhibits root growth and is often overcome in resistant plants by the release of organic acids that bind with the metal ions. This is a possible trait that could be enhanced by genetic manipulation. There are also promising examples of GM lines with salinity tolerance. Similar processes targeting increased tolerance to other undesired soil minerals could be investigated.

Crop improvement: higher yields from available water and nutrients

There is often a major difference between actual and potential yields, owing to agronomic practices, low input rates and unfavourable weather conditions. For example, the potential maize yield in the US is estimated at 25 tonnes per hectare, while the mean US yield is 9.5 tonnes and the mean global maize yield is 4.9 tonnes per hectare.[9] However, further rises in productivity in maize and other crops must be achieved without use of inputs that cause negative environmental consequences. A key to this is using biotechnological tools to develop cultivars and crop husbandry practices that use water and nutrients more efficiently.

In conventional breeding, grain yield and a number of secondary traits for higher yields, such as plant height, days to maturity and disease reaction — traits that are quite easily measured and evaluated — have been selected for. Analysing these components of yield in high-yielding lines shows that several genes are involved, and that they are often negatively correlated with one another. For example, an increase in grains per plant often leads to reduced grain weight. Biotechnological tools used in combination with plant physiology research can help understand these correlations and show how to exploit the full potential of different crops.[1, 36]

More crop per drop of water

For most crops and in many environments, yield is restricted by water availability. Thus, ensuring an adequate water supply for plants during important developmental stages is vital for increasing food-crop production. Productivity per unit of water must rise, and traits resulting in more 'crop per drop' could, for example, reduce water requirements in irrigated farming.

Agronomic and engineering approaches, as well as the use of biotechnological tools, are required to develop more water-efficient species and cultivars. Yields are determined by the balance between water loss through transpiration, how efficiently plants use the remaining water for biomass production and, finally, how much of the biomass ends up in the grain. In breeding, the time of flowering is a very important physiological trait. It can be used to identify an optimal balance between water use, leaf development and grain filling. Conventionally bred wheat that uses water more efficiently is available in Australia, demonstrating 10–15% higher harvests.

Another strategy is using the efficient C4 photosynthetic pathway in some drought-tolerant crops, such as maize and sorghum. It uses less water and energy per unit of radiant energy assimilated, and if the C3 pathway in rice, for example, could be transformed partly or fully to the C4 pathway, water use would be more efficient and yields would rise by an estimated 50%. A transfer of five bacterial genes to a C3 plant has been reported to mimic some of the effects of the C4 pathway, such as production of more biomass and harvesting of light energy.[28]

More efficient use of nutrients

Widespread use of synthetic nitrogen fertilisers and mining of phosphate for agriculture have hade adverse environmental impacts in many places. At the same time, crop production in developing countries often suffers from nutrient deficiencies. Thus, crops and improved management practices that achieve higher yields with more efficient use of nitrogen and phosphorus would be highly desirable.

In the longer run, GM techniques could help improve nutrient efficiency and yield potential in crop plants. Experiments with transgenic plants have, for example, shown promising results for genes regulating processes for leaf ageing and remobilisation of nutrients to seeds. A number of genes associated with the use of nitrogen, phosphorus and potassium have been identified, and field trials of crops with enhanced nitrogen-use efficiency are under way. Tolerance to phosphorus deficiency is also being bred for with MAS.

Another strategy is using nitrogen fixation to convert atmospheric nitrogen into ammonia. Soybean and other legumes have symbiotic soil bacteria with this trait, making these plants self-sustaining in nitrogen. Nitrogen fixation might be valuable if it could be transferred to other crops, thereby reducing the need for fertilisers. Either plants could be modified to make them symbiotic with nitrogen-fixing bacteria or the genes involved in the fixation process could be transferred directly to the plant.

There is also a growing genetic understanding of the architecture of root systems. The metabolic cost of building roots can exceed 50% of daily photosynthesis.[22] Thus, plants with a root system that acquires water and nutrients efficiently will have better resource economy, leaving more energy available for plant growth and ultimately grain production.

Breeding to optimise root systems could give higher yields in low-input farming and lead to more efficient uptake of fertilisers in high-input farming, resulting in less leaching of nutrients. For example, in low-fertility soils, plants with shallow roots in the topsoil with more root hairs have been shown to acquire more phosphorus.[22]

Interaction with microorganisms in proximity to plant root systems is also crucial for yield and nutrient efficiency. Crop improvement could be targeted at the genes that regulate the release from roots of protons, organic acids or enzymes that influence interaction with soil microorganisms. This could make phosphorus more accessible, minimise plant stress and encourage interaction with beneficial microorganisms. Enhanced plant growth could also be achieved by using GM aimed at soil bacteria that can, for example, express genes for degrading cell walls of fungal soil pathogens or helping plants degrade the ethylene they induce under abiotic stress.[29]

Traits for perennial plants and asexual reproduction

Biotechnology could also help improve fundamental crop development. For example, most of today's food crops are annual. GM techniques could use expanding genetic knowledge about regulation of plant vegetative and floral cycles. If annual crops could be converted into perennial plants they would store more carbon, use water and nutrients more efficiently and minimise some husbandry practices and their impact on soils. Programmes aimed at breeding perennial wheat, sorghum and sunflower are in progress.

Hybrid seeds often show a higher yield than inbred crops. Exploiting this 'hybrid vigour' is complicated, since it often requires a new cycle of hybridisation for each round of seed production. Asexual reproduction of seeds occurs naturally in some plant species, resulting in offspring that are exact genetic replicas of the mother plant. This trait could be introduced in major crops like wheat, potato and cassava, building on some promising experience from the use of MAS in maize breeding for asexual reproduction.

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Improvements in livestock and fish farming

Use of biotechnological tools in livestock production and aquaculture is also crucial for future food production. To bring about a sustainable rise in meat and dairy production, available resources must be used more efficiently. As in crop development, the same issues of genetic improvement, efficient resource use and protection from diseases apply. However, animals' often more complex genetics and longer life cycle bring additional challenges. Animal welfare is also an essential concern to take into account.

Livestock production with less environmental impact

Today, large areas of farmland are used for producing animal feeds and around one-third of the global production of cereals is used in livestock farming.[15] The ratio for energy conversion of animal feed to meat is, for example, 1.8:1 for chicken and 5:1–10:1 for beef.[3] Biotechnological measures can be targeted at improving animal feeds by, for example, giving them low phytic-acid levels that minimise phosphorus levels in manure.[28]

Biotechnological tools have also provided genome maps for major livestock species and MAS has, for example, been used in breeding for increased litter size in pigs. Other desired traits in livestock breeding are high growth rate and copious milk production. GM is also used, for example, to develop transgenic animals with improved digestibility of feed, with lignin and other fibrous material being the main targets. In Canada, transgenic 'Enviropigs' have been developed. These pigs' salivary glands secrete the enzyme phytase, which permits better digestion of plant material and reduces the amount of phosphorus excreted in its dung. GM can also be used for inserting a growth hormone gene in pigs, a trait that can boost meat production efficiently.

Animal farming also contributes to climate change. It causes a quarter of anthropogenic methane emissions and 14% of nitrous oxide emissions.[3] The quantities of these greenhouse gases released are set to grow considerably with increased meat production, making traits targeted at reducing them highly desirable.

An ability to reproduce animals that are highly productive or have other desirable traits by cloning may be valuable in livestock production. However, the technologies used to date are still at an early stage, as the low success rates make clear. [20]

Diseases are a major limiting factor in animal production. Climate change could extend the range of insects that spread many diseases, leading to risks of even larger losses. GM pigs that have been modified to express a gene-imparted resistance to influenza are one example of a means of mitigating diseases.

Since many diseases are caused by viruses, vaccine development is another vital application of biotechnology in animal production. For example, strains of African swine fever have been sequenced, making vaccine development feasible.[3] Another achievement is quick diagnostic tests that detect specific antibodies for diseases, enhancing speedy identification at early stages and facilitating treatment. Tests have also been developed for rinderpest, which affects cattle in Eastern Africa. These, combined with vaccines against the virus, have led to virtual elimination of the disease.[3]

Aquaculture and sustainable fish farming

Fish contributes half the dietary protein of 400 million people and is a vital food staple for many more in developing countries.[3] Overfishing is a significant threat to wild fish resources. Fish farming has been growing since the 1970s and, if developed wisely, could help relieve pressure on limited wild fish resources. To this end, improving nutrient uptake in farmed fish is crucial, since wild fish are caught and used on a large scale as feed in aquaculture. GM has been used to introduce a promoter for overproduction of growth hormone in fish. This can enhance growth dramatically in several species. Another strategy is to breed more productive strains. This has been done successfully in Nile tilapia (*Oreochromis niloticus*), a species often used in aquaculture, resulting in yield gains of 78% without higher production costs.[3] GM could also be used to transfer cold-tolerance genes from flounder to salmon, making it possible to farm them in colder regions.

Food with improved nutritional value

Developing crops and animals with traits for producing healthier food is a promising strategy for mitigating nutrient deficiencies. One example is the transgenic Golden Rice, in which genes for producing beta-carotene, a vitamin A precursor, have been introduced. The rice, which is ready for market launch, is expected to be an effective source of vitamin A, that could reduce dietary deficiency in India and save 40,000 lives a year at a low cost.[25] However, since 2002 IPR and regulatory processes have delayed its widespread release.

Other ongoing GM projects for introducing nutritional advantages include raised levels of lysine and other essential amino acids in potato, sorghum and wheat, as well as vitamin C in cereals, and modification of cassava to exclude natural toxic components that otherwise need to be removed during processing.[30] In livestock production, GM soybeans could be modified to produce a precursor for beneficial omega-3 fatty acids, and traits for producing milk with less lactose or cholesterol have been introduced in transgenic cows.[28]

Conventional breeding programmes also aim for biofortification. Protein-rich maize has been developed and is grown in several developing countries.[30] Genetic factors influencing concentrations of essential minerals in crops have been overviewed and breeding programmes are under way to raise the content of iron and zinc in staple foods.

Future potential for biofortification

Current development in biofortification focuses mainly on simple nutritional traits. With the growing genetic and biochemical understanding of connections between diet and good health, the potential for more far-reaching nutritional traits is huge. Fruits and vegetables could, for example, be improved to contain higher levels of compounds affording protection against cancer, or carbohydrates in potato could be replaced by their counterparts with lower glycaemic indices. Research could identify several other beneficial compounds that interact with biochemical pathways involved in disease development.[30]

However, there are often trade-offs between higher nutritional value and yield, either directly when plants invest energy in producing desired compounds, or indirectly when pest insects prefer fortified crops and thereby increase losses. These trade-offs call for well-considered decisions in breeding programmes and GM research, so that crops conferring the greatest socioeconomic benefits can be developed.

GM and other technologies could also be used in food processing, not only in crop development. For example, fermentation of food is important for improving bioavailability of iron, vitamins and amino acids. GM could be used for developing fermenting yeast that produces omega-3 fatty acids or reduces the precursors for carcinogenic acrylamide. Using fermentation and other food processes for biofortification could be a more cost-effective strategy than modifying crops.[30]

Biotechnology could also be a tool for developing crops containing smaller quantities of heavy metals and other toxic compounds. Some soils in Asia are naturally polluted by arsenic, cadmium and mercury, and industrial pollution with various chemicals is a worldwide problem. Modifying the accumulation of pollutants in crops could be a way of making such soils safe for food production.

Societal aspects of biotechnology in agriculture

Evidently, biotechnology affords wide-ranging potential for improving crops and livestock for future food production. However, even if these are attained successfully, several vital obstacles remain before new innovations can be approved, efficiently adopted by farmers and accepted by consumers. Using biotechnology to revolutionise agriculture will also have long-term social and economic effects at local, as well as global, level.

Concerns are expressed about large multinational companies' monopolisation of seed markets. Gains from innovations need to be extended to developing countries' agriculture, rather than benefiting industrialised food production alone. This is impeded by certain concerns applying especially to GM products, including concerns about safety, effectiveness of regulation, effects on non-adopters and the ethics of gene transfer between species.

IPR legislation and need for public investments

Introduction of strong IPR legislation in the biotechnological field has been followed by a consolidation process that has made the seed market what it is today, dominated by a few large companies.[23] Private-sector research tends to focus on major crops and large markets. IPR instruments could also inhibit seed-saving and undermine local research and public breeding Programmemes.[33]

Thus, public initiatives are needed for applications that are not, perhaps, economically motivated but have a significant impact on food security or sustainable production. The genomic resources for many key crops in developing countries are now known, through public and international initiatives. However, public plant-breeding institutions in developing countries are threatened by lack of funding, which slows down the development of locally adapted crop varieties. Reliable phenotypic data on both major and more local crops are also lacking, owing to lack of field testing infrastructure.[27]

Biotechnology is not the only solution for sustainable food production. New agricultural practices and broad social development in developing countries are equally important, and varying approaches will be needed for different regions and conditions. This calls for balanced public investments, both in radical new approaches that may have major repercussions on productivity and in ways of delivering modest improvements on a shorter timescale. There is, for example, concern about what is seen as an excessive focus on GM, leaving less money available for investment in other key areas of biotechnology and agricultural science, including conventional breeding and development of new practices. Educating farmers as well as integrating traditional and local agricultural knowledge in development are other fundamental ways of enhancing food security.[33]

Regulation of GM products

There are several concerns about how GM products could affect human health and the environment. To eliminate risks of allergies and other health problems, as well gene drift, weed resistance and biodiversity depletion, GM products are regulated with respect to field trials and final market introduction. Regulations must be designed and balanced to identify hazardous innovations and give consumers confidence in products that are released but, at the same time, not restrict technological development and lead to unnecessary costs.

In the EU, joint Community legislation on authorisation of GM organisms has been in place since the early 1990s and amended several times. New laws and authorities have been developed for handling GM products. The European Food Safety Authority is responsible for risk assessment of products, in which GM products are tested and compared with their conventional counterparts. This is followed by the European Commission's approval or refusal — a decision that must be approved by the member states.

In the US, legislation relies on pre-existing laws and agencies that do not distinguish GM products from other crops.[23] Release of GM crops requires authorisation by the Department of Agriculture, based on experimental data on food and environmental safety. GM products can also be approved by the FDA, but this is voluntary since GM products are not viewed differently from similar conventional products.

Different regulations have resulted in different assessments of GM crops. In 2008, 14 of 24 GM traits or stacked traits approved in the US were not approved in the EU. This contributes to disharmony in international trade and may lead to higher food and feed prices.[23]

Regulation costs also pose a threat to innovation, especially in public research with limited resources. Compliance costs for launching new HT or IR crops are, for example, estimated at USD 6–15 million — which often exceeds development costs.[25]

Risk assessment and precaution

GM products pose a particular challenge to legislators. They have to deal with risks that may occur in a complex system, where the outcome is hard to predict but could exert serious negative effects on both public health and the environment.

In regulation of new GM products, ways of implementing precautions effectively, without restricting the introduction of new innovations and leading to unnecessary costs, are challenging. Another difficulty is that both adopting and rejecting new technology entail risks. Assessments often concern only the risks associated with introducing a GM crop, for example, while neglecting the risks associated with missing out on its possible benefits.

The EU regulatory framework has several precautionary dimensions. However, it applies the same pre-testing measures to all products on a case-by-case basis, rather than screening for and focusing on the more problematic cases. Alternatively, pre-release testing could be applied in a series of decision processes, to identify the safer GM products as well as those where more risk information is needed.[26] Applying the precautionary principle should also include post-release surveillance of negative effects.

Identifying unintended effects

Thanks to existing regulations, GM plants are among the most thoroughly analysed food products. Today, EU regulation focuses on comparing GM crops with their traditional counterparts in terms of the composition of pre-selected nutrients and toxins. However, the fact that the analyses focus solely on known and predicted changes, and risk missing any unintended effects of the modification, is criticised. There are examples of unintended effects in GM crops, such as stem splitting and yield reduction in HT soybean, that affect agronomic performance. Unintended effects may also alter the nutritional profile of crops or affect their allergenic potential. More complex future GM traits will also increase the risk of unintended effects.[5]

New analytical tools based on modern biotechnology could help identify any unintended effects and analyse whether they may be hazardous. Broad profiling of thousands of gene expressions and compounds in plants or food products is one possible strategy. However, knowledge is still inadequate to interpret all the data from these analyses, since crop-composition databases are lacking and not enough is known about natural variation in plants.[5]

For crops developed by breeding, no risk assessments are required, even if unintended effects may also occur in new non-GM crops and cultivars. In breeding programmes, backcrossing is regarded as sufficient for removing such unintended effects. Lines are discarded on the basis of visible unwanted phenotypes and compared with control lines with known characteristics.

Labelling of GM food and coexistence

EU regulations are also being devised to ensure consumer choice regarding GM food. Mandatory labelling of GM food is stipulated. In the US, labelling is voluntary and there is a discussion about which of these strategies is preferable.[8]

The separation of GM products from other food products required in connection with mandatory labelling imposes additional costs on the food sector.[23] Mandatory labelling could also be interpreted by consumers as a sign that consuming the labelled products may be risk, although they are thoroughly tested and approved.[23] On the other hand, mandatory labelling ensures that consumers are informed about GM food and can make informed decisions, which is not the case with voluntary labelling.

Introducing GM crops could also affect non-adopters. There are concerns about pollen spreading to neighbouring farms. Gene flow may be a problem, especially for those whose markets depend on GM-free products, such as organic farmers. EU regulations therefore require GM farmers to take suitable measures during cultivation, harvest, transport, storage and processing to achieve sufficient segregation between GM and non-GM production.

Public concern about GM products

Since GM organisms were first developed in the late 1980s and the first GM crops were marketed in the mid-1990s, public opinion towards GM food in Europe has been negative. This arises from fears of health effects and potential environmental impact.

Development of herbicide-resistant weeds and gene transfer to non-GM crops have been observed.[34] Otherwise, GM products in the market have been reported safe to eat and have not led to any serious negative environmental impacts to date.[23] However, public confidence in Europe, in particular, has not recovered, even with new food-safety regulations and a moratorium on imported GM food until 2005.

One reason is that people consider the potential risks of GM products to be involuntary and uncontrollable. [11] Besides fears of health effects and potential environmental impact, public concerns include ethics and social effects of GM products.

The 'Eurobarometer' surveys of attitudes towards biotechnology have been carried out by the European Commission every three years since the early 1990s, based on a sample of approximately 1,000 in each EU member state. These surveys have provided abundant information about people's views of biotechnological applications in both the medical and the food sector, showing that GM products are the area least appreciated by the public. In the latest survey, about one quarter of respondents approved, while nearly two thirds disapproved of encouraging development of GM foods. There are differences between countries, with high positive shares in Spain, Portugal, United Kingdom and Ireland while France, Austria and Germany are more negative.

US public opinion, which is also studied in the Eurobarometer surveys, is generally more optimistic about GM food. Suggested reasons are that American consumers place more trust in regulators and perceive greater benefits from GM products. The absence of mandatory food labelling in the US, which means that consumers are less informed about the presence of GM food on the market, may be another explanatory factor.[8] Further, the intense press coverage of food biotechnology in Europe compared with the US seems to be associated with greater public concern, irrespective of whether articles are positive or negative.[14] In many European countries, too, non-governmental organisations have more access to decision-making forums and institutions than their American counterparts.[21]

Understanding attitudes to GM products

Research on public responses to GM food is growing. However, individuals' decision-making process is complex and can be influenced by a number of determinants. Attitudes to GM products can be divided into several areas. Economic issues include commercial costs and benefits, as well as corporate power and responsibility. Social issues include environmental and health implications, along with the associated risks and uncertainties. Finally, cultural issues include moral and ethical concerns that are raised by the new technologies.[21]

In general, three typical positions can be observed in public attitudes. Rejection of all GM foods may be based on ethical principles, while others may totally reject them because of the lack of perceived benefits. Thirdly, people may reject some applications and accept others, based on their assessments of the benefits and risks of each application.[19]

Initially, governments, legislators and industry thought that, given the widespread 'information deficiency' among lay people, providing facts about GM products would generate acceptance. This strategy has not worked at all well: public attitudes remain negative. Research has shown that popular opposition is not due to a lack of understanding of the technologies.[6, 32]

Rather, one reason for these persistent negative attitudes may be that the benefits of GM products are relatively unknown. Analysis of Eurobarometer data shows that nearly two-thirds of the respondents in Europe perceived no advantages, and only risks, in GM foods. Unclear benefits make rational assessment more difficult, and many people question the whole point of GM products.[12]

However, the public do not regard every benefit as important. There is a growing body of literature on consumers' acceptance of GM food and willingness to buy these products. Consumers are more willing to buy GM foods that benefit health and the environment than those with benefits in the form of lower prices and longer shelf life.[18]

Public lack of trust and government response

Government and industry are least trusted by the European public. People have greater confidence in sources that claim to protect individuals' wellbeing and the environment. Eurobarometer data show that the most trusted stakeholders concerning GM products are medical doctors, university scientists, consumer organisations and patient organisations.[18]

One reason for this lack of trust in government and industry may be that EU regulatory processes focus on GM technology only in terms of possible risks to the environment and public health, whereas ethical and social concerns are disregarded.[11] Moreover, risks are often viewed in the longer term by the public than in assessments of scientifically measurable risk. Risk assessments presented by legislators thus give the impression that public concerns are not taken seriously, and that assessment is based on insufficient scientific knowledge of long-term effects.[19]

In response to the negative attitudes and distrust in regulatory frameworks, government agencies and independent institutions have put forward several initiatives to boost public participation. Since the mid-1990s, technology reviews, citizen panels and focus groups have been designed to explore public concerns and to improve political decision-making and the democratic process.

There are also commercial aspects of public participation and including consumers early in product development, owing to the long time lag between initial research and final commercialisation of GM products. The risk of a negative market response after several years' expensive development jeopardises the return on private investment. Early involvement of consumers and other users could help developers find out which GM products are more likely to succeed on the market.[11]

Consensus conferences are perhaps the best-known tool for public participation. They are essentially forums for experts, decision-makers and lay participants. The non-experts formulate a statement after questioning the experts. This kind of conference provides input from the public to the political system and can also initiate a debate on new technologies. Large-scale public participation has been tried in the UK, for example. One lesson for future efforts to bring about public participation is that independent management is important. Another is that it is vital to develop a decision-making process that succeeds in incorporating technical, as well as social and political input.[17]

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